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Pediatric Hand and Upper Limb Surgery:

A Practical Guide

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Pediatric Hand and Upper Limb Surgery:
A Practical Guide

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What greater thing is there for human souls than to feel that they are joined for life – to be with each other in silent unspeakable memories.

—*George Eliot*

Other things may change us, but we start and end with family.

—*Anthony Brandt*

It is what you expect us to do, to dedicate this book to our supportive parents, Bill and Mary Waters, lk and Kap Bae; our lovely wives, Janet and Jeannie; and the joy of our children: Rebecca and James, Caroline and Julia. For us, it is the only thing we can do. Without them, we would be lost. Enough said.

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Acknowledgments

Service to others is the rent you pay for your room here on earth.
—Muhammad Ali

We have the good fortune of being blessed with both a talented and wonderful team. Since John Hall and Jim Kasser "opened the door" in our department for a "sternoclavicular joint to fingertip" subspecialty of pediatric hand and upper limb surgery back in 1989, our team of nurses, physician assistants, nurse practitioners, orthopaedic surgery residents, hand surgery fellows, research associates, administrative assistants, occupational and physical therapists, clinical assistants, and orthopaedic technicians, among others, have been dedicated to the children and adolescents for whom we care. We could never have learned what we have, and done what we did and still do, without their professionalism.

Our pediatric orthopaedic surgery partners are unique. There is a simple reason why no one has left our crowded hallway of offices: We openly discuss and disagree professionally without getting personal. It is all about better care, better science, and better surgery. Personal ego and reward are secondary to higher quality care. We humbly acknowledge your greatness and our good fortune to be true partners with you.

We recognize that parents trust us with the care of the most important element of their lives: their children. We understand the magnitude of that gesture, and we take it seriously every day and night. The hours spent trying to "get it right" so we can repay that trust are only remotely represented in the pages of this book.

Specifically, we recognize Virginia Brunelle, Katherine Brustowicz, and Rebecca Barron. Without your dedication, hard work, and compulsive behavior to do your best word by word, picture by picture, this book would not be what it is. We thank you.

Finally, we acknowledge it is all about the future. So this book is for all of you "youngsters" out there who will no doubt reach new horizons. Here's to you and what comes next. We spend every day trying to pave your way to greatness.

Peter M. Waters
Donald S. Bae

Introduction

A coach is someone who can give correction without causing resentment.
—John Wooden

Pediatric orthopaedics and hand surgery have evolved and merged in our professional lifetime. Sub-subspecialists are not uncommon in academic departments and clinical practices. Care of the pediatric upper limb and hand now extends from the sternoclavicular joint to the fingertip under the leadership of one team in many centers. Advances in surgery, medicine, radiology, and anesthesia have led to safer, higher quality care of patients at younger and younger ages. Conscious sedation closed reductions of fractures and dislocations in the emergency room are commonplace. Trauma care has moved from plaster casts to percutaneous pins and operative stabilization for most displaced, unstable fractures. Complex surgical reconstructions under general anesthesia in infants with congenital differences are safely performed regularly. Imaging advances (ultrasounds, magnetic resonance imaging [MRI], and computerized tomography [CT] scans) have improved analysis and care of intra-articular fractures in the skeletally immature, unusual congenital differences, malignancy resections and reconstructions, among others. Fetal imaging programs in many centers have led to an accurate diagnosis and initial consultation of congenital limb differences in utero. Arthroscopic reconstructions of shoulder instability, elbow osteochondritis dissecans, and wrist triangular fibrocartilage complex (TFCC) tears in adolescent athletes are frequent in referral-based practices. Microsurgery for digital replantations in the young; toe transfers for congenital and post-traumatic amputations; free muscle transfers; brachial plexus nerve reconstructions; and free vascularized fibular grafting of pseudarthrosis from neurofibromatosis, allograft nonunions, and the sequelae of complicated infections or trauma, though rare, are all a part of the care of the pediatric hand and upper limb. Hand transplantation in the child may well be the next application of those technical skills.

This book will guide the reader to the present indications for intervention and care in upper limb pediatric disorders. The 50 chapters are subdivided into (1) Congenital (Chapters 1-19); (2) Neuromuscular (20-23); (3) Trauma (24-38); (4) Sports (39-42); (5) Soft Tissue and Microvascular (43-46); and (6) Tumor (47-50). Each chapter and each section are meant to stand alone but together provide a comprehensive and detailed description of all elements of evaluation and treatment of infants, children, and adolescents with maladies of the hand and upper limb. The words and pictures represent our daily work but clearly include the thoughts, creative inventions, and professional expertise of many pediatric surgeons and clinicians.

Each chapter has a case presentation; series of clinical questions; and fundamentals section on etiology and epidemiology, clinical evaluation, and surgical indications. The surgical procedures portions of each chapter are divided into green circle, blue square, black diamond, and double black diamond subsections. Care of children with these disorders requires various levels of knowledge, technical skill, and experience, much like proficiency in a sport, such as downhill skiing. Similarly some problems are just harder and more complex than others, again analogous to the differences between a beginner slope and a mogul run. For general guidance, our definitions of the surgical skills and case complexity used are as follows: (1) **Green Circle**: orthopaedic, plastic, or general surgeons who by interest or geographic necessity do routine pediatric hand and upper limb surgery; (2) **Blue Square**: graduates of pediatric orthopaedic or hand surgery fellowships with an interest in a career involving some parts or all elements of specialized pediatric hand and upper limb care; (3) **Black Diamond**: subspecialist surgeons with vast experience and expertise; and (4) **Double Black Diamond**: either veteran surgeons who exclusively care for pediatric hand and upper limb disorders or the truly gifted master surgeons regardless of age or training. We hope this classification of both the surgical skill necessary and degree of difficulty of each case is helpful to the reader and not presumptuous. In the end, we only want what is best for you and the children. Our aim is the highest quality, safest care.

In addition, each chapter details postoperative care, anticipated results, complications, case outcome, and a summary section. There are **Coach's Corners** and **Sidebars** to highlight technical tips and unique situations and provide deeper insight into the conditions described in each subsection. The images and illustrations are meant for you to truly visualize the specific surgical challenges we face. We hope it works for you. Along the way, we have tried to amuse and enlighten you with our selected quotes, which are mostly aligned with our sports analogy.

One day something is going to happen on an airline that is not in the book and you need to figure it out.
—Gordon Bethune

Finally, we know this book will not be all inclusive. There are at minimum, variations of the conditions outlined herein that will require you to apply the principles of care you have learned. Also, there will be problems that you may only see once in your lifetime. Those case report–type situations are amenable to your creative, Double Black Diamond solutions.

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CHAPTER 1

Embryology and Development

CASE PRESENTATION

A 39-year-old G2P1 mother presents for prenatal consultation for an abnormality noted on screening ultrasound at 18 weeks of gestation (Figure 1-1). The mother is otherwise healthy, and the pregnancy has been uncomplicated. There is no family history of congenital upper limb differences. Prenatal consultation has been requested to discuss the etiology of the finding and potential clinical treatments.

CLINICAL QUESTIONS

- When during embryonic development do the hand and upper limb form?
- What are the signaling centers of the developing limb bud? What do they control?
- Which proteins are critical for the activity of the developing limb bud's signaling centers?
- How are congenital hand differences classified?

THE FUNDAMENTALS

Overview of Epidemiology and Treatment Principles

Congenital differences of the hand and upper limb are common, affecting up to 1:626 live births.[1–4] The true incidence of abnormalities in upper limb differences is likely to be higher, owing to the association with other systemic anomalies resulting in fetal loss as well as the fact that many differences are so mild as to not command clinical recognition or evaluation. Familiarity with normal patterns of growth and developmental milestones is essential for the pediatric hand and upper extremity surgeon. Furthermore, understanding of the normal genetic mechanisms and embryology of the hand and upper limb is critical in understanding pathoanatomy, guiding surgical treatment strategies, and directing future efforts toward biologic solutions.

It is important to remember, in all of these discussions, that the ultimate goal of the pediatric upper limb surgeon is to maximize function and outcomes, while being sensitive to issues regarding aesthetic appearance, family dynamics, and social perception.

The purpose of this chapter is to provide a primer of hand and upper limb development—embryologic and genetic—and describe the language with which we classify congenital differences. While by no means an exhaustive scientific treatise, the information here will help to guide the surgeon in understanding principles for contemporary care as well as future investigation.

Limb Development and Embryology

You got to be careful if you don't know where you're going, because you might not get there.
—Yogi Berra

The hand and upper limb arise from a single limb bud, which comes from the lateral body wall at 26 days of gestation in humans (Table 1.1).[5] The limb bud, which is comprised of mesodermal cells covered in ectoderm, bulges at the junction of the dorsal and ventral surfaces. The mesoderm of the limb bud develops from both the somatopleure and the lateral plate. The somatopleural mesoderm contains the precursors of muscle, nerve, and blood vessels, while the lateral plate mesoderm forms bone, cartilage, and tendon (Figure 1-2).[7]

Upper limb development then proceeds in a proximal-to-distal fashion, ending at the 8th week of gestation, at which time all the structures of the upper limb have been formed. The mesenchymal cells coalesce to create a preskeletal blastema in the central portion of the limb bud. These cells then

FIGURE 1-1 Three-dimensional prenatal ultrasound depicting a transverse failure of formation of the left upper extremity at 18 weeks' gestational age.

differentiate into either chondrocyte or osteoblastic precursors. Chondrification begins with the humerus at 36 days of gestation and ends with the distal phalanges at day 50.

Joints develop by repression or regression of chondrogenesis (so-called cavitation), mediated by the WNT4, WNT14, and cartilage-derived morphogenetic protein-1 proteins. The shoulder joint appears at day 36 and proceeds until the formation of the interphalangeal joints at day 47.[5,8,9]

The muscles of the upper limb are formed and identifiable by the 7th week. In general, superficial muscles develop before deep muscles, and proximal muscles precede distal ones.

Nerve ingrowth begins at day 36, though the mechanisms by which this occurs remain unknown. The neural tube is the source of future sensory nerves, whereas the neural crest gives rise to motor branches.

The subclavian artery is apparent by the third week of gestation, and the arterial tree of the upper limb is present

Table 1.1

Timeline/progression of limb development[6b]

Gestational Day	Embryonic Stage	Developmental Events
21	9	Notochord expresses Shh
26	12	Upper limb bud forms
31	14	Limb bud curves
33	15	Formation of hand paddle Subclavian/axillary/brachial arteries form
36	16	Nerve trunks enter upper limb Chondrification of humerus and forearm Glenohumeral cavitation begins
41	17	Digital rays visible Chondrification of rays Ulnar artery forms
44	18	Chondrification of proximal phalanges Radial artery forms Pectoralis muscle splits into two heads
47	19	Chondrification of middle phalanges Initial separation of digits Digital cavitation/joint formation begins
50	20	Chondrification of distal phalanges Digital separation
54	22	Humerus ossifies Digital separation complete
56	23	Ossification of distal phalanges Nutrient vessel forms in humerus

Adapted from Al-Qattan et al, JHS, 2009.

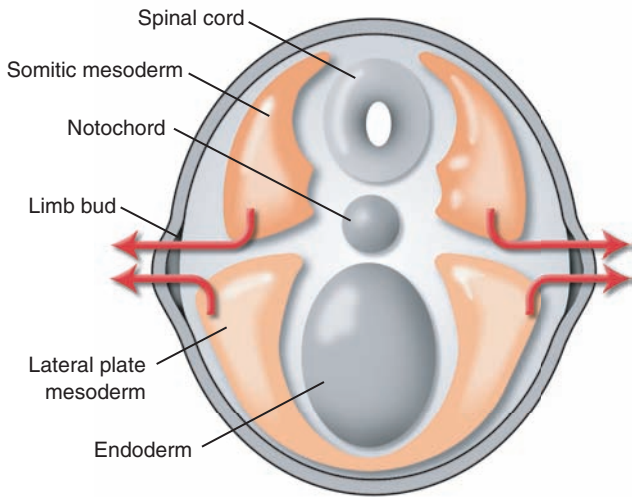

FIGURE 1-2 Schematic diagram of the developing limb bud.

at day 30. The median artery is the first to arise from the brachial artery. The ulnar artery develops shortly thereafter, forming the deep palmar arch in the hand. The radial artery is the last major distal branch to form, followed by the regression of the median artery.[10]

Hand formation begins with a single chondrogenic condensation at the end of the developing limb bud, surrounded by the precursors to tendon and muscle. With growth, this becomes the hand plate, and over time the rays form and are separated by flattened interdigital tissue. The hand plate appears at day 37, and the digital rays are identifiable by day 41. Through programmed cell death, or apoptosis, the interdigital tissue recedes, allowing formation of individual digits.[11] This process is initiated at day 47 and is completed by day 54 of gestation.[12] Digital separation proceeds in a distal-to-proximal fashion, explaining the phenomenon of incomplete simple syndactyly. The process of apoptosis is mediated by a number of gene products, including fibroblast growth factors (FGFs), Msx, and HOX7 (homeobox gene).[13–15] Each digit has its own "identity," according to its position on the hand plate. TBX2 and TBX3 are transcription factors that regulate bone morphogenetic proteins (BMPs), perhaps controlling digital formation and identity.[16,17]

The Genetics and Molecular Biology of Limb Development

Be at the right place, at the right time, and do the right thing.
—Elton Hall

The process of normal hand and limb development is exquisitely complex and coordinated. In general, limb development can only proceed uninterrupted and undisturbed with three "rights": the *right* proteins are regulated and secreted by the *right* cell(s) at the *right* time. Insights into the genetics and molecular biology of hand and upper limb development are, in essence, focused on understanding these three rights.

Three distinct signaling centers have been identified that guide and regulate limb development through cell-to-cell interactions and release of growth factors and other molecules (Table 1.2). Each signaling center is responsible for one axis of limb development: proximodistal, anteroposterior (radioulnar), and dorsoventral.

Much of the information about limb development, the role of varying signaling centers, and the factors they secrete comes from classic animal studies and human genetic evaluations, particularly those in which the factor or center of interest is removed. In general, theories about the role of certain genes or proteins are proven by three types of observations or experiments. First, a protein is deemed important for a component of development only if it is present in the correct cells at the correct time. This is typically done by in situ hybridization studies. Second, absence of a particular gene or gene product must result in failure of formation. This information is obtained via genetic manipulation of appropriate animal models (e.g., gene knockout mice) or careful genetic analysis of humans with congenital differences. Finally, normal development should be rescued or artificially induced by supplying the protein or gene product in question after it has been genetically or physically taken away. Again, technologic advances in genetic manipulation, selective gene expression, and embryonic handling have allowed such experiments to be performed.

Table 1.2

The three signaling centers of upper limb development

Signaling Center	Developmental Role	Key Mediators	Examples of Abnormalities
AER	Proximodistal; interdigital separation	Fgf2, Fgf4, Fgf8, BMP-2, WNT3a, p63	Transverse deficiency; syndactyly
ZPA	Anteroposterior (radioulnar)	Shh, Gli3, Fgf10, Msx1, Nmyc, HOX genes	Ulnar longitudinal dysplasia; ulnar dimelia
WNT signaling center	Dorsoventral	WNT7a, En-1, Lmx1, r-FNg	Palmar duplication syndrome

The Apical Ectodermal Ridge and Fibroblast Growth Factors

The apical ectodermal ridge (AER) or rim lies at the distal tip of the developing limb bud and guides proximodistal growth and development (Figure 1-3). Just beneath the AER is the so-called progress zone. The progress zone contains cells of mesodermal origin. The current theory is that the longer cells remain in the progress zone, the more distal their ultimate differentiation location will be.

The AER is induced from epithelial-mesenchymal interaction, the exact mechanisms of which are under continued investigation. Part of this interaction involves the WNT signaling center, mediated by the fibroblast growth factor Fgf10.[18,19] Indeed, in the absence of WNT signaling, the AER and thus the limb fail to form.[20,21] This highlights the recurring concept that all three signaling centers continue to interact with one another to provide proportionate, appropriate growth.

Removal of the AER results in transverse failure of development and formation.[22,23] The earlier the AER is lost, the more proximal the transverse deficiency. Indeed, the inability to form an AER results in experimental amelia, supporting its role in proximodistal development.[20,21,24] Similarly, ectopic implantation of AER tissue results in formation of an extra limb at the implantation site.[5]

AER activity is mediated by several FGFs, including Fgf8, Fgf2, Fgf4, Fgf9, and Fgf17. Fgf8 is expressed by all cells of the AER and is therefore considered an AER marker. Addition of FGF can replace or duplicate AER function. For example, in experiments in which the AER is removed, provision of Fgf2, Fgf4, and Fgf8 can restore normal proximodistal growth.[23] Furthermore, additional sources of FGFs provided in the flank (interlimb) region may result in an extra, supernumerary limb.[25] Conversely, removal of FGF will simulate AER absence. Fgf10-deficient mice, for example, demonstrate complete transverse limb defects.[26]

Although FGF is the principal mediator of AER action, the underlying mesoderm beneath the AER provides signals to stimulate FGF production and secretion.[27] Again, timely interactions between signaling centers and adjacent cells are required for appropriate, proportional limb development.

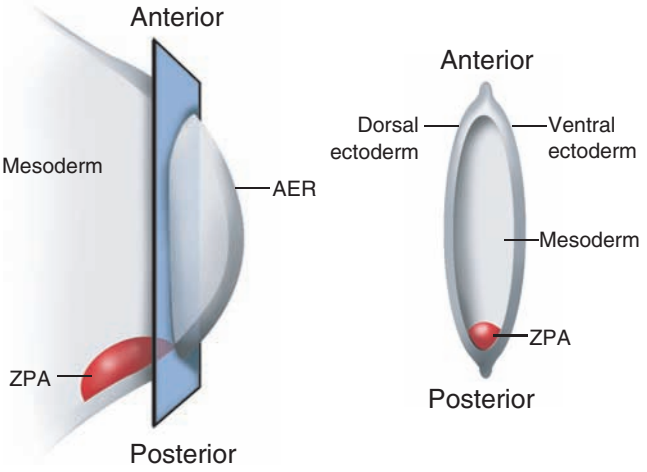

FIGURE 1-3 Schematic diagram of the limb bud, highlighting the key signaling centers.

Zone of Polarizing Activity and Sonic Hedgehog

The zone of polarizing activity (ZPA) is a cluster of mesodermal cells located on the *posterior* border of the developing limb bud (Figure 1-2). The ZPA guides anteroposterior (radioulnar) development.[28] The anteroposterior axis is the first to be defined, even before the limb bud is present. The initial description and insights into ZPA function were elucidated after classic grafting experiments, in which transplantation of posterior cells to the anterior aspect of the limb bud resulted in mirror-image ulnar duplications.[29] Furthermore, the number of abnormal digits was directly related to the number of ZPA cells transplanted.[30] Similar experimental results were obtained when retinoic acid was applied, which induced an additional or second ZPA to form.[31]

The ZPA mediates its action through the release of sonic hedgehog (Shh)[32] (Sidebar 1). Animal models of Shh deficiency have rudimentary and foreshortened limbs with absence of distal structures.[33–35] Ulnar longitudinal deficiency, for example, has been produced by eliminating Shh expression.[36,37] Conversely, ectopic expression or implantation of Shh protein into the anterior aspect of

SIDEBAR 1

I Thought Sonic Hedgehog Was a Video Game or a Fast Food Joint!

The history of Shh originates with, of all things, the fruit fly. Beginning with the classic studies of Wieschaus and Nusslein-Volhard in 1978 and culminating with the Nobel Prize–winning developmental experiments of Lewis, the hedgehog gene was discovered to control segmentation in *Drosophila melanogaster*.[73] Loss-of-function mutations of the *Shh* gene resulted in *Drosophila* embryos covered in small denticles, resembling the spines of a hedgehog.

Mammalian homologues were subsequently discovered, including desert hedgehog and Indian hedgehog, so named for the different hedgehog species. Shh, perhaps the most famous of all these developmental morphogens, was named after the eponymous character in the Sega video game released in 1991. Since then, analogous genes in other species have been named in flashes of scientific humor, such as tiggywinkle hedgehog of zebrafish. The practice of naming genes in whimsical and playful ways has been criticized by many in the scientific community, though its practice persists.[74,75]

In addition to its critical role in limb development, Shh has been found to play a part in brain, spinal cord, gastrointestinal, pulmonary, and dental development.

the developing limb in chick embryos results in mirror duplications of the limb. These findings have been corroborated by research with mutant mice, in which aberrant Shh expression from a duplicated ZPA results in polydactyly.[38]

Not surprisingly, Shh also plays a role in maintaining proximodistal growth and thus proportionate limb development. Shh induces Fgf4 expression in the AER via a positive feedback mechanism.[39,40] Deletion of Shh or ZPA results in shortened or absent limbs.[41,42]

The WNT Signaling Center

Dorsoventral patterning depends on non-AER ectoderm, though this is the least well understood of the three axes of limb development. A key protein in dorsoventral patterning appears to be the wingless-type mouse mammary tumor virus integration site family, member 7a (WNT7a), which guides the development of dorsal structures by inducing the HOX gene Lmx1. WNT7a-deficient mice have biventral limbs with duplicated palms.[6,43] Overexpression of Lmx1 results in the opposite phenotype, that of mirror-image dorsalization of the limb. Lmx1 deficiency in humans and mice results in nail patella syndrome.[44,45]

The ventral ectoderm expresses Engrailed-1 (En-1), which controls ventral patterning by restricting WNT7a expression. En-1–deficient mice, not surprisingly, develop bidorsal limbs.[46]

Again, demonstrating the interaction among signaling centers, WNT7a has been shown to induce Shh, explaining the link between shortened and ulnar-deficient limbs in animal models of WNT7a mutations.[47] A summary of signaling center interactions is seen in Figure 1-4.

While these signaling centers have been well established and the primary mediators of the functions (FGF, Shh, WNT7a) described above, a myriad of other factors also play a role in upper limb development, including the HOX genes, BMPs, transforming growth factors (TGFs), and others (see Sidebar 2).

SIDEBAR 2

What the Heck Is a HOX?

The HOX genes encode a family of transcription factors important for limb development. First discovered in *Drosophila* in 1978, these genes are remarkably conserved throughout animal species.[76] In *Drosophila*, the HOX genes are critical for segment identity along the anteroposterior body axis. Mutations resulting in loss of function or aberrant expression include, for example, flies with abnormal numbers of wings and antennae replaced by wings. Indeed, the ability of HOX genes to change one body segment into that of another gave rise to the name "homeobox" or "homeotic" genes.

There are four clusters or groups of human HOX genes, denoted by HOXA, HOXB, HOXC, and HOXD. Each cluster is located on a different chromosome (7p14, 17q21, 12q13, and 2q31, respectively), and in total they account for approximately 40 HOX genes. Differential expression of the HOX genes is known to occur during limb development. Indeed, each of the HOX genes is expressed in different locations at different times of development. Furthermore, the location of the genes corresponds to the time of their expression. Genes located at the 3′ end of the DNA are expressed earlier, anteriorly, and proximally. Conversely, genes at the 5′ end are expressed later, posteriorly, and distally.

HOXD genes, for example, are key players in radioulnar differentiation. Indeed, different HOXD genes have been shown to correlate with each of the five digital precursors of the developing hand.[77] Mutations in HOXD have been identified in synpolydactyly in humans, though the exact mechanisms of these effects and malformations are not yet completely understood.[58,78] Another example is hand-foot-genital syndrome, manifested by hypoplastic thumbs, short halluces varus, pointed distal phalanges, and abnormalities of the lower genitourinary tract.[78] This condition has been associated with HOXA13 mutations.

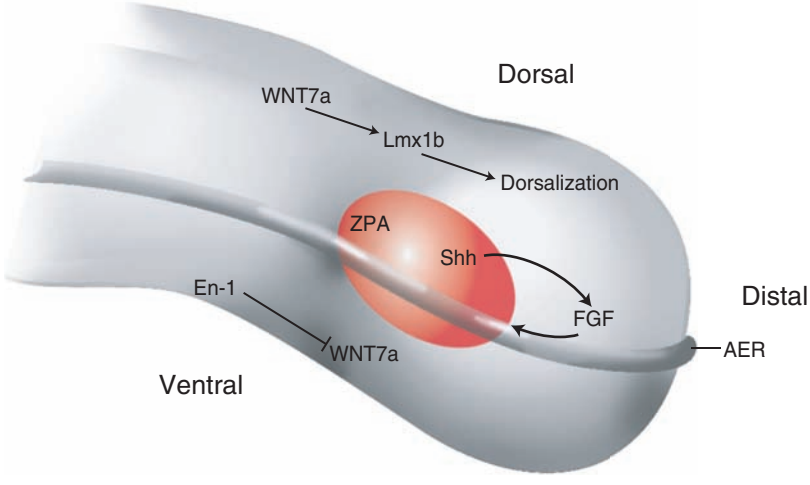

FIGURE 1-4 Summary of signaling center interactions during limb development.

Table 1.3

Genetic abnormalities in congenital hand differences

Category	Gene	Phenotype	Species	Associations
Ligands	BMP-7	Preaxial polydactyly	Mouse	Hindlimb affected
	CDMP/GDF-5	Brachydactyly	Human	Grebe chondrodysplasia; Hunter-Thompson syndrome
	Fgf10	Transverse deficiency	Mouse	
	Ihh	Preaxial polydactyly	Mouse	
	Noggin	Symbrachydactyly	Human	
	Shh	Transverse deficiency	Mouse	
	WNT1	Transverse deficiency + syndactyly	Mouse	
	WNT7a	Palmar duplication	Mouse	
Receptors	BMPR IB	Brachydactyly	Mouse	
	FGFR1-3	Brachydactyly	Human	Apert, Jackson-Weiss, Crouzon, Pfeiffer syndromes
	Patched	Preaxial polydactyly	Mouse	
Transcription factors	Alx-4	Preaxial polydactyly	Mouse	
	CBP	Broad thumbs	Human	Rubinstein-Taybi
	Gli3	Polysyndactyly	Human	Pallister-Hall; Greig cephalopolysyndactyly
	HOXA13	Brachydactyly; preaxial digital loss	Human	Hand-foot-genital syndrome
	HOXB-8	Mirror duplication of hand	Mouse	
	HOXD12	Thumb loss; polydactyly	Mouse	
	HOXD13	Synpolydactyly	Human	
	HOXD-11-13	Synpolydactyly	Mouse	
	Lbx1h	Loss of dorsal muscles	Mouse	
	Lmx1b	Nail changes	Human	Nail-patella syndrome
	Msx-2	Brachydactyly, syndactyly	Mouse	
	NF-κβ	Limb truncation	Chick	
	p63	Limb truncation	Mouse	
	Pax-9	Preaxial polydactyly	Mouse	Cleft palate
	Prx-2	Postaxial polydactyly	Mouse	
	Sall1	Polydactyly	Human	Townes-Brocks syndrome
	SHOX	Brachydactyly, mesomelia	Human	Leri-Weill mesomelic dwarfism
	Sox-9	Campomelic dysplasia	Human	
	TBX-3	Ulnar dysplasia	Human	
	TBX-5	Radial dysplasia	Human	Holt-Oram syndrome
	Twist	Brachysyndactyly, clinodactyly	Human	Saethre-Chotzen syndrome
Miscellaneous	Connexin-43	Transverse deficiency	Chick	
	CRABP-II	Postaxial polydactyly	Mouse	
	Link	Short limbs	Mouse	

Adapted from Daluiski A, Yi SE, Lyons KM. The molecular control of upper extremity development: implications for congenital hand anomalies. *Journal Hand Surg.* 2001;26:8–22.

Congenital Differences Explained (Table 1.3)

You guys pair up in groups of three, and line up in a circle.
—Bill Peterson, former FSU football coach

Polydactyly

The etiology of polydactyly is certainly multifactorial and varied, given the complex interactions and broad window of time involved with digital formation. In essence, polydactyly is based upon the size of the limb bud and thus three factors: (1) the number of progenitor cells in the limb bud, (2) their rate of proliferation, and (3) the amount and regulation of apoptosis.[48] Experimental models have supported the concept that *FGF signaling* plays a critical role in polydactyly; while limited Fgf8 and/or Fgf4 production or knockouts result in hypoplastic limbs, increased FGF signaling in ectodermal tissue results in polydactyly.[49–51] Examples include doubleridge, a mouse mutation causing thickened AER and increased FGF signaling in the underlying mesoderm resulting in postaxial polydactyly. Fibroblast growth factor receptor 1 (FGFR1) mutations have similarly been seen to cause increased FGF activity leading to increased AER function, decreased apoptosis, and preaxial polydactyly.

FGF signaling is not the only pathway to polydactyly. *BMPs* are likely involved in hand development. BMP-7 expression has been localized to the perichondrium of phalanges and the fingertip ectoderm.[52] Mice models of BMP-7 deficiency have preaxial polydactyly, suggesting a role in digital suppression and/or interdigital apoptosis.[53]

Shh signaling has proven important as well. Members of the Gli family of transcription factors, and Gli3 in particular, have been shown to play a role in limb development by affecting Shh expression. Gli3 mutations have been associated with polydactyly in animal models as well as in humans (Pallister-Hall syndrome, Greig cephalopolysyndactyly, and type A postaxial polydactyly).[54] It is believed that absence of Shh converts Gli3 from a weak activator to a strong repressor function. In other words, Shh primes the mesoderm to produce digits by eliminating the presence of the Gli3 repressor.[55]

For these reasons, geneticists have proposed that polydactyly be classified in two categories according to whether they are Shh or Gli3R dependent or not. Group 1 includes those polydactylies in which there is anterior activation of Shh, resulting in mirror-like duplications with normal digital morphology; the difference between a true mirror hand and simple preaxial polydactyly may be a result of the timing and "strength" of this Shh signaling. Group 2 is Shh independent, resulting in lack of mirror digits and digits that are not normal in "identity."[56]

A host of other genes have also been implicated in polydactyly, including lst, lx, Xpl, Rim4, hx, and Ssq.[48] The *HOXD genes* have also been shown to control digit number and patterning, by both regulating Shh expression and acting downstream of Shh.[57] Mutations in HOXD13, for example, cause synpolydactyly syndrome.[58] Finally, Hand2 is a transcription factor with expression patterns similar to HOXD12. Hand2 controls Shh expression and is thought to mediate anteroposterior development upstream of Shh. Complex interactions and continuous feedback loops exist between Shh and the HOXD and Hand2 genes.

Syndactyly

Syndactyly is likely the result of failed apoptosis in the interdigital regions of the developing hand.[11] Given the multiple gene products and cell interactions responsible for programmed cell death, it is not surprising that a host of genetic causes have been identified. Apert syndrome, for example, has been linked to mutations in FGF receptors.[59] Other candidate genes, such as Msx-2, a transcription factor found in the interdigital mesenchymal cells, have similarly been implicated.[14]

Brachydactyly

Mutations or deficiencies of the BMP cartilage-derived morphogenetic protein (GDF-5 in mice) can lead to brachydactyly. Human examples and murine models have both been identified, thus confirming this assertion.[60,61]

Tetraamelia

As a host of factors are responsible for guiding and maintaining limb bud development, absence of Fgf10, WNT3/3a, beta-catenin, or p63 will cause tetraamelia.[62–64]

Classification of Congenital Differences

Far Right Tight 966 H-Swing
Queen Right 22 Razor
Under Right 74 All Hook
84 Y Pivot
Far Right Base Hank Fiat Swing
—The terminology used by the 1998 Baltimore Ravens, Chicago Bears, Cincinnati Bengals, New Orleans Saints, and St. Louis Rams, respectively, to call the exact same pass play (flanker and tight end curls)

Understanding the fundamental embryology and molecular biology of upper limb development is a daunting task for the pediatric hand surgeon at any level, especially with the genetic knowledge expanding rapidly. Also challenging is the description and communication of congenital differences. The ideal classification system would impart information about etiology, provide prognostic information, and guide treatment. To date, the optimal means of classifying congenital hand and upper limb differences has not been developed.[65]

Historically, congenital hand differences were classified according to their gross appearance. Descriptive terms with Latin and Greek origins were used to describe abnormalities. This proved difficult to remember, let alone spell, and led to confusion given the lack of uniformity with which these terms were used.

For this reason, a universal classification system was developed and adopted by the American Society for Surgery of the Hand, the International Federation of Societies for Surgery of the Hand, and the International Society for Prosthetics and Orthotics, based upon both morphologic characteristics and patterns of embryologic failure.[66–69]

Congenital differences are placed into one of seven categories (Table 1.4). Category I consists of failures of formation, further subdivided according to the pattern of failure—transverse versus longitudinal—as well as the segment affected—proximal, middle, distal, radial, or ulnar. Examples include radial longitudinal dysplasia, cleft hand, and phocomelia. Category II comprises failures of differentiation and encompasses bony, soft tissue, and tumorous abnormalities. Characteristic failures of differentiation include syndactyly, radioulnar synostosis, and clinodactyly. Category III consists of duplications and includes rare ulnar dimelia and common polydactyly. Category IV includes the overgrowth conditions, such as macrodactyly and hemihypertrophy. Category V consists of undergrowth phenomena, such as brachydactyly and limb hypoplasia. Category VI refers to the spectrum of differences seen with amniotic band syndrome, from congenital amputation to acrosyndactyly to distal lymphedema and superficial bands. Finally, Category VII consists of systemic or generalized skeletal conditions with hand and upper extremity manifestations, such as achondroplasia, multiple hereditary exostoses, and arthrogryposis.

Since 1976, many modifications and changes have been proposed to the universal classification.[70] One such modification has been proposed by the Japanese Society for Surgery of the Hand.[71] Two additional categories were added: abnormal induction of rays (including syndactyly, symbrachydactyly, and triphalangeal thumb) and "unclassifiable." Tonkin and others have proposed reorganizing the classification system to denote only descriptive features based upon location and type of tissue involved, akin to the Association for Osteosynthesis/Association for the Study of Internal Fixation universal fracture classification.[72] Still others have advocated for classification systems based upon molecular biology and the mechanisms by which congenital differences occur.[65]

While the universal classification system and its modifications have markedly improved the description and study of congenital differences, it is clear that not every condition fits neatly into one of these seven categories. Cleft hands, for example, often demonstrate central ray deficiency (longitudinal failure of formation), syndactyly (failure of differentiation), and polydactyly (duplication). Symbrachydactyly (formerly referred to as atypical cleft hands) similarly displays features of both failure of formation and undergrowth. Finally, there continue to be classification systems for specific conditions that have stood the test of time, owing to their historical importance, ease in assignment, clear prognostic implications, and guidance in treatment. The Wassel classification of preaxial polydactyly or the modified Blauth classification of thumb hypoplasia are prime examples. These individual classification systems will be presented throughout the text.

CASE OUTCOME

Based on prenatal imaging, the diagnosis of a transverse failure of formation (congenital below-elbow amputation) was made. The parents were counseled about the etiology, natural history, and potential clinical treatment options available (see Chapter 9). The pregnancy proceeded without

Table 1.4

The universal classification of congenital hand and upper limb differences

Type	Category	Clinical Example
I	Failure of formation	Transverse deficiency; radial longitudinal dysplasia
II	Failure of differentiation	Syndactyly; radioulnar synostosis; camptodactyly
III	Duplication	Polydactyly
IV	Overgrowth	Macrodactyly
V	Undergrowth	Brachydactyly
VI	Amniotic band syndrome	Amniotic band syndrome
VII	Generalized/systemic	Arthrogryposis; achondroplasia

A "DUMB JOCK'S" GUIDE TO MOLECULAR BIOLOGY

While the complexities and subtleties of molecular biology are far beyond the scope of this textbook, a review of general terms and concepts may guide the pediatric upper limb and hand surgeon of congenital hand anomalies. Much of the genetics and molecular biology are centered around fundamental cellular processes in the developing limb bud. When everything goes according to plan, formation of a "normal" hand and upper extremity ensues. When there are genetic mutations or developmental abnormalities, differences arise.

Proteins are the essential molecules during development (Figure 1-5). These proteins may serve as signaling factors, or ligands, which are synthesized and secreted from cells into the extracellular environment to interact with neighboring cells. Examples of such ligands include FGFs, Shh protein, and BMPs.

These ligands bind to receptor proteins on nearby cells, which initiate the process of signal transduction. Once activated by ligand-receptor binding, the targeted cells may change their function, differentiate, or proliferate. Examples of critical receptor proteins involved in upper limb development include BMP receptors, FGF receptors, and TGF-beta receptors.

Transcription factors are proteins that regulate the process of DNA transcription and thus protein synthesis by binding promoter regions of the DNA itself. When activated or deactivated, transcription factors drive cellular activity.

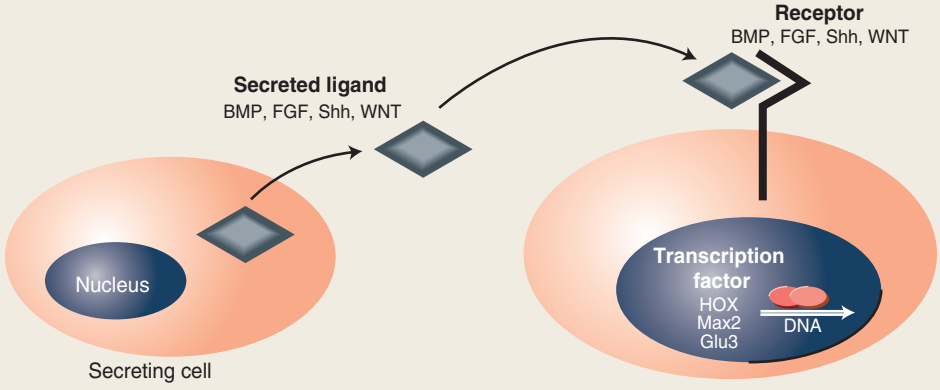

FIGURE 1-5 Schematic diagram of the proteins involved in cellular biology.

difficulty, and the child was otherwise healthy after birth, without any associated abnormalities. At 6 months of age, the option for prosthetic fitting with a passive terminal device was discussed, and the parents opted against prosthetic use.

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CHAPTER

2

Syndactyly

CASE PRESENTATION

A 6-month-old male infant presents for evaluation of a "webbed hand" (Figure 2-1). The child is otherwise healthy, and there is no family history of congenital hand differences. Examination demonstrates syndactylies involving the thumb, index, long, and ring fingers. Spontaneous but limited active motion is noted of all digits.

CLINICAL QUESTIONS

- What causes syndactyly?
- How common is it?
- Are there any associated syndromes or conditions?
- How is it classified?
- What are the indications for surgical treatment?
- When should surgery be performed?
- What are the surgical principles and techniques for syndactyly?
- What are the results of surgical treatment?
- What complications may occur with surgical care?

THE FUNDAMENTALS

Hand function is dependent upon independent digital motion. Supple web spaces allow for flexion, extension, and abduction during all activities of daily living, particularly in the keyboard-driven society we live in today.

Syndactyly, or "webbed fingers," is thought to be one of the most common congenital hand differences presenting to pediatric hand and upper extremity surgeons. Given the limitations of independent digital function, as well as aesthetic differences, surgical treatment is typically recommended in patients with congenital syndactyly.

Etiology and Epidemiology

Simple syndactyly occurs in approximately 1:3,000 live births.[1,2] Males are affected more commonly than females, and Caucasians more than Blacks or Asians. Inheritance pattern is thought to be autosomal dominant with variable expressivity and variable penetrance, though sporadic cases are quite common. Often bilateral, the feet and toes may also be involved. In general, the third web space is most commonly affected, followed by the fourth, second, and first web spaces. The pneumonic "5-15-50-30" may be used to remember the frequency of web-space involvement from first to fourth (Figure 2-2).

Syndactyly results from a failure of differentiation. During upper limb development, the hand segment forms as a "paddle" at roughly the fifth week of gestation. Interdigital clefts are created via apoptosis, mediated by the apical ectodermal ridge and proceeding in a distal-to-proximal fashion. Failure of proper or complete interdigital separation leads to syndactyly and explains the clinical phenotypes commonly encountered. Efforts

FIGURE 2-1 A 6-month-old male infant with syndactylies of the first, second, and third web spaces.

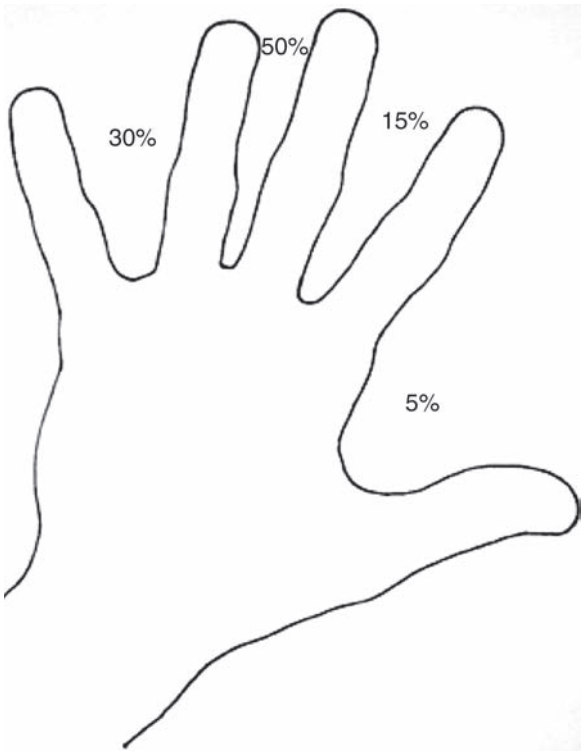


FIGURE 2-2 Schematic diagram depicting the prevalence of web-space involvement in cases of simple and complex syndactylies.

continue to characterize the genetic and molecular mechanisms behind syndactyly.[3] In cases of autosomal dominant syndactyly, candidate regions have been identified on the second chromosome (2q24–q36).[1] Other variations of syndactyly have been linked to mutations in the HOXD13 gene, also located on chromosome 2.[4,5]

Clinical Evaluation

You can observe a lot just by watching.
—Yogi Berra

Understanding of normal digital web-space anatomy is necessary to evaluate abnormal situations. Typically, the index-long and ring-small finger commissures are U shaped, while the long-ring web is V shaped. The nonglabrous skin of the normal web space is sloped approximately 45 degrees from proximal-dorsal to distal-volar, extending to roughly the midpoint of the proximal phalanx. The natatory ligaments (or superficial transverse metacarpal ligament) help form the web contour and join adjacent lateral digital sheets. This supple skin and soft tissue complex allows for interdigital abduction of up to 35 and 70 degrees of abduction between the thumb and the index.[6]

Normally, each digit receives its vascularity in part via a radial and ulnar digital artery, which arises from the bifurcation of the common digital arteries. However, of critical surgical importance is the fact that the bifurcation of the digital arteries and nerves may be abnormally distal in cases of syndactyly.

The diagnosis of syndactyly is not subtle, and the extent of digital involvement (i.e., incomplete vs. complete) is readily apparent on clinical inspection. More careful observation will typically distinguish between cases of simple, complex, and complicated syndactylies. The presence of passive and active interphalangeal (IP) joint motion with well-formed flexion and extension creases implies normal joint anatomy and is consistent with simple syndactyly. In patients where creases are absent and IP joint motion is absent, complex or complicated syndactylies should be suspected.

Standard plain radiographs of the affected hand will confirm the presence of fused bony elements and any other associated anomalies. In cases of syndactyly associated with other clinical syndromes, such as Poland, Apert, or amniotic band syndrome, evaluation of the entire upper extremity, chest, feet, and head/face will reveal other abnormalities.

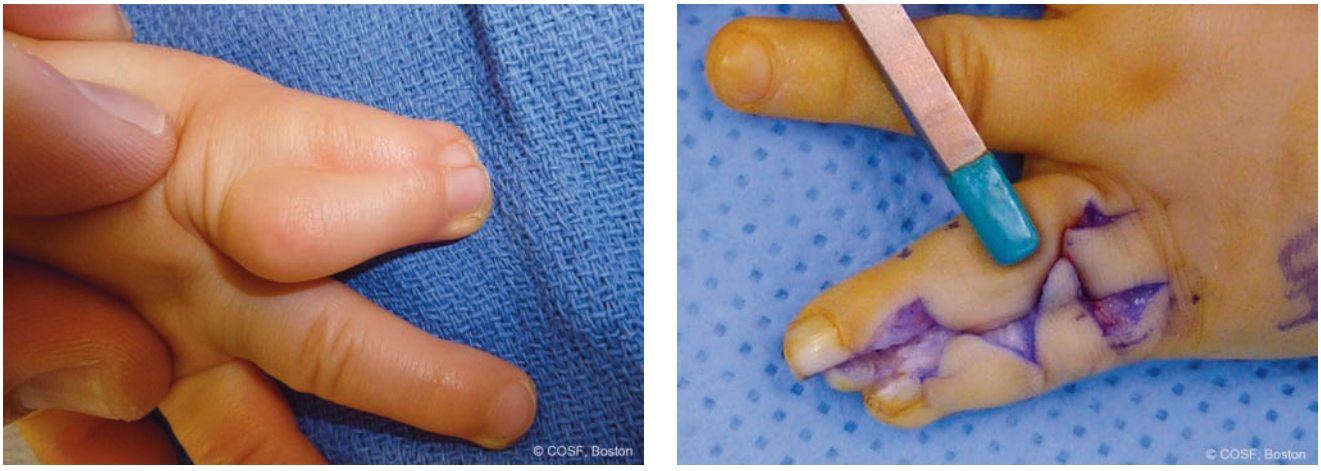
Syndactyly is classified according to the extent of digital involvement and the character of the tissue involved. "Complete" syndactyly extends to the digital tips, whereas "incomplete" syndactyly ends proximal to the fingertips. "Simple" syndactyly refers to digits connected only by skin and soft tissue. The nail plates may or may not be fused. "Complex" syndactyly denotes bony fusions between adjacent phalanges. "Complicated" syndactyly refers to the interposition of accessory phalanges or abnormal bones between digits. In simple syndactyly, the joints, ligaments, and tendons of the affected digits are usually normal.

Surgical Indications

There are really only two plays: Romeo and Juliet, and put the darn ball in the basket.
—Abe Lemons on basketball

Surgical release is recommended in all but the most mild of incomplete syndactylies. While indications for surgery are clear, controversy continues to surround issues related to the timing and technique of separation. Indeed, the question is not "whether to do surgery" but often "when" and "how" to do it.

Timing of surgery remains controversial and must be determined on an individual patient basis. Flatt has previously written: "I believe one should ask not how soon the operation can be done but rather how late the functional demands of the hand will allow postponement of surgery."[7] In general, surgical release of simple complete syndactylies of the second or third web spaces may be safely and appropriately delayed until 18 months of age with no adverse effect on hand function or fine motor development.[8–10] Advantages of later surgery include operating on



A B

FIGURE 2-3 Deformity secondary to syndactyly of border digits. **A:** Clinical photograph of a fourth web simple complete syndactyly. Note is made of flexion and angular deformity of the ring finger, due to the tethering effect of the small finger. **B:** After surgical release, the ring finger is easily extended, and longitudinal alignment is restored.

a hand after much of the subcutaneous fat has involuted, allowing for easier mobilization of skin flaps and greater coverage. In addition, the hand will roughly double in size during the first 3 years of life; operating on a hand after more of this growth has occurred will minimize the complications of web creep and clinically significant scar contractures. Earlier surgery is recommended for the border digits, as syndactylies of digits of disparate length will result in flexion and angular deformities if left unattended (Figure 2-3). In these cases, surgery may be initiated at 9 months of age. Currently our preference is to perform syndactyly releases of the second and third web spaces at 12 to 18 months of age, with earlier releases of the thumb and small finger for the reasons described above.

Contraindications to surgical release are few. First and perhaps most importantly, great caution should be taken when attempting to release a "super digit."[11] This term is used to describe a large digit supported by two metacarpals (type I) or syndactylized digits supported by a single metacarpal (type II). Although surgical separation may be technically feasible, this often results with angular deformity and loss of motion in the separated digits, leading to compromised hand function. Indeed, the presence of a single, functioning, though aesthetically different super digit is preferred over two separate, stiff, crooked, nonfunctioning digits. The second contraindication to surgical release applies to cases of complex synpolydactyly, in which multiple conjoined digits (or bony elements) are fused yet move and function as one. Again, while technically feasible, surgical release may result in compromised hand function due to the unpredictability of motion and alignment postoperatively.

SURGICAL PROCEDURES

Perhaps the single most important element in mastering the techniques and tactics of racing is experience. But once you have the fundamentals, acquiring the experience is a matter of time.
—Greg Lemond

While techniques of separation vary, a number of general surgical principles apply to almost all syndactylies. First, digits of differing lengths should be released early to prevent deformity and growth disturbance of the affected digits. Second, both sides of a single digit should not be operated upon at the same time to avoid vascular embarrassment. Third, local vascularized skin flaps should be used to re-create the commissure to avoid scar contracture and "web creep." Fourth, interdigitating zigzag lateral flaps should be created to avoid longitudinal scar contracture. Fifth, judicious defatting of the skin flaps should be performed to facilitate skin closure, reduce tension across the flaps, and improve the aesthetics of the reconstructed fingers.[12] And finally, full-thickness skin grafts are typically utilized to cover "bare areas" after syndactyly release.

In cases of simple complete syndactyly, the combined circumference of the separated digits is 22% greater than the circumference of the syndactylized digits.[7] While the need for full-thickness skin grafting is accepted by most hand surgeons, often this concept may be difficult for patients/families to understand. A simple demonstration may be performed in the office to illustrate the need for skin grafting (Figure 2-4).

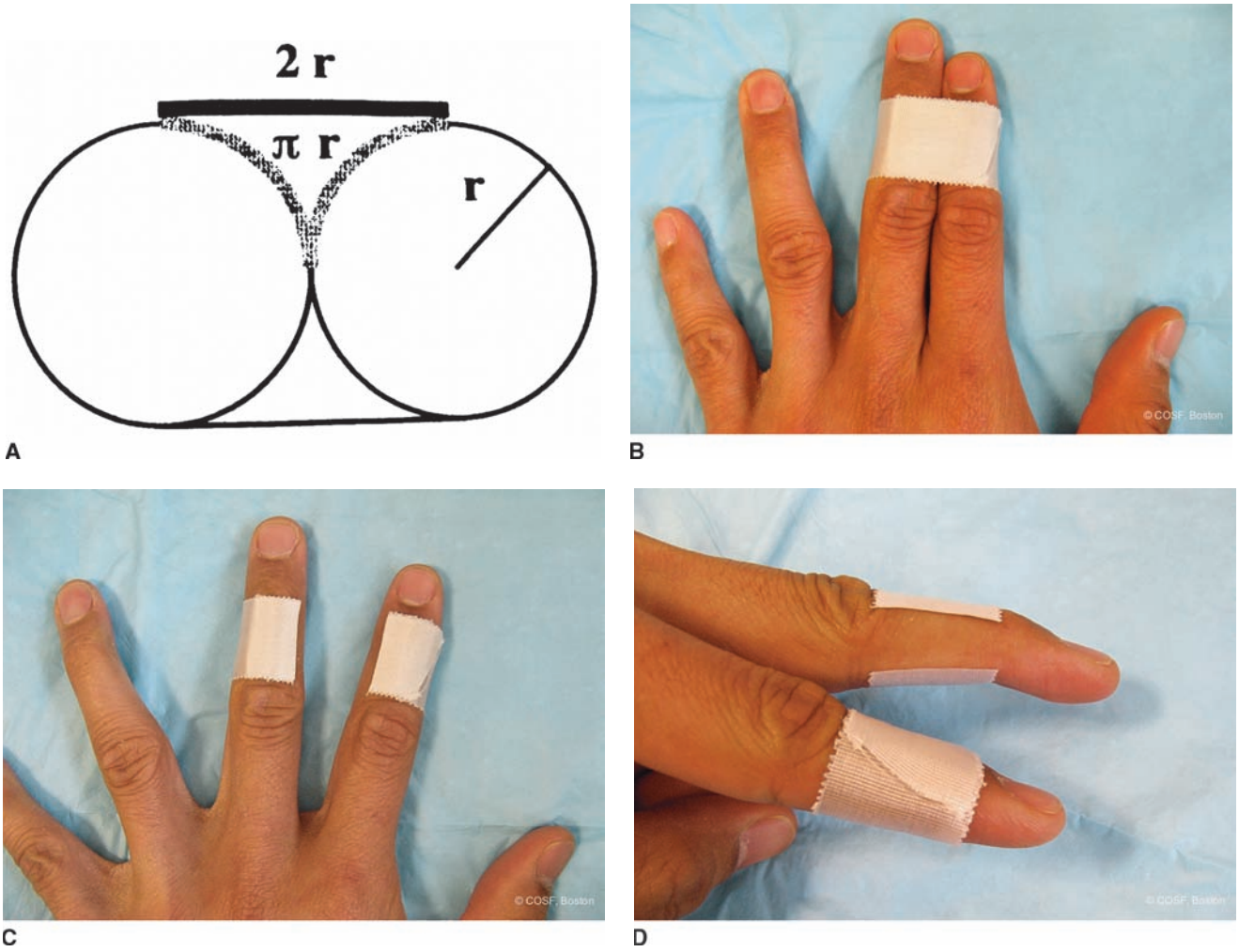


FIGURE 2-4 Illustration of the need for skin grafting in syndactyly release. **A:** Schematic diagram depicting the difference in circumference of syndactylized (10.28*r*) versus separated (12.57*r*) digits. **B:** Clinically, this may be demonstrated to patients/families by taping two fingers together. **C, D:** After the fingers are separated by cutting the tape, the resulting defects will be easily seen.

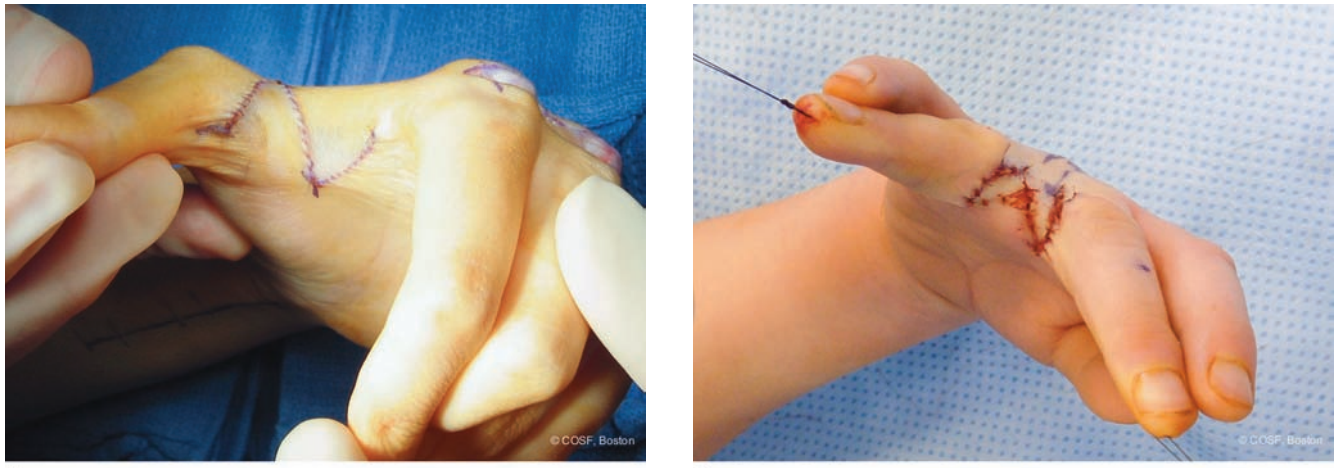
Simple Syndactyly Release

Simple Incomplete

In patients with simple incomplete syndactylies where the distal web commissure is proximal to the proximal interphalangeal (PIP) joint, simple skin rearrangement will provide adequate release with minimal morbidity. Options in these cases include simple Z-plasties, four-part Z-plasties, double-opposing Z-plasties, or variations thereof [13–15] (see Sidebar). Our preference is to utilize two- or four-part Z-plasties for the first web space, and double-opposing Z-plasties for the second, third, and fourth web spaces (Figure 2-5). After the skin incisions are created, with care being made to ensure that all limbs are of equal length, the tourniquet is inflated and skin incised. Care is made to preserve full-thickness flaps to preserve vascularity. After release, flaps naturally rotate into place and are sewn in with 5-0 polyglactin (Chromic, Ethicon, Inc., Somerville, NJ) interrupted sutures. A sterile bandage is applied, followed by a soft dressing or cast, depending upon the age of the patient.

Simple Complete

Patients are placed supine with the affected upper limb supported on a hand table. A nonsterile tourniquet is placed in the upper brachium, taking care to maintain access to the antecubital fossa, if full-thickness skin graft is to be taken from that site. If skin graft from the inguinal crease is to be harvested, the ipsilateral groin is also prepped and draped sterilely into the surgical field. Skin graft from the inguinal region should be taken well lateral to the palpated femoral pulse to minimize harvest of hair-bearing skin, and a surgical marking pen may be placed into the inguinal crease with the hip flexed to identify the most aesthetic axis from which to harvest skin; this will allow for easy primary closure of the harvest site with a scar that lies inconspicuously in the skin folds.



A B

FIGURE 2-5 **A:** Clinical photograph of the first web space after two-part Z-plasty. **B:** Clinical photograph after third web-space five-part Z-plasty.

SIDEBAR

A Simple Approach to Z-Plasty

Z-plasty is a powerful tool in syndactyly surgery and other surgical procedures of the hand and upper limb. Given its wide applications, a fundamental understanding of the principles and techniques of Z-plasty is imperative.

While references to the use of Z-plasties date back to the 1800s, much of the mathematical modeling is attributed to Limberg.[43,44] Although many modifications have been made, the fundamental principles are well established. Simple Z-plasties are named according to the length of the limbs and angle subtended by the limbs (Figure 2-6). Each limb is the same length, allowing for easy interchange of skin flaps. The central line lies in the axis in which lengthening is desired. The theoretical lengthening achieved by simple Z-plasties can be easily calculated with simple geometry (Figure 2-6).

In the example provided, a 60-degree Z-plasty is depicted with limbs of equal length, *x*. By dropping a vertical perpendicular line from one end of the Z-plasty to the other, two 30-60-90 triangles are created. Using the Pythagorean theorem, the length opposite the 60-degree angle is calculated. After the flaps are rotated, the previous horizontal distance *x* has now been increased to *x* times the square root of 3, approximately 1.732*x*. This simply explains the theoretical 75% increase in length obtained by a simple two-part 60-degree Z-plasty.

Simple two-part Z-plasties may be combined to increase their clinical applications. Z-plasties may be placed in series, to relieve acquired longitudinal scar contractures of the digits or tight circumferential skin associated with amniotic band syndrome (Figure 2-7). They may be expanded to form four-part or even six-part Z-plasties, such as are used for releases of simple first web-space syndactylies. Or they may be combined as double-opposing (or "kissing") Z-plasties, as used in releases of simple incomplete syndactylies of the lesser digits (Figure 2-8). Note that in these circumstances, a "stem" is often placed on the Z-plasty to avoid flap tip necrosis and allow for easier flap rotation and insetting. All of these applications, however, are based upon the simple geometry of the simple Z-plasty.

A host of surgical incisions have been proposed, all of which adhere to the above-stated surgical principles (Figure 2-9). In general, all utilize a dorsal skin flap measuring two-thirds the length of the proximal phalanx to reconstitute the web commissure, with interdigitating zigzag flaps for lateral coverage. Volarly, the proximal extent of the skin incision will become the new palmodigital crease; we try to extend the proximal extent of the volar incision more proximal than normal in efforts to account for "web creep" that inevitably occurs.

Skin incisions are thus marked, and a tourniquet is inflated (Figure 2-10A and B). Dorsal flaps are raised first, preserving dorsal veins whenever possible and maintaining full-thickness flaps to preserve vascularity. Volar skin flaps are then raised, identifying neurovascular bundles, and in particular the digital arterial bifurcation, which marks the proximal extent of the release. Occasionally, a very distal bifurcation is discovered. Options in these situations include performing an incomplete release (not preferred) or ligating a digital artery to allow for deeper, more proximal separation. If there is any concern for vascularity to the digits, vessel clamps may be applied and

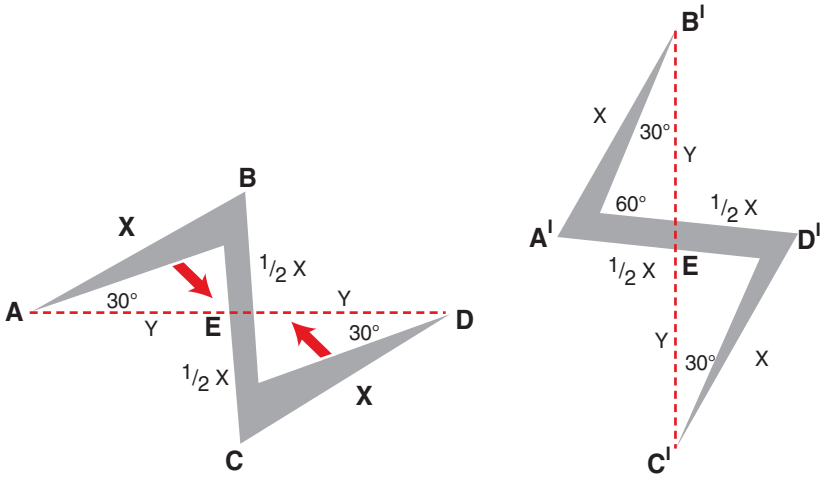


FIGURE 2-6 Schematic diagram of a simple two-part 60-degree Z-plasty. Following flap rotation, note is made of the approximately 75% increase in horizontal distance.

A

B

C

FIGURE 2-7 **A:** Preoperative images of a longitudinal burn contracture in a young child. **B:** This was treated with multiple Z-plasties in series. **C:** Following flap rotation, full digital extension is achieved with elimination of the prior longitudinal scar.

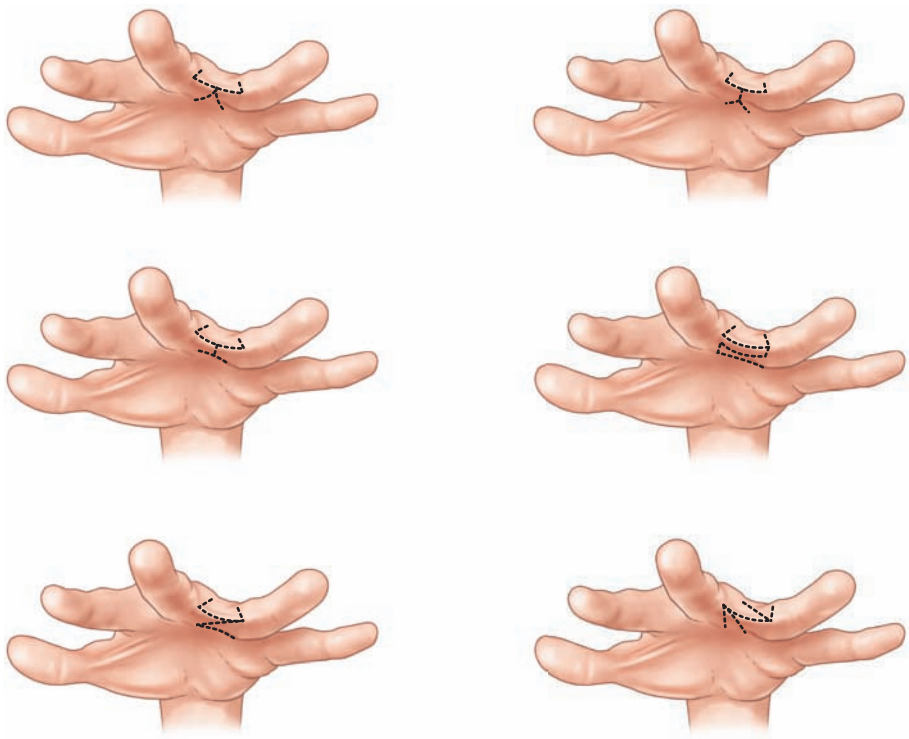


FIGURE 2-8 Illustrations of various Z-plasty variations for web deepening. (From Wiesel S, et al. *Operative Techniques in Orthopaedics.* Philadelphia, PA: Lippincott Williams & Wilkins; 2010.)

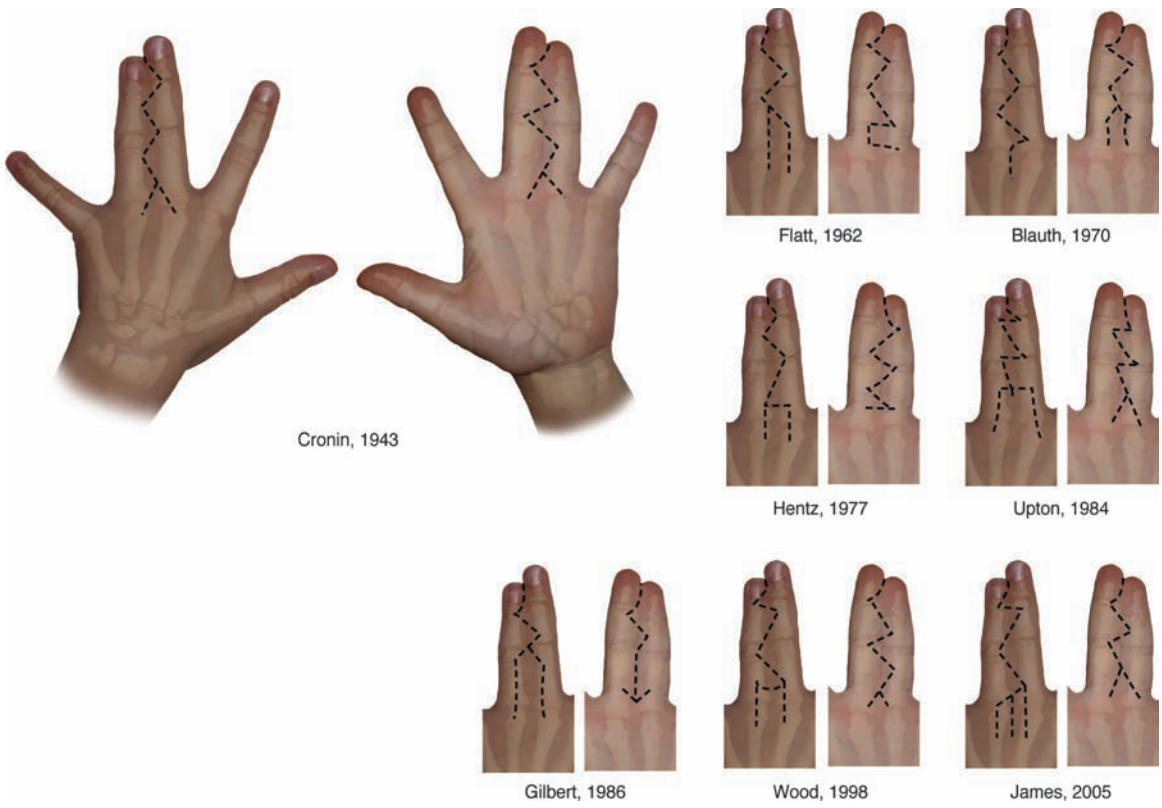
tourniquet deflated to ascertain no vascular insufficiency will occur prior to proceeding. (In cases of isolated syndactyly releases, the smaller caliber vessel may be sacrificed. If a syndactyly release is planned for the other side of a digit, its proper digital artery should be preserved if possible.) After flaps are raised, the fibrous connections between digits may be released from distal to proximal, protecting the neurovascular bundles. The dorsal skin flap is then advanced and inset into the proximal volar skin edge, re-creating the web commissure. This is secured with multiple 5-0 or 6-0 polyglactin (Chromic, Ethicon, Inc., Somerville, NJ) sutures. Skin flaps are allowed to interdigitate and are reapproximated using multiple interrupted sutures. This usually results in two proximal bare areas (the dorsoradial aspect of the more ulnar digit and dorsoulnar aspect of the more radial digit), which are then covered with full-thickness skin grafts.[16,17] Our preference is to anchor the corners of these skin grafts with simple interrupted sutures and reapproximate the edges with running sutures (Figure 2-10C).

In cases of simple complete syndactyly, the nail plates of the involved digits are conjoined (the so-called synonychia). While division of the midportion of the nail plate is easily performed, care must be made to reconstitute the nail folds, the technique of which merits special mention. Ideally this is performed using local tissue from the digital pulp[18] (Figure 2-11). Laterally based flaps are incorporated into the skin incisions, raised from the shared hyponychium at the digital tips. The length of the flaps should equal the length of the nail plate. Once these flaps are raised and the digits separated, these are easily rotated and reapproximated adjacent to the new nail plates, re-creating a paronychial fold. Alternative solutions—including the use of skin graft, thenar or hypothenar flaps, or free composite toe grafts—are more involved and may provide less pleasing aesthetic results.[19,20]

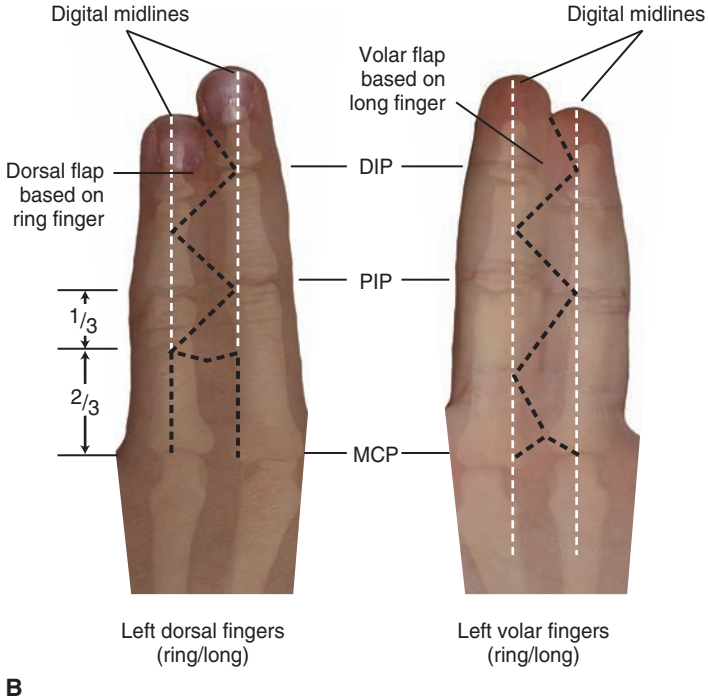
Following completion of the release, the tourniquet is released and vascularity of the digits confirmed. A sterile bandage is applied, and this is perhaps the most important part of the case. Our preference is to place a petroleum-impregnated gauze (Xeroform, Coviden, Mansfield, MA) bolstered with saline-soaked cotton in the newly formed web space to apply gentle compression to the skin grafts and prevent resyndactylization during the healing process. Patients are then placed in a long-arm cast with the elbow in 90-degree flexion and appropriate supracondylar mold.

Graftless Syndactyly Release

Efforts have been made to perform releases of complete simple syndactylies without the use of full-thickness skin grafts, the so-called graftless technique.[21–29] While the general principles of syndactyly surgery still apply, vascularized skin from the dorsum of the hand is raised and advanced to reconstitute the web commissure, leaving the skin over the dorsal aspects of the adjacent proximal phalanges available to cover the separated digits (Figure 2-12). The resulting donor defect is closed primarily in the fashion of a V-Y advancement flap. Areas of skin deficiencies distal to the web commissure are closed primarily with interdigitating skin flaps after aggressive defatting.



A



B

FIGURE 2-9 **A:** Examples of skin incisions used for release of simple complete syndactyly. **B:** Diagram depicting the landmarks and incisions of the author's preferred approach.

A

B

C

FIGURE 2-10 **A, B:** Clinical incisions for release of a third web simple complete syndactyly. **C:** Flaps are reapproximated, full-thickness skin grafts sewn into place, and the release is completed.

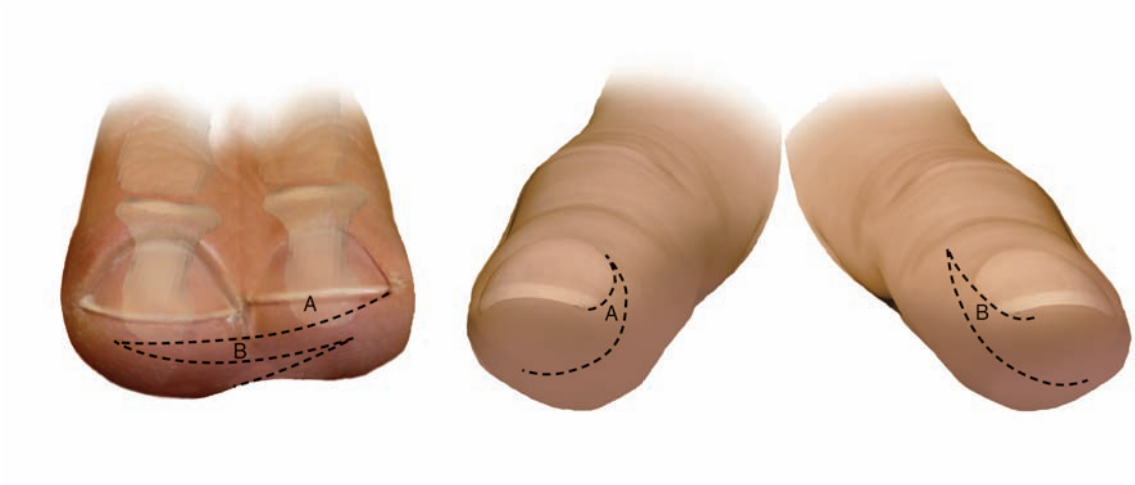


FIGURE 2-11 Schematic diagram depicting synonychia reconstruction.

COACH'S CORNER

For the inexperienced surgeon, designing and marking the skin incisions for a simple complete syndactyly release can be daunting. A few easy steps can be utilized to ensure appropriate skin incisions are created.

First, measure the length of the proximal phalanx dorsally on the affected digits from the palpable metacarpal head to the PIP joint. Calculate two-thirds this length and make a corresponding mark on the dorsum of the affected digits. This will be the distal extent of the dorsal vascularized flap, which will be advanced to form the web commissure. Making the distal margin of this rectangular flap zigzag instead of straight transverse will help avoid scar contracture postoperatively.

Next, draw zigzag flaps from the corner of this dorsal rectangular flap to the PIP extensor crease in the midline of the opposite digit. Extend this zigzag to the midline of the opposite digit at the level of the middle of the middle phalanx. Again extend this to the midline of the opposite digit at the level of the distal IP joint. Finally, extend this to the center between the syndactylized digital tips. This will be the dorsal skin flaps.

Next, at the apex of each "triangle" on the dorsum of the hand, draw a solid line wrapping around to the volar side of the digit (see solid lines in Figure 2-10A). Then draw dotted lines from the center of each "triangle base" and wrap this around to the volar side of the digit (Figure 2-10B).

Turn the hand over to the volar surface. Create a reciprocal "zagzig" a few millimeters proximal to the palmodigital crease; this will accept the leading edge of the dorsal advancement flap to form the new commissure. Then mark the zigzag incisions extending from the apex of this "zagzig" using the previously marked solid and dotted lines. To ensure the flaps interdigitate appropriately, on the volar surface, each apex should correspond to a dotted line, and each triangular base should match with a solid line. Using this simple marking technique, appropriate skin incisions can be made each time.

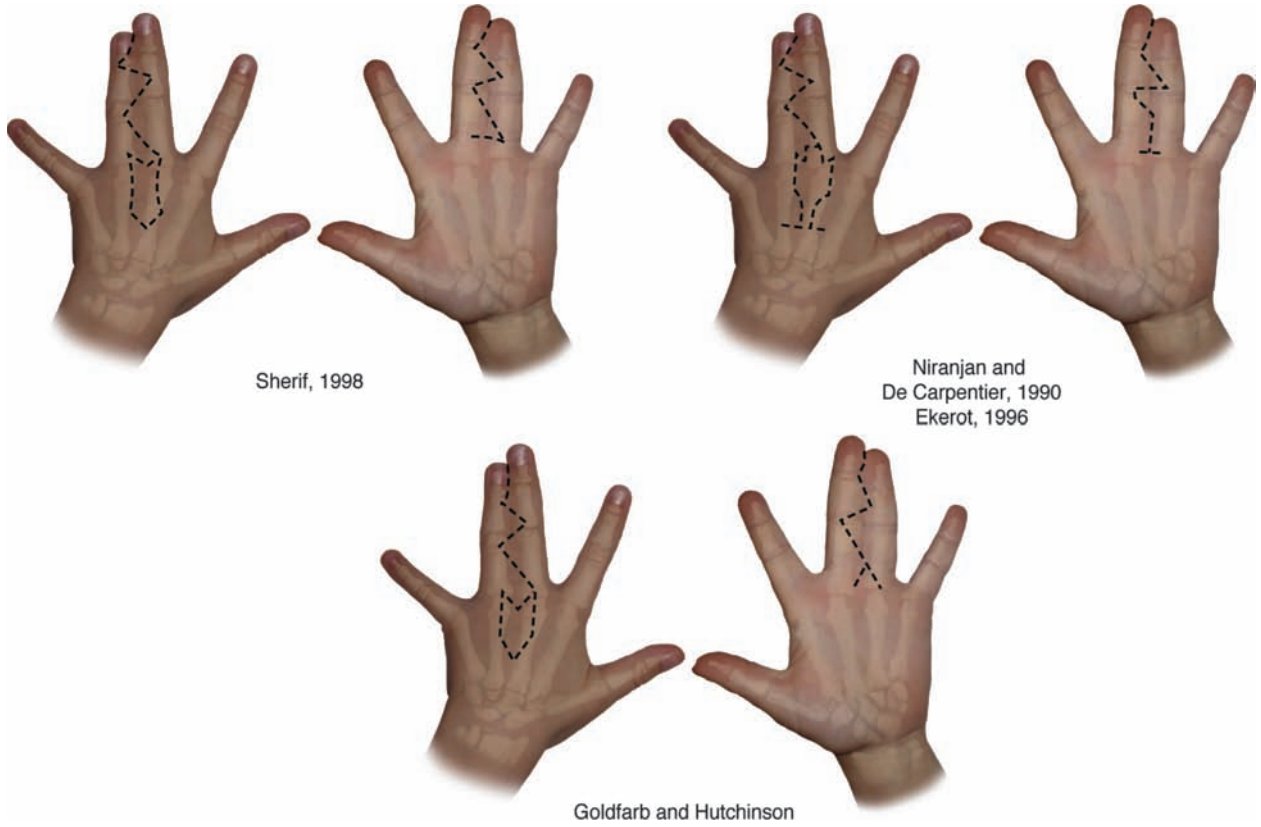


FIGURE 2-12 Schematic diagram depicting clinical incisions used for "graftless" syndactyly releases.

In theory, techniques of graftless syndactyly obviate the need to perform full-thickness skin grafts, therefore eliminating donor site morbidity and mismatch between grafted and recipient skin color and texture.

Currently, we do not utilize this technique for a number of reasons. First, these techniques do not adequately address distal skin deficiencies, particularly in cases of complex syndactylies. Second, though the donor site of the advancement flap may be closed primarily, it leaves a conspicuous, aesthetically unappealing linear scar on the dorsum of the hand. Finally, it is unclear what the effects of the dorsal scar have on subsequent web creep and need for secondary procedures.

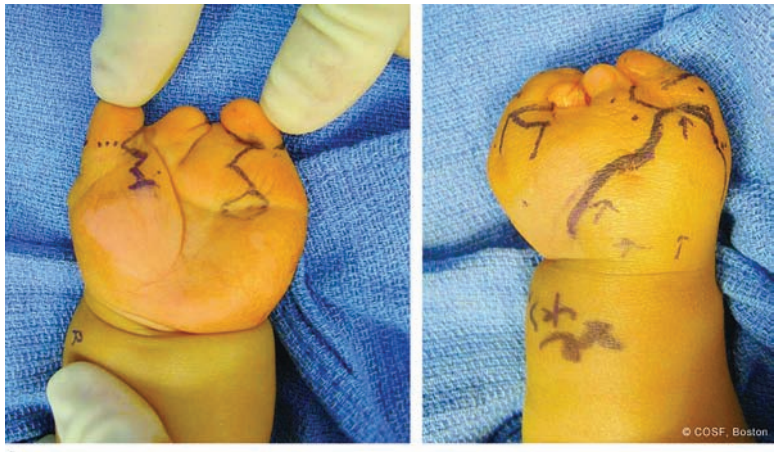
Others have utilized tissue expansion to increase the available skin and thus eliminate the need for grafting.[30,31] We believe that the risks and costs of this strategy outweigh the theoretical benefits.

First Web Syndactyly

While a variety of Z-plasties may be used in cases of incomplete simple first web syndactylies, modified surgical techniques are required for separation of a complete thumb-index syndactyly. It is imperative that a wide, deep first web space is reconstituted to optimize hand function, and ideally this space is reconstructed using a single, scarless, vascularized flap of native tissue.

A number of dorsal rotation advancement flaps have been utilized to achieve this goal.[32–34] All take advantage of the redundant mobile skin from the dorsoradial aspect of the hand. The radial portion of this broad flap is advanced distally into the thumb, while the ulnar portion is rotated radially to provide additional skin to the web commissure and allow for primary closure of the donor site. Flaps are raised in an epifascial fashion, preserving the vascularity of this random pattern skin paddle.

We currently use Ghani modification of the Buck-Gramcko flap in these situations.[34] Patients are positioned as previously described. The planned skin incisions are marked on the dorsum of the hand (Figure 2-13A). Dorsally, the distal transverse extent of the flap lies at the junction of the distal one-third and proximal two-thirds of the thumb proximal phalanx. The radial incision lies over the thumb metacarpal. The ulnar incision is curvilinear—almost bilobed—extending from the index to the small metacarpal



A

B

FIGURE 2-13 First web-space release using a dorsal rotation advancement flap. **A:** Incisions for first web-space release of the left hand. Arrows marked on the skin indicate the direction of flap advancement. **B:** Intraoperative photographs after release has been completed, with reconstitution of a deep web space and placement of the suture line volarly, away from the leading edge of the first web commissure.

as proximal as the wrist crease. Volarly, Bruner-type zigzag incisions are made from the leading edge of the syndactyly to approximately 1 to 2 cm proximal to the thumb metacarpophalangeal (MCP) joint, where the incision is tied to allow for insetting of the leading edge of the dorsal flap. Under tourniquet control, the skin and subcutaneous tissues are incised, and hemostasis is achieved with bipolar electrocautery. Dissection is performed at the epifascial level, preserving perforating vessels whenever possible. Volar incisions are similarly made, preserving the neurovascular pedicles to both the thumb and index fingers. After flap elevation, the deep fascia of the adductor pollicis as well as any fibrous connections between the thumb and index metacarpals are released, allowing for volar and radial abduction of the thumb. The dorsal skin flap is then advanced and rotated into place, and skin closed using multiple interrupted 5-0 polyglactin (Chromic, Ethicon, Inc., Somerville, NJ) sutures (Figure 2-13B). The tourniquet is released, and after vascularity of the flap and separated digits is confirmed, a bulky sterile dressing applied. Patients are placed in a long-arm mitten cast for 3 weeks.

◆ Apert and Complex Polysyndactyly

Apert syndrome, or acrocephalosyndactyly, refers to a constellation of clinical manifestations including coronal craniosynostosis, midface hypoplasia, and characteristic syndactylies of the hands and feet, due to a mutation in the FGFR2 gene on chromosome 10q.[35] The hand is quite involved, typically with complex syndactylies of the central digits and simple syndactylies of the border digits/thumb. Bony and joint abnormalities are common, resulting in the so-called spade or hoof hand.

Hand involvement can be varied and has been previously classified by Upton as well as Van Heest.[36,37] Type I hands (spade hand) have incomplete first web syndactylies with a relative flat central mass and good MCP joints with varying degrees of symphalangism and IP stiffness. Type II hands (mitten or spoon hand) have complete syndactylies of the first and fourth webs with fusion of the digital tips and increasing concavity of the palm. Type III hands (hoof or rosebud hands) represent complete complex syndactylies of all digits in which the thumb is incorporated into the central, cupped hand mass with a single synonychia.

In general, the reconstructive goals in Apert are to maximize hand function by digital separation, reconstitution of a wide first web space with a stable thumb in opposition, and/or mobilization of the small ray.[38] Depending upon the status of the hand and underlying bony anatomy, reconstruction of a four- or three-fingered hand may be sought.

POSTOPERATIVE

Patients remain in casts for 3 to 4 weeks, after which casts are removed and wounds examined. While not necessary, our preference is to have patients work with our occupational therapists for scar mold (silicone or elastomere), scar massage, and range-of-motion exercises to optimize healing.

ANTICIPATED RESULTS

There is limited information available on the long-term outcomes following syndactyly release.[8] Furthermore, interpretation of the published information is difficult owing to the diversity of clinical presentations, variety of surgical techniques, and limitations on quantifying results. In general, however, syndactyly release may be expected to provide safe and reliable digital separation with independent digital function and acceptable aesthetic results, provided that the accepted surgical principles are followed.

COMPLICATIONS

You win some, you lose some, you wreck some.
—Dale Earnhardt

Digital necrosis is the most serious potential complication of syndactyly release, though in reality it is extremely rare if the above-stated surgical principles are followed. Careful identification and protection of the neurovascular bundles during surgical release will allow for safe separation without risk of vascular embarrassment.

Skin graft failure may result from hematoma formation beneath and/or shear stresses imparted upon the grafts in the postoperative period. This risk may be greater in younger patients, in whom appropriate graft tensioning is more difficult and in whom postoperative immobilization is a greater challenge. If allowed to heal by secondary intention, subsequent hypertrophic scar formation may lead to suboptimal aesthetic and functional results.

Nail plate deformity is common after complete syndactyly release in the presence of a synonychia. While techniques of nail fold reconstruction using distal pulp tissue will optimize aesthetic results, patients and families should be counseled in advance of this common occurrence.

"Web creep" refers to the distal migration of the reconstructed interdigital commissure with continued growth and is a common occurrence following syndactyly release (reported incidence between 7% and 60% of cases).[8,16,17,39] There is some evidence to suggest that the risk of web creep may be diminished if release is performed after 18 months of age.[10] Other factors that may contribute to web creep include inappropriate flap design for commissure reconstruction, the use of split thickness as opposed to full-thickness skin grafts, skin graft loss, and creation of a transverse linear scar in the reconstituted web space. In cases of clinically significant web creep, secondary releases may need to be performed (Figure 2-14).

FIGURE 2-14 **A:** Preoperative views of an adolescent male with web creep after prior syndactyly release. **B:** Intraoperative photographs following revision release using double-opposing Z-plasties.

While hypertrophic scar and true keloid formation are rare, they may lead to unsightly and dysfunctional digits following syndactyly release.[40–42] Seen commonly in patients with digital enlargement due to macrodactyly, hemihypertrophy, and vascular anomalies, keloid formation may be treated with scar massage, scar molds, topical steroids, and ultimately surgical excision with or without adjunctive corticosteroids. Recently, short-term low-dose methotrexate has been advocated for keloid prophylaxis, with promising results in limited numbers of patients.[40]

CASE OUTCOME

Clinically, the patient was diagnosed with simple incomplete syndactyly of the first web space, simple complete syndactyly of the second web space, and complex complete syndactyly of the third web space. This was corroborated by radiographs, which demonstrated conjoined distal phalanges of the long and ring finger but no other abnormalities. After discussion with the family, staged surgical reconstruction was performed beginning at 8 months of age. The first procedure involved Z-plasty release of the first web space and third web syndactyly release utilizing full-thickness skin graft. Three months later, the second web was released, again using full-thickness skin grafting. The patient went on to develop full hand and independent digital function with no delays in developmental milestones. At most recent follow-up, there has been minimal scar contracture and web creep. No late deformity has been noted.

SUMMARY

Syndactyly is among the most common congenital hand differences and is associated with a number of syndromes. Surgical release is recommended at an early age for border digits to avoid secondary deformity and at a later age in the third web space to minimize web creep. Use of vascularized dorsal skin for commissure reconstruction, zigzag skin incisions, and liberal full-thickness skin grafting will result in functional and aesthetic improvements.

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CHAPTER

3

Postaxial Polydactyly

CASE PRESENTATION

An orthopaedic hand surgery consultation is requested from the newborn nursery for an "extra finger" (Figure 3-1). An otherwise healthy full-term infant presents with an extra digit on the ulnar border of the hand. Although the sixth digit appears to have cartilaginous or osseous elements to it and a rudimentary nail plate, it is attached to the hand via a thin skin bridge. No other abnormalities are noted.

CLINICAL QUESTIONS

- How common is postaxial polydactyly?
- How is postaxial polydactyly classified?
- Are there any associated syndromes?
- What are the surgical treatment options?
- What are the expected outcomes after surgical excision/reconstruction?

THE FUNDAMENTALS

Baseball players are smarter than football players. How often do you see a baseball team penalized for too many men on the field?
—Jim Bouton

Etiology and Epidemiology

Postaxial polydactyly refers to a sixth or "extra" digit on the ulnar border of the hand.[1] While preaxial polydactyly is more common in people of European and Asian descent, postaxial polydactyly is more common in patients of African heritage. The reported incidence is variable, likely reflecting the differences among distinct populations around the world. Although it is reported to affect 1:1,339 live Caucasian births, postaxial polydactyly may be seen in up to 1:143 live births among Blacks.[2] Although typically an isolated abnormality, syndromic associations have been reported among Caucasian patients.[3] Inheritance is autosomal dominant in most cases, with incomplete penetrance and variable expressivity. Autosomal recessive inheritance patterns have also been reported, particularly with syndromic associations.[4–6]

The exact etiology of postaxial polydactyly is unknown. Numerous genetic mutations and chromosomal abnormalities have been identified, including those involving chromosome 19, chromosome 13, and the Gli3 gene on chromosome 7.[7–9]

Clinical Evaluation

Clinical evaluation is based upon history and physical examination. Given the inheritance pattern, often a family history of postaxial polydactyly will be obtained. While not unexpected, this information provides important insight into the family's experience with prior treatment and may provide direction in treatment.

Careful physical examination will provide all necessary information. The presence or absence of a well-formed

FIGURE 3-1 Photograph of a type B (simple) postaxial polydactyly.

osteoarticular base to the extra digit will guide treatment. In cases where the polydactylous finger is well formed and connected by more than just a skin pedicle, examination of the flexion and extension creases over the interphalangeal joints will provide information regarding joint formation and tendon function; in cases where the digit is extended, stiff, and without skin creases, it is unlikely that any meaningful flexor or extensor tendons are attached to the extra finger.

While simple, the classification of Temtamy and McKusick[10] is useful. Type A postaxial polydactyly refers to the well-formed digit that articulates with the fifth (or sixth) metacarpal and has its own set of tendons, neurovascular bundles, and soft tissue structures. Type B polydactyly refers to the rudimentary, underdeveloped digit, which typically is attached to the ulnar border of the hand by only a small skin bridge and neurovascular pedicle.

Stelling[11] and Turek[12] proposed that postaxial polydactyly be classified into one of three types. Type 1 denotes a rudimentary, hypoplastic digit attached via a small skin bridge. Type 2 postaxial polydactyly refers to a "partial duplication," in which a normal digit articulates with a bifid or enlarged metacarpal. Type 3 represents the rare complete duplication of metacarpal and phalanges.

Surgical Indications

While some families/patients choose not to treat postaxial polydactyly due to personal, cultural, or religious reasons, in most situations, surgery is recommended to remove the extra digit and provide a more aesthetically normal, functioning hand.

SURGICAL PROCEDURES

It ain't like football. You can't make up no trick plays.
—Yogi Berra

Ligature in Nursery versus Surgical Excision

For the type B postaxial polydactyly, two categories of treatment exist: early ligature versus formal surgical excision. Early ligature offers several advantages. It is easily performed in the newborn nursery without the need for general or local anesthesia. Furthermore it is nearly universally successful and cost-effective, with a low rate of minor complications. Potential disadvantages include a small risk of infection and bleeding, as well as the possibility that following necrosis and autoamputation of the extra digit, a small "nipple" or "nubbin" of soft tissue may remain. While functionally inconsequential, this may be aesthetically displeasing. Formal surgical excision via an elliptical incision around the base of the skin bridge and primary wound closure is universally successful. Furthermore, formal excision allows for appropriate nerve transection and coagulation of the arterial pedicle, thus avoiding risks of bleeding and symptomatic neuroma formation. However, surgical excision typically involves anesthesia and therefore must be delayed until the child is of appropriate age. While these advantages and disadvantages are seemingly easy to weigh, there continues to be a lack of consensus on the optimal treatment of the type B postaxial polydactyly, among both providers and families.[13,14]

FIGURE 3-2 Clinical photograph depicting suture ligature. Note the suture is placed at the base of the polydactyly, which immediately turns white due to the interruption of vascular flow.

The technique is straightforward (Figure 3-2). Ligature may be performed using a surgical staple, 4-0 absorbable or nonabsorbable suture applied tightly at the base of the pedunculated extra digit. For best results, the suture or staple should be placed as low as possible on the skin bridge, flush with the ulnar border of the hand, to avoid leaving a soft tissue nipple. The digit is allowed to necrose and fall off, which typically occurs in 1 to 2 weeks. No formal dressing changes or aftercare is required.

If formal surgical excision is pursued, it is done in the operating room under general mask anesthesia after 6 months of age. Under tourniquet control, an elliptical incision is made around the base of the rudimentary digit. If the major (longitudinal) axis is twice the length of the minor (dorsovolar) axis, the skin margins can be easily closed primarily without tension. During formal excision, spreading in the subcutaneous tissues will allow for identification of the rudimentary digital nerve and artery supplying the digit. The nerve is cut under traction and allowed to retract to avoid neuroma formation. The vessel is cauterized to avoid postoperative bleeding. The skin is reapproximated with 5-0 polyglactin sutures (Chromic, Ethicon, Inc., Somerville, NJ). Postoperatively, soft bandage will suffice.

Reconstruction of Type A Postaxial Polydactyly

Principles and techniques of type A postaxial polydactyly reconstruction are nearly identical to those of preaxial polydactyly. Under general anesthesia and tourniquet

hemostasis, a racquet-type incision is made around the base of the extra digit, extending proximally in a zigzag fashion along the ulnar border of the hand to avoid longitudinal scar contractures (Figure 3-3). Skin flaps are raised. Dorsal dissection will often reveal a bifid or duplicated extensor mechanism; the ulnar slip is released from its insertion and preserved for subsequent realignment. Volar dissection will allow for identification of the abductor digiti quinti (ADQ), which is often attached to the more ulnar digit. The abductor is released from its distal insertion and tagged for later reconstruction. At this time, the ulnar collateral ligament of the metacarpophalangeal (MCP) joint is then elevated with a distal strip of periosteum off the ulnar proximal phalanx, based proximally. The extra digit is removed, and the metacarpal head examined. If the metacarpal head is bifacet, a chondroplasty may be performed with a surgical blade to restore a normal contour to the articular surface. The ulnar collateral ligament may then be advanced and sutured to the volar base of the preserved radial proximal phalanx. The ADQ is then advanced and sewn into the proximal phalanx and extensor apparatus. The ulnar slips of the flexor and extensor tendons—if previously identified—may then be centralized and sutured to the preserved tendons, therefore "balancing" the extrinsics

A

B

C

D

FIGURE 3-3 Technique of reconstruction for type A (more complex) postaxial polydactyly. **A:** Preoperative radiograph depicting a well-formed sixth digit. **B, C:** Clinical photographs of the hand, depicting the surgical incisions. Superficial dissection demonstrates a bifid extensor mechanism. **D:** Volar dissection demonstrates attachment of the ADQ to the more ulnar small finger.

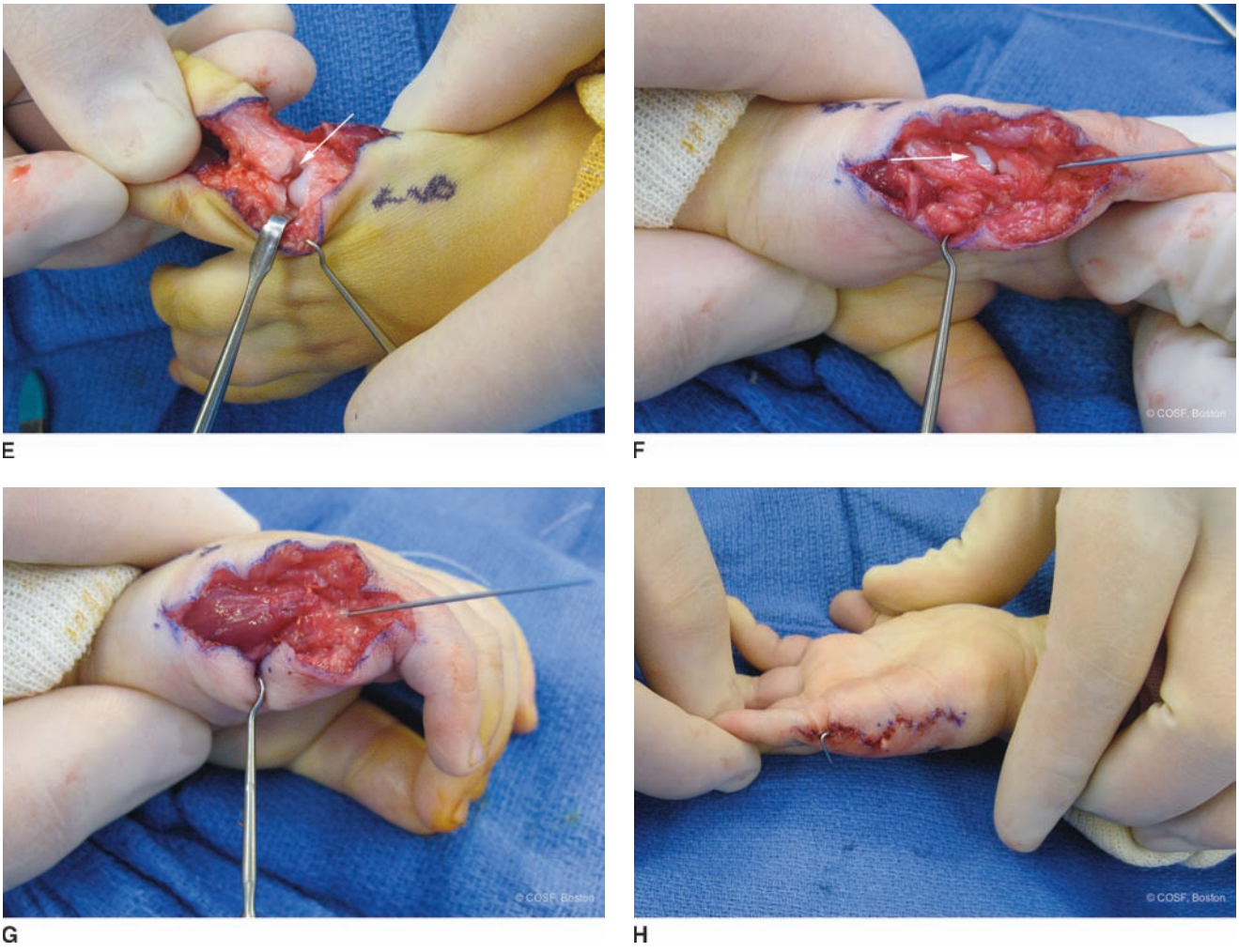

FIGURE 3-3 (*continued*) **E:** Arthrotomy of the MCP joint reveals a bifacet metacarpal head (*arrow*), typical of type A postaxial polydactyly. **F:** After the digit is removed and chondroplasty of the metacarpal head completed (*arrow*), the ulnar collateral ligament is reconstructed and advanced to its anatomic insertion on the proximal phalanx. **G:** The ADQ is reapproximated, and a stabilizing smooth pin is placed for postoperative protection. **H:** Final appearance of the hand after wound closure.

and preventing late dynamic deformity. Redundant skin flaps are trimmed and reapproximated with interrupted absorbable sutures. If desired, the MCP joint may be stabilized with an oblique or longitudinal smooth wire, typically 0.028 inches or 0.035 inches in size. Tourniquet is released and vascularity of the small finger confirmed. A long-arm mitten cast is then placed over a bulky soft tissue dressing.

POSTOPERATIVE

Following surgical excision of a simple type B postaxial polydactyly, postoperative dressings are removed after 2 weeks. Following this, hand use is advanced as tolerated without restrictions.

After reconstruction of a type A postaxial polydactyly, the stabilizing wire is removed after 4 weeks and cast immobilization discontinued. Hand therapy is initiated for scar management and gentle motion exercises. The hand may be splinted for 2 additional weeks to confer additional protection of the soft tissue reconstruction.

ANTICIPATED RESULTS

Suture ligation is nearly universally successful in causing necrosis and autoamputation of the postaxial polydactyly. Watson and Hennrikus[2] reported an average of 10 days until the digit fell off in their series of 21 patients. While they reported no complications, Rayan and Frey[15] reported minor complications in nearly 25% of the 105 patients treated with suture ligature, including infection, bleeding, and a residual soft tissue nubbin (Figure 3-4).

While no large series has been published on the results of type A postaxial polydactyly reconstruction, excellent outcomes are anticipated using the techniques described here. Late deformity is rare, particularly as

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FIGURE 3-4 Suboptimal suture ligature. Note the suture is not placed at the base of the polydactyly, which will result in a residual "nipple" of tissue. In addition, as the suture is tied too loosely, there is venous congestion but incomplete necrosis of the polydactylous digit and risk of infection.

there is less skeletal malalignment than seen in cases of preaxial polydactyly. As with all congenital situations, the quality of the preserved digit will influence the quality of the reconstruction. Families should be counseled about this preoperatively, particularly in cases where the more developed, radial small finger is stiff or hypoplastic.

COMPLICATIONS

Complications after treatment for postaxial polydactyly are rare. In cases where suture ligature of the newborn is performed, often a small soft tissue nubbin or "nipple" persists (Figure 3-4). While functionally of little consequence, this soft tissue prominence can be aesthetically displeasing and occasionally viewed as a "failure" of treatment. In rare situations where these soft tissue nubbins are perceived by the family to cause pain (e.g., the patient is observed picking, scratching, or biting the soft tissue remnant), surgical exploration will reveal a symptomatic neuroma at the site of prior cutaneous nerve ligation.

As described in the preceding section, occasionally there may be stiffness or progressive deformity following reconstruction of the type A postaxial polydactyly. Adherence to the surgical principles outlined above will allow for the best results.

CASE OUTCOME

Based upon clinical evaluation, the diagnosis of type B postaxial polydactyly is made. After further query, it is determined that there is a family history of postaxial polydactyly among multiple family members and relatives, including the patient's father. Given the family's understanding of this condition—as well as their disappointment with the persistent "nipples" after suture ligation in other family members—decision was made to pursue formal surgical excision in the operating room. At 6 months of age, the child underwent uneventful polydactyly removal under general mask anesthesia.

SUMMARY

Postaxial polydactyly is among the most common congenital hand differences seen by pediatric orthopaedic and/or hand surgeons. Type B polydactyly may be successfully treated by either suture ligature or surgical excision; appropriate discussion with the family is needed to highlight the advantages and disadvantages of each approach. In cases of type A postaxial polydactyly, formal surgical reconstruction is necessary to reconstitute a normal appearing and functioning hand.

COACH'S CORNER

Due to the difficulties in placing suture ligatures at the often broad base of type B postaxial polydactylous digits, a number of other techniques have been considered. One alternative is to use a vascular clip rather than a suture to induce ischemia, necrosis, and amputation. The advantages of the vascular clip lie in the ability to place the clip in line with and immediately against the ulnar border of the hand. Furthermore, it is inexpensive, simple, and quick, obviating the difficulty in tying knots on the moving hand in a crying, fussy child.

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CHAPTER

4

Preaxial Polydactyly

CASE PRESENTATION

A 6-month-old male presents for evaluation of an "extra thumb" (Figure 4-1A). The family that reports this was present at birth. The child is otherwise healthy, and there is no family history of congenital hand differences. On examination, there are two well-formed thumbs, each with nail plates and flexion and extension creases over the interphalangeal (IP) joint. The metacarpophalangeal (MCP) joint appears broad but is stable. There appears to be active flexion and extension of the MCP joint of the more radial thumb, as well as abduction. No other abnormalities are seen. Plain radiograph is shown in Figure 4-1B.

CLINICAL QUESTIONS

- What causes thumb duplication? How common is it?
- Are there any associated syndromes or anomalies?
- How is it classified?
- What are the treatment principles?
- What types of surgical procedures are done?
- What are the expected results and potential complications of surgery?

THE FUNDAMENTALS

Preaxial polydactyly—often referred to as thumb duplication, thumb polydactyly, radial polydactyly, or split thumb—is among the most common congenital conditions presenting to the pediatric hand and upper extremity surgeon. Understanding of the pathoanatomy and principles of surgical reconstruction is critical to provide these patients with stable, mobile, functional, and aesthetically acceptable thumbs.

Etiology and Epidemiology

Preaxial polydactyly occurs in approximately 1:10,000 live births.[1,2] It is more common in Asians and Native Americans and affects Blacks and Caucasians with equal frequency. Males are more commonly affected than females.

While most cases are sporadic, and unilateral, in some patients there may be an autosomal dominant inheritance pattern. Several syndromes have been identified that have been associated with thumb duplication.[3] Wassel VII thumb duplications (see below) are the exception, as these anomalies have a higher hereditary predisposition and are associated with other hematologic, cardiovascular, or musculoskeletal conditions.[3]

The etiology of thumb duplication has been evaluated through a series of human and animal investigations.[4–6] Most have concluded that delayed involution of the apical ectodermal ridge on the preaxial border of the hand results in induction of thumb duplication. The single mesenchymal condensation along the preaxial border of the hand that is destined to form the thumb is therefore cleaved or split.

These embryologic observations confirm what is clinically seen. Rather than two separate well-formed digits, each of the thumbs is deficient, containing elements that combined account for the expected anatomy. For this reason, the term "thumb duplication" is a misnomer, and "split" or "bifurcated" thumb is more accurate.[7]

Clinical Evaluation

If you don't look, you can't see.
—Bob Knight

While a host of classification systems have been proposed, the Wassel classification has proven to be the most simple in application and helpful in surgical planning[8] (Figure 4-2) (see Sidebar 1). This system classifies the deformity depending upon the level of duplication from distal to proximal, with odd numbers assigned to the bones and even numbers assigned to the joints. A bifid distal phalanx is type I, a duplicated distal phalanx is a type II, a bifid proximal phalanx is type III, and so on. (The easy way of remembering this is that the classification type refers to the number of abnormal bones.) Type VII, by definition, refers to any thumb duplication with a triphalangeal thumb.

A

B

FIGURE 4-1 **A:** Clinical photograph depicting a "thumb duplication." **B:** Corresponding plain radiograph illustrating the skeletal elements of the "thumb duplication." This is a typical Wassel type IV thumb.

SIDEBAR 1

The History behind the Wassel Classification

I learn teaching from teachers. I learn golf from golfers. I learn winning from coaches.
—Harvey Penick

Classification systems are most helpful for surgeons if they are simple to use, portend prognosis, and guide treatment. Based upon these criteria, it is no surprise that the Wassel classification is the most widely used and commonly accepted system for the characterization of preaxial polydactyly. Although many additional classification systems have been proposed, none have duplicated the simplicity or elegance of Wassel's scheme.

It is fair and proper to recognize that Wassel's original description of the classification and results of surgery for thumb duplication, published in 1969, was written when Wassel was a clinical fellow working with Dr. Adrian Flatt at the University of Iowa. Indeed, the observations and results described therein were directly the result of Dr. Flatt's clinical efforts, careful documentation, and academic perspective. Although Flatt was appropriately acknowledged in a footnote on the 1969 publication, the classification system continues to bear Wassel's name.

Using the Wassel classification, type IV thumbs are the most common, representing approximately 40% to 45% of cases; Wassel type II is the second most common pattern (15%), followed by type VII.[8]

While the Wassel classification effectively describes the bony anatomy and guides surgical treatment, not all thumb duplications are the same. Practically, there is a great difference between divergent or parallel thumb duplications and the zigzag (or divergent-convergent) duplications (Figure 4-3). In the latter situation, angular deformity is caused by both abnormal bony alignment and eccentric tendon insertions. Recurrent deformity is more commonly seen in these situations, and greater care is needed to restore longitudinal bony alignment and dynamic muscle pull during surgical reconstruction.[9]

In addition, in cases in which there is considerable IP joint stiffness and abduction of the thumb, the presence of a pollex abductus should be considered (Figure 4-4). This abnormal connection between the flexor pollicis longus (FPL) and extensor pollicis longus (EPL) tendons has been reported in up to 20% of thumb duplications.[10,11]

Surgical Indications

Almost universally in the Western world, the presence of a thumb polydactyly is an indication for surgical reconstruction. There are some cultures, however, where this is not the case. Given that surgery and anesthesia can safely be performed in many parts of the world over the age of 6 months, the timing of reconstruction can precede fine motor development. Rudimentary grasp precedes pinch. Tip-to-tip pinch does not begin to develop until later, up to 15 months of age, and patterns of fine motor function do not become established until 3 years of age. Surgery may be safely and appropriately performed at 9 to 12 months of age in most advanced care settings.

FIGURE 4-2 Schematic representation of the Wassel classification of preaxial polydactyly. (Wassel HD. The results of surgery for polydactyly of the thumb. A review. *Clin Orthop Relat Res.* 1969;64:175–193.)

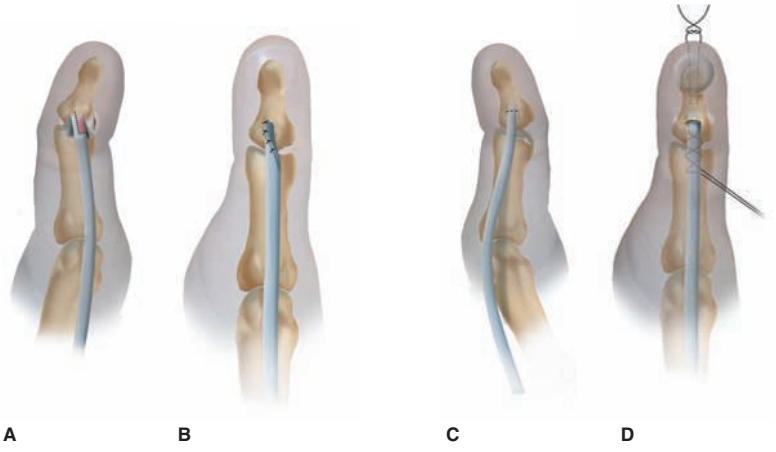

FIGURE 4-3 **A:** Clinical photograph of a divergent-convergent Wassel IV thumb duplication with syndactyly. **B:** Schematic diagrams depicting surgical strategies to realign the dynamic deforming forces of divergent-convergent thumbs.

SURGICAL PROCEDURES

The goals of surgery are to create a single, stable, mobile, straight thumb. As the radial thumb is typically most hypoplastic, it is the thumb that is most commonly removed. Based upon this observation, Kanavel is attributed as stating that simple amputation of the more hypoplastic thumb "…requires no ingenuity and creates no problem."[12] However, in the vast majority of situations, simple ablation is not sufficient.[13] Amputation of the radial thumb, while tempting, is often doomed to failure, as the abductor pollicis brevis (APB), radial collateral ligament (RCL), and bifid tendons are not reconstructed and the longitudinal skeletal alignment is not corrected.

Preservation of vascularity is usually not an issue, as both thumbs are supplied by at least one digital artery in the vast majority of cases.[14] Kitayama and Tsukada have previously shown that in 74% of cases, there is a digital artery to each thumb. In 12% of cases, there were two arteries to the ulnar and one artery to the radial thumb. In

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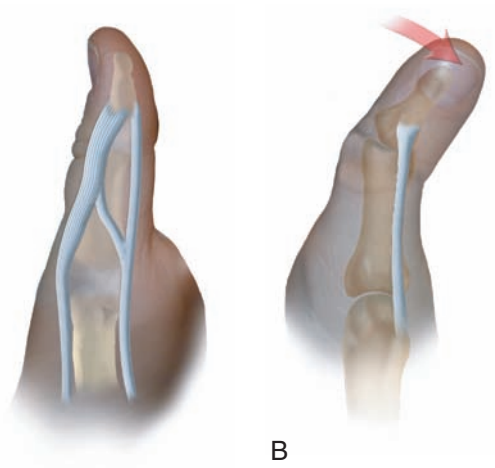

FIGURE 4-4 Schematic diagram of the pollex abductus as seen from the radial **(A)** and dorsal **(B)** aspect. Note the resultant thumb abduction and IPJ stiffness.

9% of cases, each thumb is supplied by two digital arteries. There is a single digital artery—typically to the more ulnar thumb—in only 5% of cases. For these reasons, caution is needed when ablating the rare, hypoplastic ulnar thumb.

Surgery should address all elements of the deformity at the initial procedure if at all possible. This includes skin, extrinsic tendon, and instrinsic muscle rebalancing along with longitudinal bone and joint realignment and stabilization. At times, this means wedge osteotomies of the reconstructed thumb with bone from the ablated thumb. This extensive surgery can be delicate so as to achieve anatomic restoration without vascular compromise. These principles are applied to simpler Wassel IIs and IVs, the more difficult divergent-convergent Wassel IVs and 50-50 IIs, the rarer Wassel VIs, and the assortment of Wassel VIIs. The bifid Is, IIIs, and Vs are a bit more straightforward due to stable, aligned joints.

Simple Ablation

When you come to a fork in the road, take it.
—Yogi Berra

In rare situations, a simple soft tissue nubbin on the radial aspect of the hand can present as a thumb duplication (Figure 4-5). In these cases, there are no bony or clinically important soft tissue connections between the more developed "ulnar thumb" and the radial nubbin, which is often only connected by a skin stalk. Clearly in these situations, simple ablation of the nubbin can be performed without the need for bony work, ligamentous reconstruction, or muscle/tendon transfers.

A few technical steps should be considered during these simple ablations. First, despite the hypoplastic appearance of the nubbin, there is always a very real vascular pedicle within the soft tissue stalk, which should be identified and cauterized during ablation. In addition, to avoid a symptomatic neuroma, the accompanying digital nerve should be withdrawn, sharply transected, and allowed to retract into the soft tissues. Finally, an elliptical skin incision around the base of the soft tissue stalk should be made to allow for primary closure without "dog ears" or the aesthetically displeasing "nipple" of tissue that can form with careless or inexact skin incision or soft tissue resection. Also, always look for tendon or muscle insertion even in the most rudimentary thumbs. Surprisingly, there is often an intrinsic attachment that should be transferred.[15]

FIGURE 4-5 Clinical photograph of a preaxial polydactyly in which the accessory thumb is attached by a rudimentary soft tissue pedicle.

Wassel IV Reconstruction (Parallel Thumbs with Dominant Ulnar Digit)

The most common reconstruction involves a Wassel IV deformity with parallel thumbs, of which the ulnar thumb is dominant. In these situations, surgery involves removal of the radial proximal and distal phalanges, reconstruction of the RCL of the MCP joint, advancement of the APB, osteotomy of the bifid metacarpal (MC) head, and closure via converging zigzag incisions.[16–21] While seemingly complicated at the blue square level, in general, these procedures are straightforward with excellent reproducible results.

Patients are placed supine with the affected extremity supported by a hand table. A nonsterile tourniquet is placed in the upper brachium. After the limb is exsanguinated and tourniquet inflated, a zigzag incision is created on the radial border of the hand, beginning at the thumb carpometacarpal (CMC) joint and extending to the base of the more (hypoplastic) radial thumb (Figure 4-6A–C).

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The incision is then curved around the radial thumb in a racquet-type fashion and extended along the radial aspect of the ulnar thumb to the IP joint level. Full-thickness flaps are elevated. The extensor and flexor tendons are identified, as are the neurovascular bundles. The EPL is often bifid or split at a level corresponding to the skeletal duplication (Figure 4-6D). The radial EPL tendon is identified, elevated from its insertion back to the normal bony anatomy, and tagged for subsequent transfer to the ulnar thumb. The FPL may also be identified, and, if there is a slip to the radial thumb, it is similarly released and tagged for transfer.

The APB tendon and muscle belly are identified as they course from the thenar eminence to insert on the more radial thumb. The APB tendon is elevated off the radial proximal phalanx and tagged with a 4-0 polyglactin suture (Vicryl, Ethicon, Inc., Somerville, NJ) for subsequent transfer; care is taken during this step to avoid violating the underlying RCL of the MCP joint (Figure 4-6E). The MCP joint is then entered from distal on the dorsal side. Inspection of the joint will determine if the proximal phalanges are truly duplicated or, as sometimes is the case, a conjoined cartilaginous proximal phalangeal epiphysis exists. The fibrous or cartilaginous connections are transected longitudinally from distal to proximal to enter the joint. The MC head is examined, and often a wider, bifacet MC head will be seen (Figure 4-6F). Next, the RCL is elevated with a strip of periosteum from its attachment to the radial proximal phalanx; taking the RCL with a slip of periosteum is critical, as it increases the working length of the ligament, facilitating subsequent transfer (Figure 4-6G). The proximal origin of the RCL may similarly be lifted with a periosteal sleeve off the MC to provide additional exposure of the MC, which is needed in cases of angular deformity or bifid articular surfacing that needs shaping.[22] At this point, the radial thumb is amputated at the level of duplication.

Attention is next turned to skeletal realignment. The preserved ulnar thumb is radially deviated and reduced onto the MC head until a straight longitudinal alignment

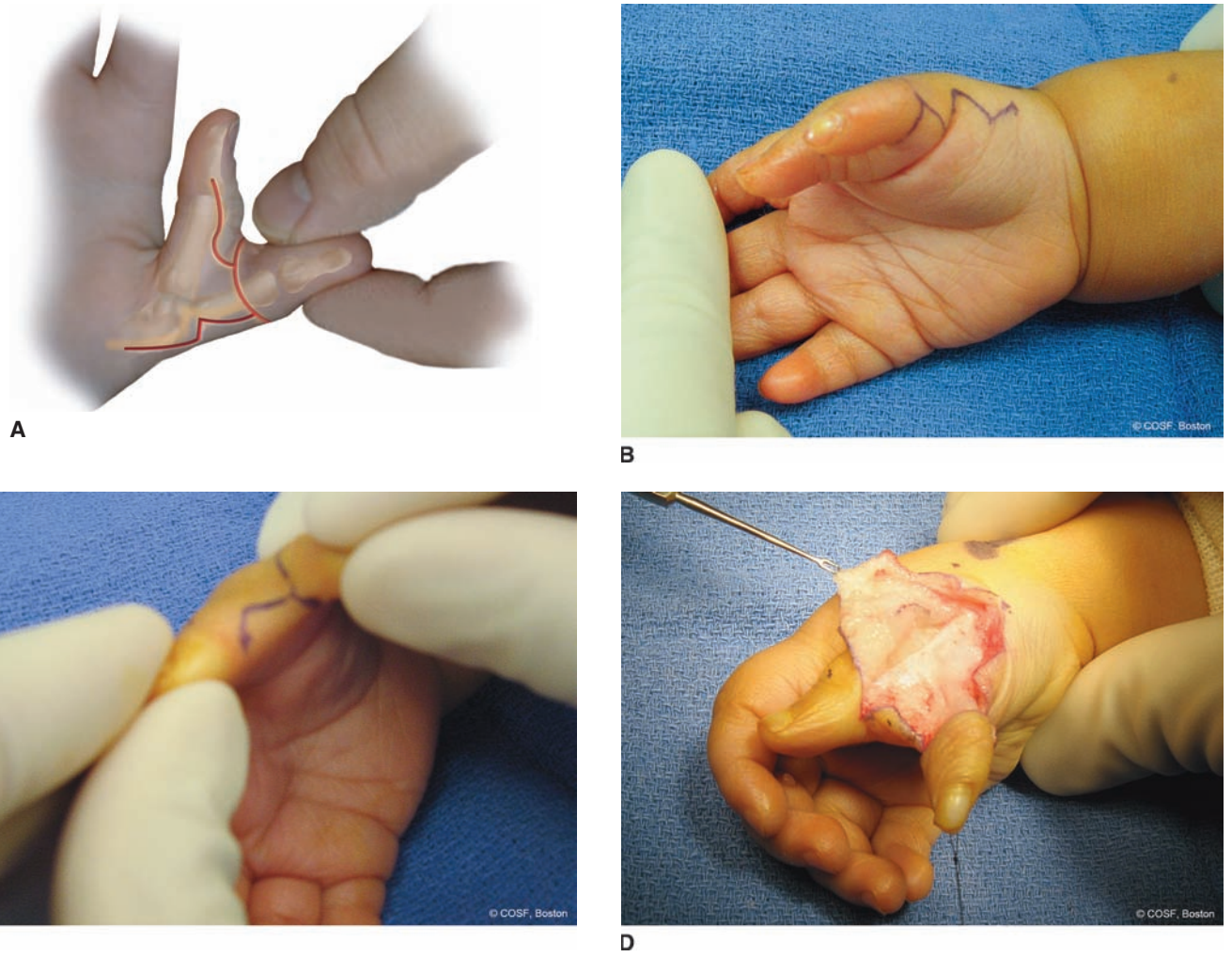
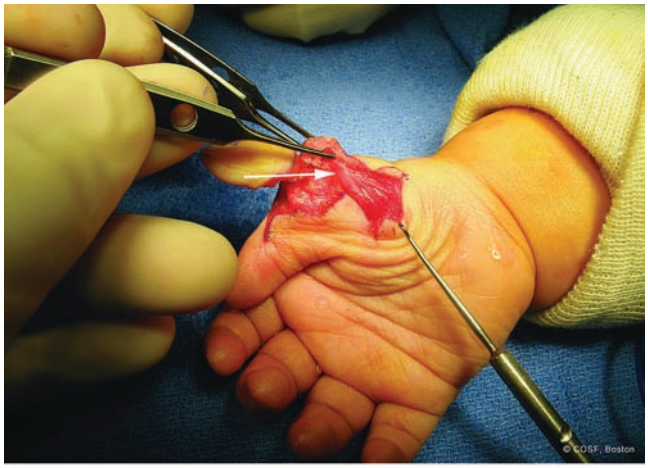


FIGURE 4-6 Reconstruction of the Wassel IV thumb duplication. **A:** Schematic diagram of the radial zigzag incisions with circumferential racquet extension around base of hypoplastic radial thumb used for a Wassel IV reconstruction. **B, C:** Clinical photographs depicting the surgical incisions. **D:** After dorsal skin flap elevation, a bifid extensor mechanism is commonly encountered.



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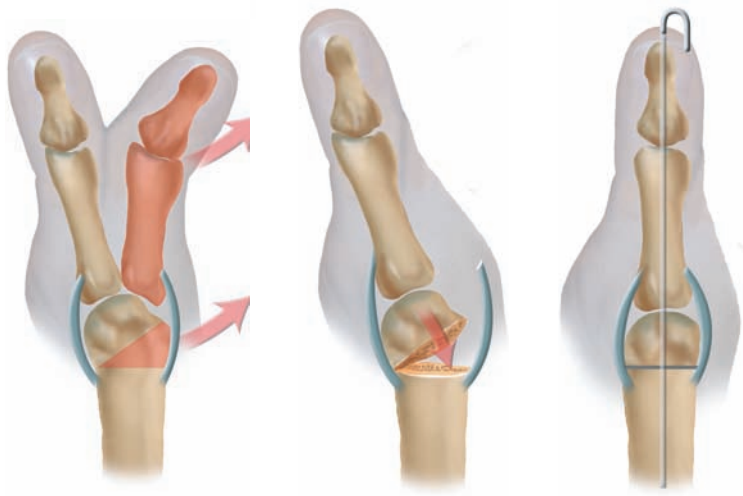

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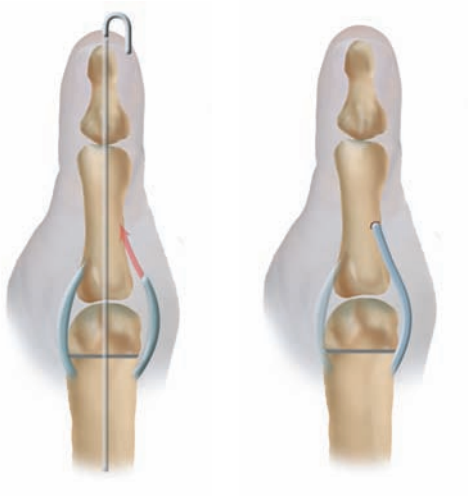

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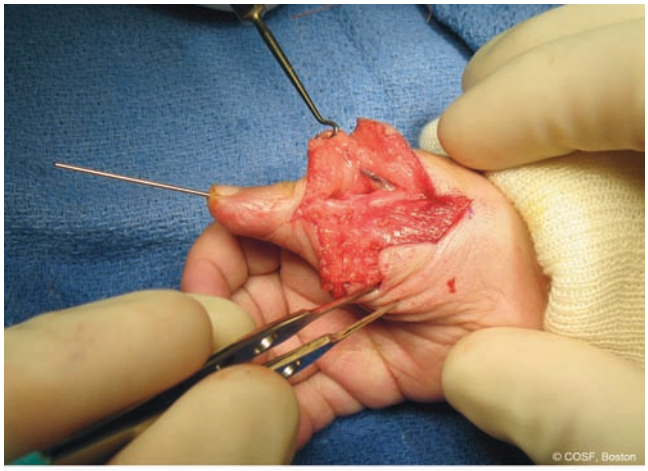

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FIGURE 4-6 *(continued)* **E:** The tendon and muscle belly of the APB are elevated (*arrow*), with care being made to preserve the underlying RCL of the MCP joint, and prepared for later transfer. **F:** A wide, bifacet MC head is characteristically present. **G:** Schematic diagram depicting the RCL elevation with a strip of periosteum distally and an intact periosteal base proximally. If additional correction of the longitudinal alignment is needed, a closing wedge osteotomy through the distal MC may be done. **H:** Schematic diagram and **I:** clinical photo depicting advancement of the RCL into the base of the ulnar thumb proximal phalanx. The APB is similarly advanced and sewn into the base of the proximal phalanx and extensor hood.

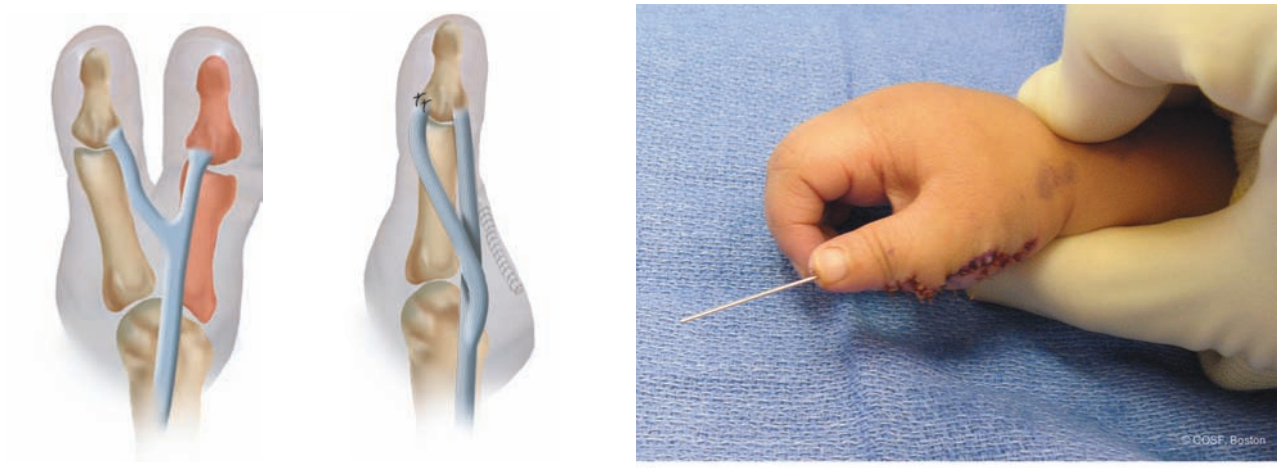

FIGURE 4-6 *(continued)* **J:** Centralization of the EPL and FPL slips will help "balance" the extrinsic forces and avoid a dynamic deforming force on the newly reconstructed thumb. **K:** After reconstruction, the redundant skin may be trimmed and the wound closed primarily via a zigzag incision. Note the straight longitudinal alignment of the thumb.

is achieved. A 67 Beaver blade is used to score the MC head cartilage at the radial margin of the proximal phalanx. The ulnar thumb is moved out of the way, and a chondroplasty of the MC head is performed; a 67 Beaver or No. 15 blade may be used to remove the accessory radial facet of the MC head, flush to the level of the previous score mark. If additional deviation of the MC exists—which should have been noted based upon the preoperative radiographs—a radial closing wedge osteotomy of the MC neck may then be performed, preserving the ulnar cortex and periosteum[23] (Figure 4-6G). At this point, the ulnar proximal phalanx is placed in appropriate position and a 0.028″ C-wire is passed in a retrograde, longitudinal fashion from the digital tip to the MC shaft, stabilizing both the MC osteotomy and the MCP joint.

The RCL is then advanced and sewn into the base of the proximal phalanx, and the dorsal joint capsule is closed. The APB is then advanced and similarly sewn into the radial aspect of the proximal phalanx (Figure 4-6H and I). The bifid components of the EPL and FPL tendons are then sewn into the preserved EPL and FPL slips, thus centralizing the pull of the long extensor and flexor to avoid the potential for late angular deformity (Figure 4-6J). The prior zigzag flaps are then allowed to rotate into place. Redundant skin is trimmed, and skin is reapproximated using multiple interrupted 5-0 or 6-0 absorbable suture (Chromic, Ethicon, Inc., Somerville, NJ) (Figure 4-6K). The pin is bent and cut outside the digital tip, and a sterile bandage is applied. Tourniquet is deflated, vascularity to the thumb and flaps is confirmed, and the limb is placed in a long-arm thumb spica cast. (The thumb may be covered to protect the pin, but we prefer the leave the other fingertips exposed; this way, if the family notices that the fingertips have "disappeared," they will realize the cast is migrating and may soon fall off!)

Other Wassel Reconstructions

The principles of treatment for a Wassel VI duplication are the same except the joint reconstruction and tendon transfers occur at the CMC joint. On occasion, the ulnar thumb can be adducted. The abductor pollicis longus will need to be transferred from the radial to the ulnar thumb. The CMC joint will need to be realigned with ligamentous reconstruction. The MC may require osteotomy. In addition, there are times when the first web space requires a Z-plasty and intrinsic release to attain proper thumb opposition.

Similarly, most Wassel VIIs[24,25] are like IVs except the radial thumb is usually the triphalangeal thumb. Bifid Wassel IIIs and Vs allow for an oblique excision of the radial duplication while preserving the proximal physis, collaterals, and joint. Wassel I reconstructions follow the principles outlined for Wassel II reconstructions below.

◆ Wassel II Reconstruction

In cases of Wassel I and II deformities, surgical removal of the radial distal phalanx, advancement of the RCL, and reconstruction of the eponychium may be performed using converging dorsal and volar zigzag incisions.[16–21] The most challenging of these situations are in the "50-50" thumbs, in which both radial and ulnar distal phalanges and thumb tips are of similar size. While the Bilhaut-Cloquet procedure has been advocated for these situations, our preference is to use converging dorsal and volar zigzag incisions—excising one distal phalanx and preserving the other distal phalanx—for reconstruction (see Sidebar 2). In addition, we use extra pulp skin and subcutaneous tissue to give the appearance of a more balanced, normal thumb rather than a sharpened pencil tip appearance.

SIDEBAR 2

Bilhaut-Cloquet Procedure

On paper, every play's a touchdown.
—Coach Forti

The Bilhaut-Cloquet procedure has been proposed for the reconstruction of Wassel type I and II deformities.[29] This procedure calls for the central resection of a wedge of tissue, including bone, soft tissue, nail bed, and nail plate and reapproximation of the radial and ulnar components in the midline (Figure 4-7). While appealing in concept, in reality this procedure requires meticulous surgical technique and commonly results in nail plate deformity, physeal disturbances, articular incongruity, and aesthetic asymmetry of the reconstructed thumb.[13,23] For these reasons, we do not currently utilize this technique. Recent modifications to the original Bilhaut-Cloquet, however, have resulted in improved aesthetic and functional results[30,31] (Figure 4-8). Future modifications of the Bilhaut-Cloquet principles may make this technique easier and more reproducible.

Patients are placed supine with the affected limb supported on a hand table. A nonsterile tourniquet is placed in the upper brachium. After the limb is exsanguinated and tourniquet inflated, converging zigzag incisions are created on the dorsal and volar surfaces of the duplicated thumb (Figure 4-9A). Full-thickness flaps are raised, and the radial and ulnar neurovascular bundles are retracted with the soft tissue flaps. Split EPL and FPL tendons are indentified and the radial slips released from their insertions on the radial distal phalanx. The IP joint may then be entered. The RCL is then released from the radial distal phalanx, and, proximally, the origin of the RCL is elevated with its

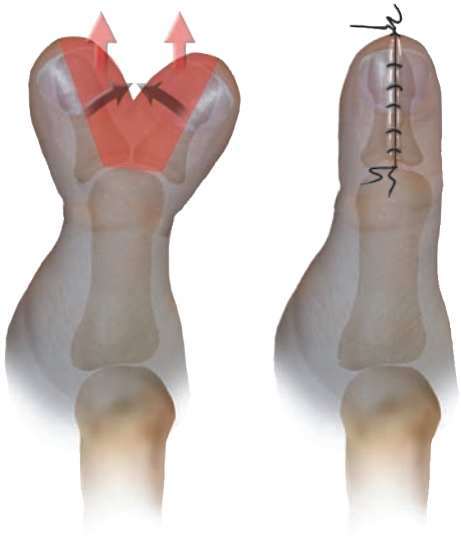

FIGURE 4-7 Schematic diagram of the Bilhaut-Cloquet procedure.

FIGURE 4-8 Schematic diagram illustration of one modification of the Bilhaut-Cloquet procedure.

periosteum to allow exposure of the proximal phalangeal head. At this point, the radial distal phalanx is circumferentially dissected free and may be excised with the central wedge of overlying skin and soft tissue. Chondroplasty of the radial condyle may then be performed if a bifacet proximal phalangeal head is noted. The ulnar distal phalanx is reduced to an anatomic position, restoring the longitudinal alignment of the thumb. A 0.028″ C-wire is passed in a retrograde fashion from the thumb tip across the IP joint, stabilizing the new thumb. The RCL is advanced distally and volarly and reapproximated to the distal phalanx. Slips of the EPL and FPL may then be reapproximated to the sole distal phalanx to prevent eccentric pull of the flexors and extensors and thus avoid secondary deformity. Skin flaps are then interdigitated and closed primarily with multiple interrupted 5-0 or 6-0 suture (Chromic, Ethicon, Inc., Somerville, NJ) (Figure 4-9B). The radial-based flap is bulkier to give a fuller appearance to the digit. If done well, the only apparent asymmetry is the oblique orientation to the retained nail plate.

Approach the game with no preset agendas and you'll probably come away surprised at your overall efforts.
—Phil Jackson

◆◆ Reconstruction of the Thumb Duplication with Dominant Radial Thumb

There are rare situations in which the radial-based thumb is more developed[25]. This can create complex reconstructions. The best way to view this is by extensile exposure with Z-plasty rotation flap incisions. Leave all your options open as you assess the extrinsic and intrinsic insertions and anatomic pathways. Understand that when you are done, you will need the adductor and abductor pollicis intrinsics to

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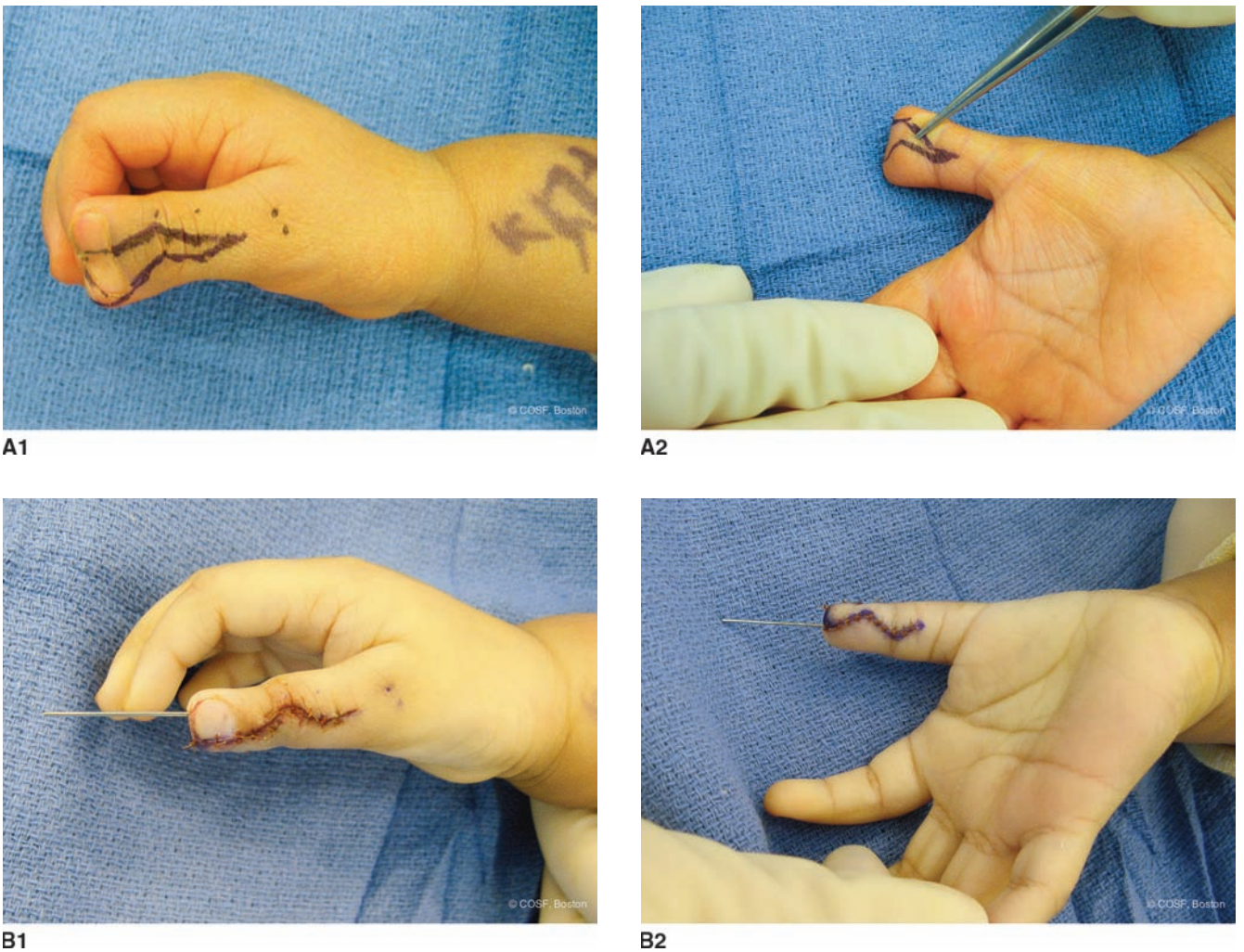

FIGURE 4-9 Wassel II reconstruction. **A:** Converging dorsal and volar incisions, preserving the nail plate, nail bed, and eponychium for soft tissue reapproximation. **B:** Completed reconstruction after excision of radial distal phalanx, RCL reconstruction, EPL centralization, reduction and pinning of IP joint, and skin closure. Note the straight longitudinal alignment of the thumb and preserved contour and width of the thumb tip.

maintain pinch and opposition alignment and strength, the flexor and extensor tendons and muscles to have anatomic pull, and the joints and bones to be aligned and balanced. The first web space needs to be broad, deep, and flexible. Obviously the neurovascular pedicles need to be preserved. As you progress from this reconstruction to the next on-top plasty, you realize that there is no "paint by numbers" here.

◆◆ On-Top Plasty: Reconstruction by Combining the Distal Radial and Proximal Ulnar Thumbs

There are even rarer situations where you have to combine parts of each thumb. The most dramatic we have encountered is a thumb triplication in which parts of all three "thumbs" were used in the final reconstructed thumb. The neurovascular pedicles here are imperative. Skin flaps have to remain viable, particularly the distal flaps that include the final pulp and nail bed/plate. Extensive but careful exposure with broad flaps is important to visualize the unique anatomy and then begin careful excision and reconstruction. We wish we could tell you more, but basically each time we find this, we carefully follow the principles and take what the child gives us to make the best thumb possible.

POSTOPERATIVE

Postoperatively, patients remain in a long-arm thumb spica cast for 4 weeks. At that point, the cast is discontinued, and the pin is removed. A custom-fit orthoplast forearm-based thumb spica splint is fabricated and worn full time for an additional 2 weeks, followed by nighttime splint wear for the next 1 to 2 months. Occupational therapy is

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initiated for scar management, including massage and scar molds if needed, and range-of-motion exercises.

ANTICIPATED RESULTS

Long-term follow-up studies reveal that after successful surgical reconstruction, IP joint motion may be limited, averaging 0 to 30 degrees.[26] Despite this, surgical reconstruction of Wassel type I to VI deformities generally result in stable, functional, and aesthetically acceptable thumbs with little limitations in hand use.

COMPLICATIONS

If it is understood that preaxial polydactyly represents a "split thumb" rather than a "thumb duplication," it is understandable that the reconstructed single thumb will be, by definition, smaller and narrower than the normal contralateral thumb. While surgical techniques such as the Bilhaut-Cloquet have tried to address these aesthetic concerns, often the results are more noticeable and unsightly than a smaller but well-functioning thumb. For these reasons, patients and families should be counseled preoperatively regarding the aesthetic differences that will likely remain after surgical reconstruction. These are usually subtle if surgery is extensive and addresses all elements of the deformity with initial reconstruction.

The most common complication is late deformity requiring revision surgery. Historically, revision surgery rates were reported in up to 25% of patients.[13,20,26,27] However, some of these revision rates are reported in series in which simple amputation of the radial thumb was performed. With attention to the above-stated surgical techniques, however, the risk of late deformity may be considerably reduced. In our experience, the need for secondary surgery is quite unusual. However, we are very aggressive in our initial surgery in attempting to restore all anatomic elements.

In the rare situations in which secondary reconstruction is required, the key is to identify the cause of the secondary deformity and/or dysfunction. In general, late complications are due to joint or bony malalignment or soft tissue imbalance.[28] A common problem is the failure of the inexperienced to excise the bifid MC in a Wassel IV reconstruction (or bifid proximal phalanx in a Wassel II reconstruction). This prominence can be aesthetically displeasing and painful to touch, almost like a great toe bunion. If the collateral ligament was not properly reconstructed or failed over time, the joint instability can result in deformity and pain. This will require either a collateral ligament reconstruction or, in cases of severe deformity or articular incongruity, an arthrodesis.

Bony abnormalities are typically due to angular deformities and/or longitudinal epiphyseal brackets. Corrective osteotomies may be performed to reorient the longitudinal skeletal axis of the thumb.

Soft tissue imbalances may be due to scar contracture, eccentric extrinsic flexor/extensor moments, or the presence of a pollex abductus. Reconstructions are aimed at releasing hypertrophic scar, deepening the first web space, centralizing the flexor and extensor tendons, and releasing the abnormal connections of the pollex abductus, when present.

CASE OUTCOME

This patient was diagnosed with a Wassel IV preaxial polydactyly. No other congenital anomalies were identified, and no formal genetics evaluation was pursued. At 12 months of age, the patient underwent preaxial polydactyly reconstruction, ablating the more hypoplastic radial thumb. At the time of surgery, the RCL was reconstructed, the APB was advanced, the extrinsic tendons were centralized, and

COACH'S CORNER

How to Make a Thumb Straight

If you are going to the bank, you better cash it in.
—Shannon Fish

Just throw strikes. Just make your free throws. Just ski down the fall line. Just cross the finish line first. Just do it. Sports can sound so easy.

While seemingly intuitive, one of the goals of thumb reconstruction is to restore the normal longitudinal alignment of the thumb, both for functional and for aesthetic reasons. Just make it straight. Although easy in principle, a number of surgical steps are needed to achieve this goal. First, skeletal structures must be aligned. This may require angular osteotomies to restore the alignment of the phalanges or MCs and orient the joint surfaces such that they are perpendicular to the long axis of the thumb. In complex situations, this has to be done without physeal or neurovascular injury. Second, the extrinsic flexor and extensor tendons, which often run and insert eccentrically on the phalanges, must be centralized. The thenar intrinsics must be properly reinserted. This will balance the dynamic forces and minimize the risk of late deformity. Third, the collateral ligaments must be advanced or reconstructed to impart static stability to the affected joints. This may be facilitated by using the extended ligamentous-periosteal flap previously described. Finally, skin incisions and flaps must be designed so as to avoid longitudinal scars. This will prevent development of late scar contractures. When all these issues—bone, dynamic stabilizers, static stabilizers, and skin—are addressed, the risk of late deformity is diminished.

a chondroplasty of the bifacet MC head was performed (Figure 4-6). Following surgery, the thumb was mobile, stable, and functioning well, with no evidence of late or recurrent deformity.

SUMMARY

Preaxial polydactyly is among the most common congenital differences encountered by pediatric hand surgeons. Typically sporadic and not associated with other systemic abnormalities, preaxial polydactyly can rarely be treated with simple ablation alone. In addition to removal of the "extra" thumb, the RCL, APB, eccentrically oriented extrinsic tendons, and longitudinal skeletal alignment must all be carefully reconstructed to ensure maximal long-term function and avoidance of recurrent deformity.

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CHAPTER

5

Central Polydactyly

CASE PRESENTATION

A newborn presents with central synpolydactyly. The father has the same condition and has never had surgical treatment (Figure 5-1). The mother is very interested in surgical correction, and the father feels that his nonoperated hands have been highly functional and socially acceptable his whole life as a laborer.

CLINICAL QUESTIONS

- Under which category is central polydactyly classified?
- What are the genetics of this malformation?
- Are there associated syndromes or conditions?
- What is the spectrum of presentation?
- When should surgery be performed?
- What are the surgical techniques?
- What are the expected results?
- What are the complications of surgical intervention?
- What is the natural history if untreated?

THE FUNDAMENTALS

Six aligned, mobile digits, whether independent or syndactylized, do not negatively impair function. However, digital crossover during flexion for grasp and/or failure to clear a digit from the palm during release will limit hand use. Central polydactyly is a rare condition, much less common than preaxial (thumb) or postaxial (small finger) polydactyly, which can impair grasp and release function. Central polydactyly or synpolydactyly can have psychosocial implications, including simple but potentially isolating issues such as learning to count on your fingers in preschool with peers.

Etiology and Epidemiology

Central polydactyly has been classified by the International Federation of Societies for Surgery of the Hand[1] as a type III polydactyly. The Japanese Society for Surgery of the Hand has proposed this malformation be classified with cleft hands and osseous syndactyly under a new category of failure of ray induction.[2] This is based on experimental work with embryonic rats treated with a chemotherapeutic agent (busulfan) in which the tetrogenic effects resulting in cleft hands, central polydactylies, and osseous syndactylies were all from defects in the central hand plate due to failure of induction.[3] The experimental data indicate there is diffuse cell death in the central ectoderm and mesoderm with decreased expression of fibroblast growth factor in the apical ectodermal ridge as well as bone morphogenetic protein-4 and sonic hedgehog in the mesoderm. A similar pattern of interdigital apoptosis and cartilage condensation leads to abnormal induction of digital rays in cleft hands, central polydactylies, and osseous syndactylies.[4,5]

Central synpolydactyly was one of the first two limb malformations identified as being caused by a genetic mutation in a homeobox (HOX) gene.[6] Specifically, it is deletions in HOXD13 on chromosome 2 (2q31) that result in this malformation. It is an autosomal dominant inheritance pattern.[7] There is a spectrum of presentation in each family but generally with marked osseous deformity (Figure 5-2).[8]

Clinical Evaluation

Central polydactyly by definition involves the ring, long, and/or index fingers. It is much less common than postaxial polydactyly or preaxial polydactyly. It occurs most often in the ring > long > index fingers. Bilateral involvement is typical, and associated foot anomalies are frequent. Partial duplications can occur and appear similar to those partial polydactylies of the thumb and small finger by both clinical exam and radiographs. Independent, mobile complete polydactylies also occur. At times, it is unclear which central digit is duplicated. In the presence of syndactyly, the numbers of bones and their alignment can be hard to assess by clinical exam. Radiographs are necessary to determine the presence of bracketed epiphyses, crossed bones, bifid bones, synostoses, joint malalignment, and physeal growth potential. The osseous abnormalities may extend into the palm. Radiographs are mandatory to decide on surgical intervention and planning.

FIGURE 5-1 Photograph of father with untreated central synpolydactyly.

Central polydactyly is associated with Grebe chondrodysplasia and syndrome C (trigonocephaly). Central synpolydactyly is an autosomal dominant inherited mutation of the HOXD13 gene on chromosome 2. Children of consanguineous pregnancies have a more severe form of the osseous disorder that extends into the metacarpals and carpus, metatarsals and tarsal bones.[7]

Surgical Indications

It is what you learn after you know it all that counts.
—Earl Weaver

The hardest decision in central synpolydactyly is to know when natural history will be better than the outcomes of surgical intervention. The biggest risk to surgical separation is transforming a highly functional block of syndactylized digits into a five-digit hand with less functional ability. Unfortunately there is a risk that surgery can result in stiffness, malangulation, and malrotation that negatively impacts hand function. The parents can be on opposite sides of the fence on this decision. The affected parent with the genetic condition often views the psychosocial and functional future of his or her child differently than the unaffected parent. The parents and grandparents often assume that current surgeons are smarter and more skilled than a generation ago. Why shouldn't they? Hasn't everything else from computers to televisions to cars improved in technical expertise? It is a hard negotiation, a difficult decision, and should not be taken lightly. You have to be the child's advocate and realistic about your surgical capabilities. If in doubt, seek additional opinions.

FIGURE 5-2 Anteroposterior radiograph of complex central synpolydactyly with osseous synostoses distal phalanges, bifid middle phalanges ring finger polydactyly, bracket epiphysis proximal phalanx, and cross bone between the ring polydactyly and the middle finger.

SURGICAL PROCEDURES

Life is not always a matter of holding good cards, but sometimes of playing a poor hand well.
—Robert Louis Stevenson

Ray Resection

A central digit duplication with independent, aligned, adjacent fingers is the best indication for surgical reconstruction (Figure 5-3A). The absence of phalangeal bony synostosis or joint fusion and the presence of mobile metacarpophalangeal and interphalangeal joints is ideal for reconstruction. Radiographs usually reveal a bifid (Figure 5-3B) or duplicated metacarpal. When there is no or limited major soft tissue (tendons, nerves) interconnections, a ray resection will yield excellent long-term results.

Standard setup is utilized. Volar and dorsal Z-plasty incisions are utilized (Figure 5-3C). These are preferred to straight incisions because: (1) excision of redundant skin is more precise and (2) scar contracture with growth is less likely. An elliptical incision is outlined around the ray selected for resection. The choice is the more hypoplastic, less functional digit; in the case presented here, the ulnar middle finger is hypoplastic and was excised. Barsky flap incisions are outlined on the central aspects of the retained digits—here the radial middle finger and the ring finger—for web reconstruction after ray resection. Broad exposure

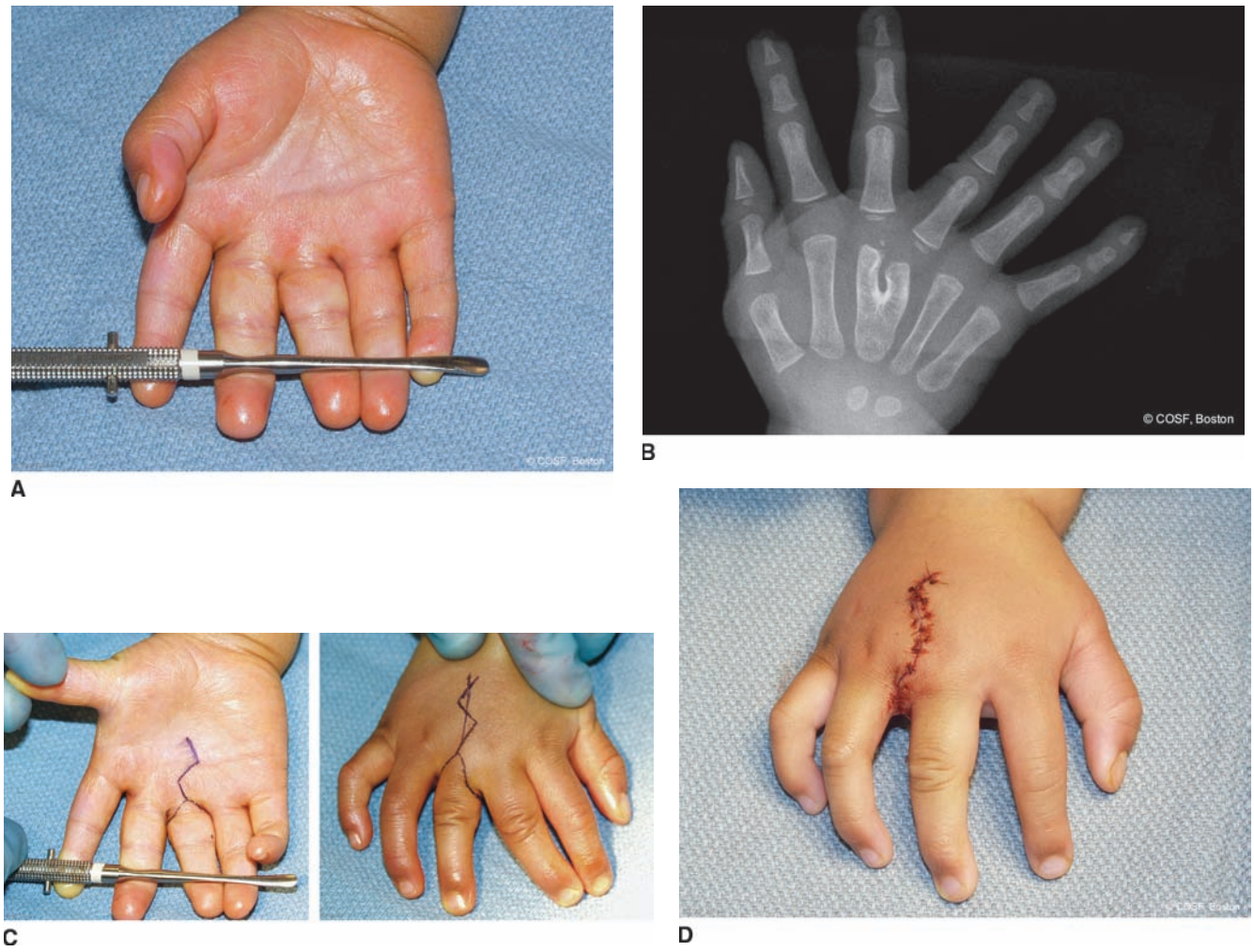


FIGURE 5-3 **A:** Palmar views of central polydactyly with mobile, independent digits. The middle finger here is the polydactylous digit. **B:** Radiograph of the same patient with duplicated phalanges and bifid metacarpal. **C:** Surgical incision markings for excision of ulnar middle finger and reconstruction of web between the radial middle finger and the ring finger. Note the nonlinear Z-plasty incision is preferred to a longitudinal incision. **D:** Intraoperative closure after ray resection and reconstruction of web.

is obtained to identify the neurovascular anatomy, tendon connections, and underlying bone and joint constructs. This is done with final reconstruction in mind. Each situation can be different, and you have to define the anatomy of each case in order to make your final reconstruction plan.

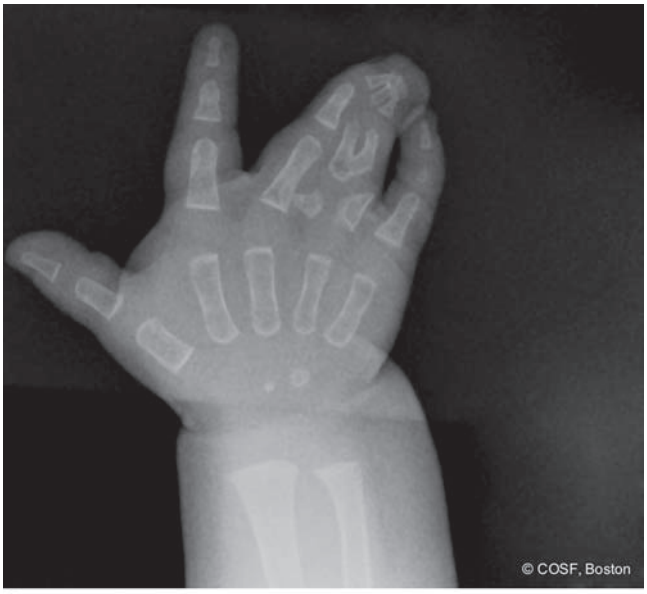
Ray resection is carried out. Transection of the transverse metacarpal ligaments is performed while protecting the neurovascular bundles to the retained fingers. The incision through the ligaments is close to the resected metacarpal for maximum length to facilitate later ligament reconstruction. Digital arteries to the resected ray are ligated. Proper digital nerves are traced to the common digital nerve in each web and transected sharply. Flexor and extensor tendons to the resected ray are detached; they can be utilized for muscle rebalancing or ligament reconstruction. Otherwise, they are removed. Intrinsic muscle rebalancing is performed as necessary. Bone resection is performed with resection of the entire ray or through the bifid metacarpal. Osteotomies are performed for axial alignment if necessary. Resected bone can be used as wedge grafts if required. Reconstruction and closure then follows cleft hand principles (see Chapters 36 and 50 for other ray resection indications). Transverse metacarpal ligaments are repaired. Barsky flaps are closed for commissure repair. Redundant skin is excised with palmar and dorsal curvilinear closure (Figure 5-3D). Tenodesis is used throughout the reconstruction and closure to be certain alignment is correct. Digital overlap is not acceptable. Transverse smooth pin fixation (two 0.28- to 0.45-inch C-wires) is performed to maintain axial and rotational alignment and protect reconstruction. Long-arm cast immobilization is maintained for 4 weeks followed by pin removal and occupational therapy. Splint protection is usually carried out for 2 to 4 more weeks.

◆◆ Complex Central Synpolydactyly Reconstruction

Man can learn nothing except by going from the known to the unknown.
—Claude Bernard

As previously mentioned, surgical intervention in its present state has its limitations in central synpolydactyly. The joints in the central osseous polydactyly are usually malaligned and have been relatively immobile since embryonic formation. The bones are frequently distorted with synostoses, delta phalanges, cross bones, and bifid bones from the distal phalanx through the metacarpals. The nails are conjoint; the skin is taut and limited. The tendons are rarely independent but can have crossover or be absent. Radiographs help extensively in planning, but, ultimately, you never know what that child has until you are in the operating room.

Almost by definition, the middle finger is better aligned and developed than that complex osseous deformity of the ring finger polydactyly (Figure 5-4A and B).



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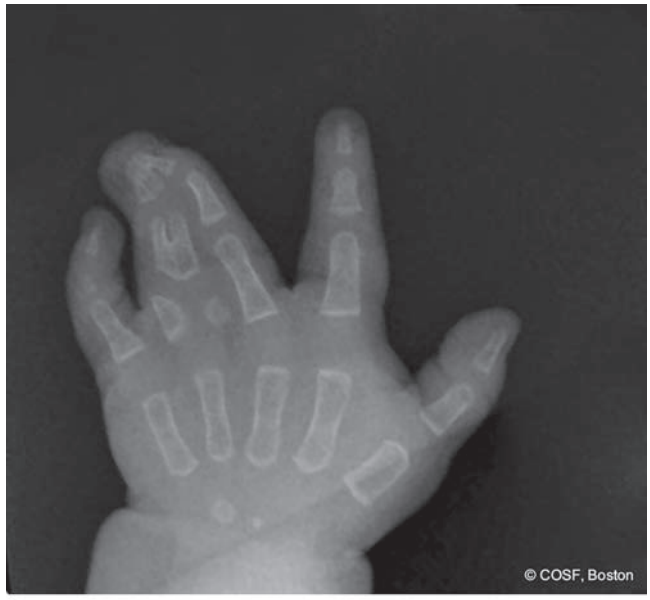

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FIGURE 5-4 **A**: Anteroposterior radiograph of complex osseous central synpolydactyly. **B:** Radiograph of the opposite side in the same patient. **C:** Postoperative after partial separation and soft tissue reconstruction. A portion of the cross bone had to be retained for joint alignment and stability.

The distal phalangeal synostosis usually includes parts of three hypoplastic phalanges and nails. The first goal is a straight and more mobile middle finger. The second goal is more realistic: a straight, stiff, shorter ring finger that does not impair hand function by getting in the way. The family needs to understand the limits of our present abilities to accomplish more than those goals.

A wide, dorsal-based, rectangular web flap is utilized. Z-plasty incisions are carried distally. Planning for distal phalangeal osteotomies and central resection of the redundant bone and nail plate is incorporated in the eponychial flap incisions. Mirror-image volar Z-plasties are incised. Resection of the central bone is from distal to proximal. The proximal extent of the reconstruction is dependent on (1) vascular pedicles, (2) osseous separation and reconstruction, and (3) risk of malangulation and malrotation with more proximal separation. The resected bone can be utilized for bone and/or joint alignment as opening wedge osteotomies if necessary. The extent of bone and joint correction in one setting is dependent on vascular concerns for flaps, small bone segments, and digits as a whole. Generally the border (radial for middle finger, ulnar for ring finger) neurovascular pedicles are normal and serve as the source of viability of the digit if central pedicles are deficient or surgically impaired. Anytime you are really concerned, drop the tourniquet and check the viability before sacrificing a vessel or getting in too deep with your reconstruction. At times, bony synostosis or fragments need to be retained to maintain joint stability or bony alignment (Figure 5-4C). Extrinsic and intrinsic tendon rebalancing is often necessary. Compromised situations often occur with conjoint flexors and abnormal tendon alignment and connections. It is not unusual to find a central flexor tendon that splits with malaligned attachments to the interconnected digits.[9] Simply, you do the best you can with what you have to work with. This is why the highest level of skill, experience, and knowledge is required for this surgery. Pin fixation is performed before flap rotation and closure. Full-thickness skin graft is necessary.

POSTOPERATIVE

Cast and pin protection is used for 1 month followed by prolonged splinting and scar molding to maintain alignment. Therapy with mobilization of joints is performed.

ANTICIPATED RESULTS

The best outcomes are from complete ray resection. This can include surgical reconstruction to a four-digit rather than a five-digit hand. A positive outcome from reconstruction of a central complex synpolydactyly will have a more mobile, aligned middle finger and a relatively straight, stiff, short ring finger (Figure 5-5). This may or may not be acceptable to the patient and family.

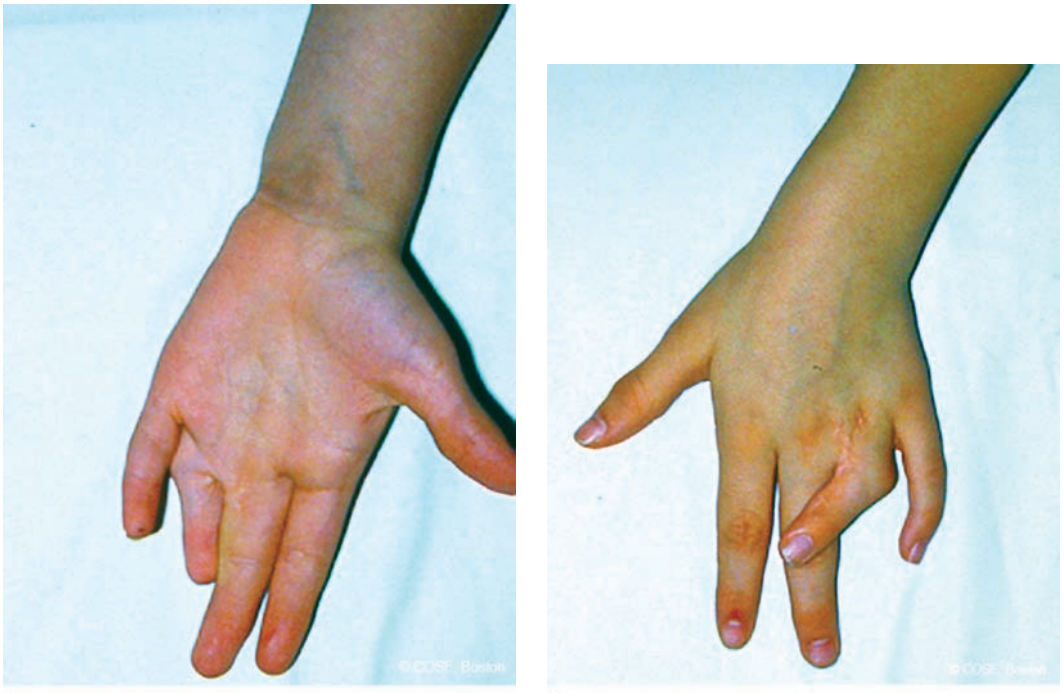

FIGURE 5-5 Palmar **(A)** and dorsal **(B)** view of foreshortened and malaligned ring finger after central polysyndactyly reconstruction. The dorsal view is most dramatic with crossover of ring on long finger. Corrective osteotomy is indicated and was performed.

COMPLICATIONS

The most common surgical complication is malangulation and malrotation that impairs hand function. The worst situation is that the reconstructed finger gets in the way and limits the use of the mobile, strong adjacent fingers and thumb. It is slightly advantageous to hand function if the nonfunctional digit is dorsal and out of the way of the other digits[9] (Figure 5-5). Wood cites excessive surgery (10/20 patients with three or more operations, maximum number of 15 operations in one patient) and a high number of poor (6/14) and fair (3/14) outcomes with central synpolydactyly reconstruction for a five-digit hand. Be careful in your operative selection.

CASE OUTCOME

In the end, the mother's desires won out. Surgical separation was performed on each hand. The right required only one reconstruction and the left two reconstructions (the original separation and a secondary osteotomy) (Figure 5-5). The ring finger on each hand was shorter, with limited motion, but not a functional or cosmetic determinant to the child or parents.

SUMMARY

Central synpolydactyly is a genetic condition of the HOXD13 gene on chromosome 2 with autosomal dominant inheritance. Reconstructive surgery is complicated if there is osseous synostoses and deformity. Negotiated decision making with parents for the future best interests of the child is complex. Surgical outcome should be better than natural history.

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CHAPTER

6

Clinodactyly and Camptodactyly

CASE PRESENTATION

A 6-month-old infant presents with bilateral flexion contractures of the small finger proximal interphalangeal (PIP) joints: 30 degrees on the left and 60 degrees on the right by passive exam. Active motion is more limited than passive motion. The parents think this has been present since birth but thought it was a normal, clenched fisting posture of newborns. There is no family history of congenital hand differences. No associated conditions have been noted by the primary care physician on exam.

CLINICAL QUESTIONS

- What are clinodactyly and camptodactyly?
- What is a delta phalanx? Bracket epiphysis?
- What is the normal anatomy around the PIP joint of a finger?
- What is the abnormal anatomy in clinodactyly and camptodactyly?
- What are the associated conditions and syndromes?
- When is nonoperative treatment indicated?
- What are the indications for surgery?
- Is surgery commonly performed?
- What techniques are used to correct camptodactyly of the fingers and clinodactyly of the fingers and thumbs?
- What are the downsides and complications of surgery?

THE FUNDAMENTALS

Do not let what you cannot do interfere with what you can do.
—John Wooden

"Crooked" fingers and thumbs are normal to a certain degree as long as they do not interfere with adjacent digital and/or overall hand function. Every patient will have straighter fingers when they actively flex into the palm than when passive alignment is checked by tenodesis. Check yourself now and see what you find out about your passive and active alignment differences. Most if not all nonpathologic, digital malalignment and malrotation in people are symmetric. So, always examine the other side to determine if what you and they are seeing is really abnormal. In general, <30 degrees of a flexion contracture at the PIP joint or 15 degrees of radioulnar deviation does not compromise hand function. The patient's and parents' aesthetic perception is another issue altogether.

Grasp and power grip on the ulnar side are important hand functions that are not impaired by a flexion contracture of the interphalangeal (IP) joint. Digital release is well maintained by compensatory hyperextension of the metacarpophalangeal (MCP) and distal interphalangeal (DIP) joints, especially in ligamentously lax young patients.

Etiology and Epidemiology

Clinodactyly

Clinodactyly by definition is >10 degrees of digital deviation in the radioulnar plane. This is usually due to abnormal bony anatomy. It can involve any digit but is most common in the small finger due to an abnormally shaped middle phalanx. Asymmetric longitudinal growth of the physis results in digital malalignment, usually radial deviation of the small finger. Up to 1% of the population will have clinodactyly of the small finger (Figure 6-1). Bilateral involvement is common. There is an autosomal dominant inheritance pattern in isolated, familial clinodactyly of the small finger.[1]

Clinodactyly of the index finger is a unique entity that presents at birth with marked deformity (Figure 6-2). It is often unilateral, with male predominance. It is commonly associated with brachydactyly and a hypoplastic trapezoidal or triangular middle phalanx. It is not associated with systemic anomalies or mental retardation. The index finger is usually radially deviated.[2]

Triphalangeal thumb is a unique form of clinodactyly in which the "extra bone" is triangular or trapezoidal shaped. This delta phalanx leads to malalignment of the thumb and, if severe, can impair pinch. Too much length with a rectangular extra phalanx can also impair thumb

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FIGURE 6-1 Mild, nonprogressive clinodactyly with radial deviation of small finger due to trapezoidal-shaped middle phalanx.

function. Inheritance is autosomal dominant. It is seen with other thumb malformations, such as thumb polydactyly. It is usually not seen with other systemic conditions or syndromes.

Associated syndromes and conditions are common. Delta phalanges and bracket epiphyses are often a part of other, more complex hand conditions (see Chapter 5). They are seen as a frequent part of chromosomal, central nervous system, and craniofacial abnormalities (Table 6.1). Many conditions that include symptoms of impaired intelligence have clinodactyly as part of their clinical spectrum. In utero ultrasound screening for Down syndrome includes clinodactyly as one of the diagnostic criteria. Clinodactyly of the thumb is seen most often with Rubinstein-Taybi syndrome, Apert syndrome, and dystrophic dysplasia (hitchhiker thumb).

Clinodactyly can be congenital (as above) or acquired. Acquired situations are due to physeal changes from trauma, infection, and benign tumors (intra-articular osteochondroma enchondroma) (Figure 6-3).[3]

Camptodactyly

Camptodactyly by definition is a flexion posture or contracture of the PIP joint. Like clinodactyly, it usually involves the small finger and is often bilateral, though typically asymmetric (Figure 6-4). There is an autosomal dominant inheritance pattern of variable penetrance and expressivity with isolated small finger camptodactyly. Less than 1% of people have camptodactyly. Unlike clinodactyly, camptodactyly is usually secondary to soft tissue abnormalities. The most commonly implicated anatomic structures are the flexor digitorum superficialis (FDS) and the lumbrical. The abnormal volar static and dynamic forces lead to skin, fascial, volar plate, check rein ligament, and collateral ligament tightness. Eventually bone and joint deformity develops (Figure 6-5). Camptodactyly often presents during periods of accelerated growth. Since infants usually double their size in the first 6 months and triple their size in

A

FIGURE 6-2 **A:** AP clinical view of index finger clinodactyly. *Arrows* outline deformity due to middle phalangeal delta phalanx.

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B

C

FIGURE 6-2 (*continued*) **B:** Anteroposterior radiograph of same patient with middle phalanx bracketed epiphysis and distal phalanx partial duplication. **C:** Surgical correction. Z-plasty flaps are seen on the radial aspect of the index finger. Skin markings outline the planned corrective osteotomy *(arrow)*.

the first year, this is a common time for presentation. Similarly, you can almost hear teenagers grow as they eat their way through their families' refrigerators, so adolescents are the second-most common presenters of this condition to the office.

Camptodactyly is seen with other orthopaedic or generalized conditions. The most common orthopaedic condition with camptodactyly is arthrogryposis, usually involving multiple digits. Various types of skeletal dysplasias can have camptodactyly. Beal arachnodactyly is another syndrome that has associated PIP joint flexion contractures. Marfan syndrome has PIP joint flexion posturing. The extreme form of a flexion contracture at the PIP joint is symphalangism. Like clinodactyly, the associated syndromic conditions include genetic and craniofacial abnormalities (Table 6.2). There is a unique genetic condition described in Saudi Arabian families, the camptodactyly-arthropathy-coxa vara-pericarditis (CACP) syndrome. It is an autosomal recessive disorder caused by mutations in the proteoglycan 4 (PRG4) gene. Manifestations vary across families as well as between affected individuals from the same family, with digital camptodactyly and arthropathy of the knees the most ubiquitous, while pericarditis is evident in only one-fifth of all reported cases.[4,5]

Table 6.1

Representative syndromes associated with clinodactyly (not exhaustive but representative)

Chromosomal
Partial trisomy 4, trisomy and monosomy 18, trisomy 9, trisomy 13, tetrasomy Y, chromosome 11 duplications, CDMP 1 gene mutations, Klinefelter
Central nervous system
Russell-Silver, Dandy-Walker, Feingold, Andersen, Down, Axenfeld-Rieger, Saethre-Chotzen, Coffin-Siris, epidermal nevus syndrome, Fabry
Craniofacial
Oral-facial-digital, Robinow

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FIGURE 6-3 Anteroposterior radiograph of middle finger clinodactyly secondary to intra-articular osteochondroma from middle phalanx ulnar condyle.

Clinical Evaluation

About the only thing that comes to us without effort is old age.
—Gloria Pitzer

Clinodactyly

For both clinodactyly and camptodactyly, careful physical examination and thorough patient/parental counseling are critically important. In clinodactyly, measurement of the angular deformity from proximal to distal aspects of the digit through the point of maximum deformity is recorded. This is remeasured with each visit to assess progression, or lack thereof, with growth. The usual pathology is asymmetric longitudinal growth of the middle phalanx physis in the finger and proximal phalanx in the thumb. The

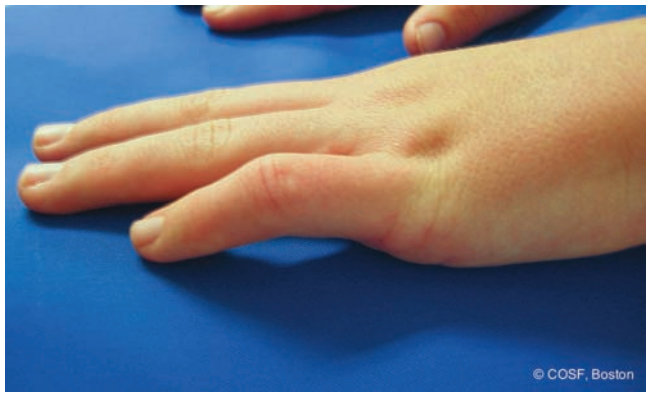

FIGURE 6-4 Lateral clinical view of mild small finger camptodactyly. Note normal PIP creases.

FIGURE 6-5 Lateral radiograph of clinodactyly demonstrating "parrot beaking" of proximal phalanx and flexion contracture of the PIP joint.

quality of the volar digital flexion creases at the IP joints provides insight into the underlying bony architecture. In clinodactyly, the PIP and DIP converge on the radial side rather than remain parallel (Figure 6-6). You must distinguish between static and progressive deformity with growth over the first 5 to 10 years of life. If progressive and/or severe, the involved digit can overlap the adjacent digit during grasp and alter function. The most common situation is the small finger crossing over or under the ring finger. In the thumb, marked radial deviation impairs tip-to-tip pinch and allows for only lateral pinch against the ulnar aspect of the thumb IP joint. Similarly, index finger clinodactyly can impair pinch, though the deformity is

Table 6.2

Representative conditions with associated camptodactyly (not exhaustive but representative)

Craniofacial
Pierre Robin, Freeman-Sheldon syndrome, Robinow
Genetic
CACP and familial arthropathy, partial trisomy 16
Central nervous system
Blau, Hunter-MacDonald, fetal alcohol, Pena-Shokeir, Aicardi, Gordon

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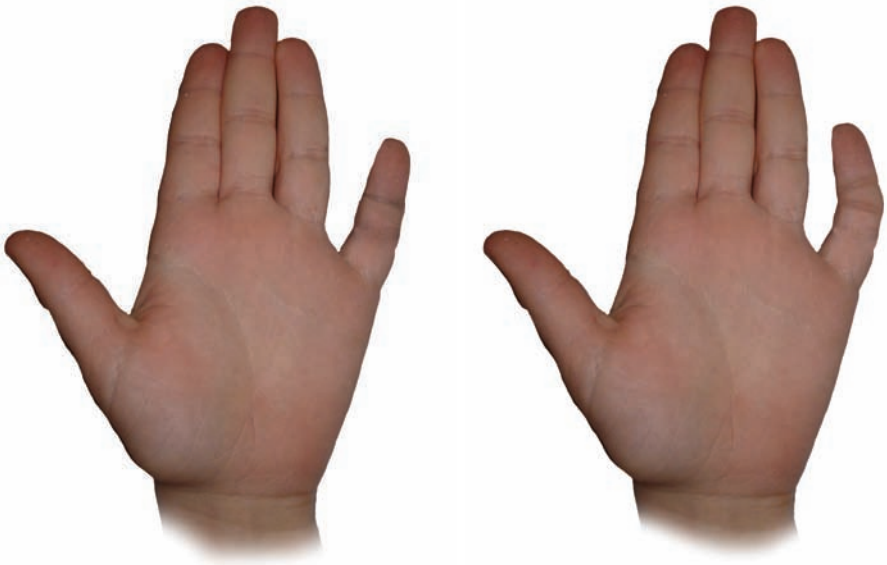

FIGURE 6-6 Illustration diagram of parallel and converging IP joint creases in normal and in clinodactyly.

almost always to the radial side. Radiographs define the bony architecture. Generally there is a delta phalanx or even a C-shaped longitudinal epiphyseal bracket.[6,7] The triangular, trapezoidal, bracket-shaped epiphysis, or intra-articular osteochondroma of the involved phalanx, defines the deformity and guides surgical correction, if needed.

Cooney classified clinodactyly as a combination of simple, complex, and complicated (Table 6.3). The deformity can be isolated with single bone involvement, complex involving multiple bones as a part of a congenital hand malformation, or complicated as a part of a systemic syndrome. The clinodactyly will either be static, remaining stable with growth, or progressive, eventually impairing hand function. With progression of the bone and joint deformity, a corresponding soft tissue contracture develops on the concave side of the digit. Unfortunately, there is no role for splinting or therapy in clinodactyly. A major issue for parents and patients is the cosmetic appearance. However, their concerns should not lead you to initiate "pointless" treatment[8] or perform unnecessary and potentially problematic surgery.[8] The preferred treatment for mild-to-moderate clinodactyly is to avoid surgery.

Camptodactyly

The degree of PIP joint passive contracture, age of the patient, and general medical condition defines the camptodactyly. The passive limits of extension are recorded and monitored throughout growth and treatment. The degree of active PIP joint extension lag is compensated by MCP and DIP joint hyperextension in order to clear the digit from the palm and not interfere with adjacent digital function and release activities. This results in a highly functional situation because grasp remains strong, and release is not impaired, though differences in appearance remain.

The pathoanatomy is at the core of camptodactyly and usually relates to an abnormal FDS and/or lumbrical insertion and/or origin. The abnormal insertion of either of these structures pulls the PIP joint into flexion without balanced extension. The deformity can be flexible (usually early in course) or fixed. Fixed deformity implies shortened flexor tendon and sheath, contracted check rein and collateral ligaments, thickened volar plate, and possibly bony deformity. As with any intrinsic-extrinsic imbalance or MCP-IP joint cascade malalignment, the PIP flexion contracture must be assessed with varying degrees of wrist and MCP flexion and extension to define the pathoanatomy. In addition, you need to distinguish by exam the presence or absence of the small finger FDS and whether it is conjoined to the ring finger.

Presentation and progression usually occurs during periods of rapid growth acceleration, thus the classification system of infantile/congenital (type I), adolescent/acquired (type II), and syndromic (type III). In marked, fixed deformity, all the local anatomic structures become involved with contracture of the volar skin, fascia, collateral ligaments, volar plate, and flexor tendons. The extensor mechanism becomes attenuated and displaced. Eventually, deformity of the proximal phalangeal head and neck (flattening into a "parrot beak" deformity with loss of convexity) and middle phalanx base (flattening with asymmetric loss of concavity) develops with volar joint subluxation (Figure 6-5). At this stage, opportunity for successful intervention is more limited.

Differential diagnosis includes traumatic boutonniere deformity, inflammatory arthritis, juvenile palmar fibromatosis, trigger fingers, arthrogryposis, Beal syndrome, pterygium syndrome, symphalangism, extensor tendon hypoplasia, congenital delta phalanx in flexion, and ulnar or C8-T1 neuropathy with clawing, among others.

Table 6.3

Modified Cooney Classification

Simple	Soft tissue	<45 degree deviation
Less simple	Soft tissue	>45 degrees
Complex	Bone involvement	<45 degrees
Complicated	Bone involvement	>45 degrees

Adapted from Cooney, WP. Reconstruction of the Child's Hand. Carter, P. ed. Philadelphia. Lea and Febiger. 1991, pp209-235.

Surgical Indications

The only thing I will remember from my hand fellowship when I am drooling on my chin in the nursing home is "Never operate on a PIP joint unless you have to."
—Peter Waters countless times

Our advice is to leave mild-to-moderate clinodactyly and camptodactyly in your office, in the therapist's office, and out of your operating room. Leave alone the deformities for which the other digits and a smart brain can compensate without thought or inefficiency of action. That said, marked deformity does need to be addressed. With clinodactyly, osteotomy of the involved phalanx coupled with skin rebalancing is the indicated intervention. With camptodactyly, soft tissue releases and rebalancing are most important, though often must be combined with bone and joint procedures. Knowing when you or someone else should do surgery is a major step on the congenital learning curve. Indicated surgeries are (1) camptodactyly >60 degrees that is unresponsive to stretching and splinting and (2) clinodactyly >30 degrees that interferes with grasp or pinch. Less clear indications are (1) physiolysis for progressive clinodactyly in children younger than 5 years and (2) camptodactyly between 30 and 60 degrees in a compliant family and patient.

SURGICAL PROCEDURES

Splinting Techniques

All the evidence obtained so far indicates there is no role for splinting in clinodactyly. Splinting and therapy will not correct bone or joint deformity in either clinodactyly or camptodactyly. However, passive extension stretching and splinting is the predominant treatment for most cases of camptodactyly. In infantile (type I) camptodactyly, the pathoanatomy is soft tissue contractures and muscle imbalance without bone and joint deformity. Progressive extension splinting with forearm-based orthoplast techniques have been effective in reducing and maintaining correction (Figure 6-7).[9] Also, splinting with an active and passive range-of-motion program will often reduce the deformity to an acceptable level for function in an adolescent situation provided the patient is compliant. The splinting and therapy approach is also a good test of patient and family compliance with a tedious, methodical program of care. Without compliance, postoperative care will fail and greatly affect the outcome of any surgical intervention.

◆ Soft Tissue Releases and Rebalancing with Z-Plasties for Camptodactyly

In theory there is no difference between theory and practice. In practice there is.
—Yogi Berra

Symmetric serial Z-plasties are outlined from palm through distal phalanx for volar skin and subcutaneous tissue rearrangement. The Z-plasty limbs can be as small as 5 mm and up to 1 cm depending on the age of patient and degree of contracture. A combination of Z-plasties and full-thickness skin grafting may be necessary for marked deformity (a black diamond level case with bone and joint deformity). Postoperative viability and pliability of the flaps are critical for successful outcomes. During elevation of the flaps, the digital neurovascular

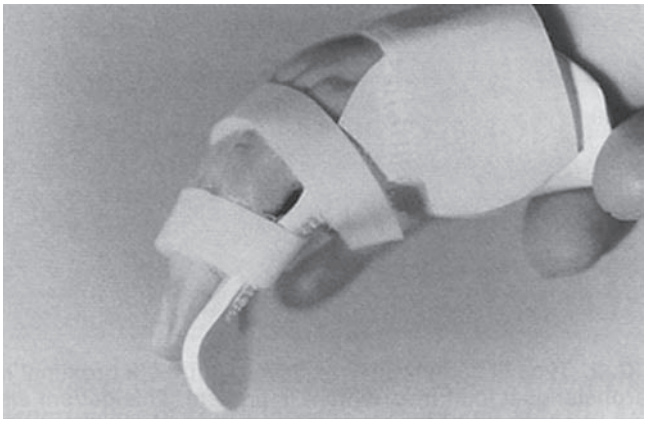

FIGURE 6-7 Illustration of a forearm-based, volar extension splint used for progressive static stretching of camptodactyly. (Reprinted from Benson 96 LS, Waters PM, Karnil NI, et al. Camptodactyly: classification and results of nonoperative treatment. *J Ped Orthop.* 1994;14(6):814–819, with permission.)

pedicles are identified and protected. They can be quite close to the flaps and vulnerable to injury directly or by stretch with correction of marked deformity. An avascular or dysvascular digit is a disaster that must be avoided at all costs. Fibrous bands, distinct from the neurovascular bundle (NVB), are released. Exposure and identification of the FDS and flexor digitorum profundus (FDP) tendons are performed proximal to A1 pulley and through A3 pulley; these may be controlled with vessel loops. The pathoanatomy of the FDS is defined from palm to insertion, including ring and small finger interconnections, aberrant pathways, abnormal insertion, or tendon consistency. Generally, the FDS is released near its insertion and either resected (fibrotic, foreshortened) or prepared for dorsal transfer (pliable, healthy excursion) through the lumbrical canal. The distal aspect of the FDS chiasm insertion to the middle phalanx is preserved to avoid late hyperextension deformity. The FDP is mobilized and checked for full excursion. The lumbrical anatomy is outlined from origin at FDP to its insertion. Often, it does not pass normally through the lumbrical canal to its insertion onto the extensor mechanism. If abnormal, the lumbrical is either released or transferred through its normal pathway to insertion into the extensor mechanism. The clinical results of the FDS and lumbrical transfers are often not as good as they sound. Do not transfer fibrotic or foreshortened tendons and muscles, as their limited excursion and abnormal length will lead to disappointing postoperative motion.

At this point, passive extension is checked. Deeper release continues if incomplete extension has been achieved. The volar plate may need to be elevated from proximal to distal from the proximal phalanx to the PIP joint. The middle phalangeal physis is protected. The check rein ligaments may need to be released. Again, the status of the neurovascular pedicles is monitored closely during gentle correction of the flexion contracture. Often the joint is pinned in 20 to 30 degrees of flexion after full passive motion is achieved. The Z-plasty flaps are rotated and sutured with care taken not to impair blood supply to flaps with deep sutures. The flap closure needs to be tension free. If it is not, utilize full-thickness skin graft. Otherwise, a necrotic flap will become fibrotic scar that later limits outcome. The tourniquet is deflated to check the vascularity to the digit or flaps. If there is any compromise to the digit, the pin is removed and appropriate adjustments are made before final dressing. Similarly, if the flaps are compromised, they are released and skin graft or revision flaps performed before final dressing. Do not leave the operating room with impaired vascularity to the digit or flap(s).

◆ Excision of Delta Phalanx in Clinodactyly Associated with the Triphalangeal Thumb

In a malaligned triphalangeal thumb, the surgical options for correction of middle phalangeal deformity are osteotomy or excision of the middle phalanx. In the young patient, delta phalangeal excision with collateral ligament reconstruction is feasible as long as there will be a congruent joint between the proximal and distal phalanges in the new IP joint. In the presence of marked joint incongruity or an older child with risk of soft tissue instability, an osteotomy is more appropriate (Figure 6-8).

A midaxial approach is used on the convex side of the thumb. Direct exposure of the delta phalanx is performed between the volar NVBs and the dorsal extensor mechanism. Careful elevation of the periosteum with scalpel and sharp elevator is performed to maintain continuity of the soft tissue envelope circumferentially. This protects both the NVBs and flexor and extensor tendons. The PIP and DIP joints are entered sharply from the longer, convex side of the delta phalanx. Maximum length of the collateral ligaments, volar plate, and dorsal capsule is preserved by detaching them as distally as possible from the proximal phalanx and as proximally as possible from the middle phalanx. This length on both ends is critical to reconstructing a stable joint. The delta phalanx is excised subperiosteally (Figure 6-9), with preservation of the collateral ligaments on the concave side. Reduction of the joint is performed and pinned

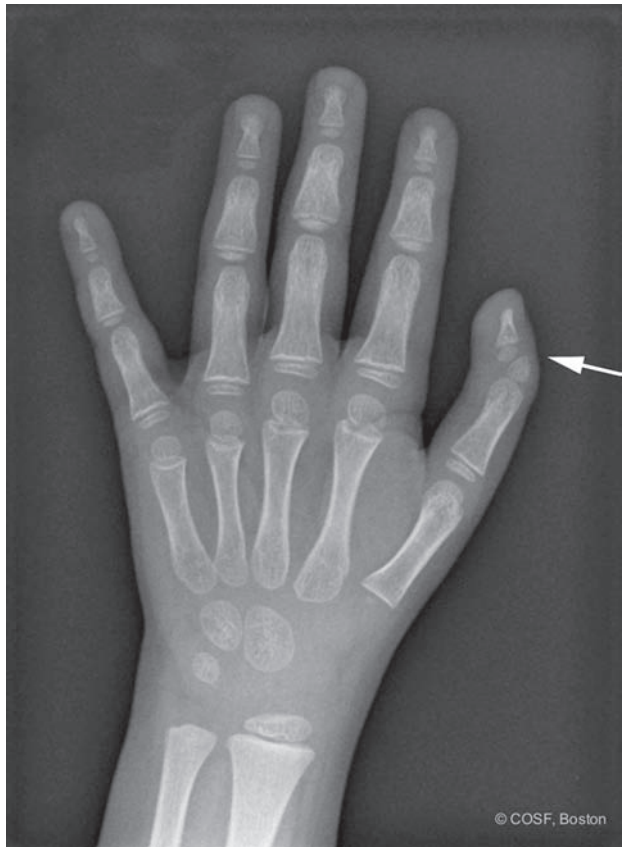

FIGURE 6-8 Anteroposterior radiograph of triphalangeal thumb with delta phalanx *(arrow)*.

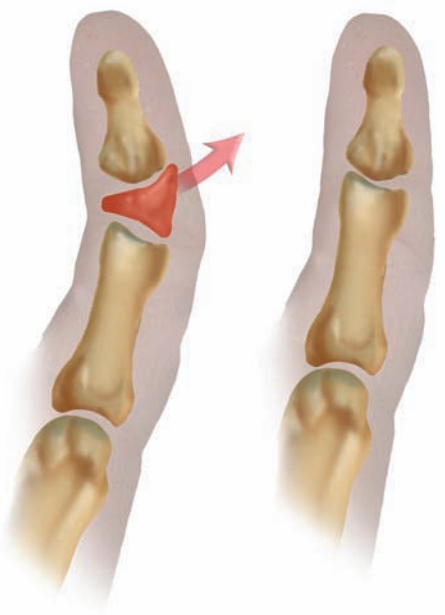

FIGURE 6-9 Illustration of excised delta phalanx.

longitudinally with a smooth, small-diameter C-wire. The collateral ligaments, volar plate, dorsal capsule, and periosteum are closed with absorbable suture. There will be some redundancy of the skin and subcutaneous tissue. This is excised with distal and proximal triangular flaps while protecting the underlying NVB. Closure is performed without tension or redundancy.

The greatest challenge to any thinker is stating the problem in a way that will allow a solution.
—Bertrand Russell

◆◆ Correction of Severe Camptodactyly

The operative technique for severe contractures of ≥90 degrees follows the blue square principles of soft tissue rebalancing and releases with Z-plasties outlined above. However, skin grafting to supplement volar skin closure is often required. Sometimes a cross-finger flap is considered and used to provide vascularized skin and subcutaneous coverage over the exposed tendons and joint.

In addition, there is usually bone and joint deformity (loss of convex-concave congruency with volar subluxation) making reduction difficult and potentially incongruent. The joint release required for correction is quite extensive and performed through the volar plate and partial collateral ligaments. The joint often rocks in and out of alignment with flexion-extension passive motion in the operating room. The risk to the neurovascular pedicles is more real with full correction. Corrected position often puts the FDP under maximum tension with a resultant DIP flexion contracture. Rebalancing may be needed with Z-lengthening; conversely, a decision can be made to gradually stretch the FDP and correct the resultant tightness over time postoperatively. Surgical results are more limited when loss of flexion is exchanged for improved passive and active extension. In essence, this is similar to a "soft tissue osteotomy," and the patient and family need to be aware of this preoperatively. The arc of motion changes but does not necessarily increase. In syndromic conditions with severe deformities, multiple digits can be done under one anesthetic. However, many patients accept their situation rather than have that extensive of a surgical intervention and postoperative rehabilitation.

Osteotomy and Z-Plasty for Clinodactyly

Options for bony correction with marked clinodactyly are closing wedge, opening wedge, or reverse wedge osteotomies. Closing wedge is the simplest but makes an already shortened digit even shorter. A modification of the reverse wedge allows for both correction and maintenance of length. The bone graft for opening the foreshortened side comes from the wedge harvested from the opposite (long) side. This technique avoids the need for remote bone graft harvest and any associated risk or morbidity. For these reasons, we prefer simple closing wedge osteotomies for the index through small digits but perform reverse wedge osteotomies of the thumb to maximize length.

Midaxial exposure of the malaligned phalanx is performed on the convex or long side. On the concave side, a Z-plasty incision is utilized for soft tissue lengthening, osseous or cartilaginous bar resection, and the opening wedge portion of the reverse wedge osteotomy.

The Z-plasty flaps are elevated prior to osteotomy in order to identify and protect the NVB on the concave side. The IP joints are isolated. At times, this requires localization with a 25-gauge needle and fluoroscopic guidance. The physis is identified and protected throughout surgery. Wedge osteotomy is outlined parallel but distal to the physis and PIP joint proximally and DIP joint and collateral ligaments distally. The bone is removed by scalpel, osteotome, or microsagittal saw depending on the age of patient and the size and consistency of the phalanx. The medial cortex and periosteum are left intact. The last part of the bone is removed in a gentle fashion so as not to disrupt the contour of the bone in the young. The cartilaginous or osseous bar on the convex side is transected above the physis while protecting the nerve. In the young, this is done with a knife or small (2 to 4 mm) osteotome. The wedge of bone harvested from the convex side is then inserted into the short, concave side to realign the proximal and distal joints in a parallel fashion. Longitudinal smooth pin fixation is performed. The periosteum is closed to keep the bone graft in place. The Z-plasty flaps are rotated and closed without tension. Triangular resection of redundant skin may be necessary to a minor degree on the opposite

side. The tourniquet is deflated to check for flap and digital viability. If there is compromise, revision of closure with a full-thickness skin graft or sequential Z-plasties may be necessary (Figure 6-10).

COACH'S CORNER

Vicker Physiolysis for Clinodactyly Correction[10]

The epiphyseal bracket resection and fat interposition technique has been utilized in young patients to correct deformity. The method is dependent on accelerated longitudinal growth of the untethered physis. The best correction has been reported in patients <6 years of age. Through a midaxial incision on the foreshortened, concave side, the middle phalanx is exposed. Resection of the osseous or cartilaginous bar and bracket is performed. This involves resection of metaphyseal bone and exposure of the physis similar to a post-traumatic physeal bar resection. The horizontal portion of the physis is protected to prevent complete or asymmetric growth arrest. Fat interposition is required, and harvesting of a small section is possible from anywhere there is sufficient donor tissue (i.e., forearm, thigh, buttocks, abdomen). Harvesting from the involved limb makes postoperative dressing and care easier. The operation is not complicated and allows for early mobilization. Correction literally takes years (2 to 3) and works better in more marked deformities (>40 degrees). The biggest issue is failure to achieve satisfactory or complete correction. Overcorrection has not been an issue. Most of us are too impatient for a slow correction and perform a definitive, single-stage correction with an osteotomy and corrective Z-plasties.

POSTOPERATIVE

Clinodactyly

Pin fixation and cast immobilization are continued for 1 month. Radiographs out of cast should indicate osteotomy healing. Protective splinting and therapy is initiated. Passive and active range of motion for all joints is stressed. Motion is usually achieved by 6 weeks post pin removal.

Camptodactyly

Early motion is important. Flaps and skin grafts are healed by 2 weeks. Conversion to splinting and therapy is begun then if the deformity is not complex. If there was bone and joint deformity, the joint is held reduced with a pin for 1 month before conversion to a splint and therapy program. Nighttime extension splinting and scar mold are continued for 3 months. Passive and active motion of all joints is stressed. Therapy and splinting are continued for 3 to 6 months to prevent recurrence.

ANTICIPATED RESULTS

In clinodactyly, the goal is a straight mobile digit. Severe deformities will usually achieve and maintain correction to within 10 degrees of anatomic alignment. Aggressive therapy and a cooperative family and child will usually regain full PIP and DIP motion.

In camptodactyly, the goal is better passive and active extension in order to get the finger out of the palm without compromising grip strength or grasp function. Surgery usually results in a more functional but not normal arc of motion. There often is incomplete digital flexion only to the palm rather than distal palmar crease.

COMPLICATIONS

In clinodactyly, recurrence with growth does occur, especially if the osseous or cartilaginous bar is not resected. Recurrent deformity after attempted correction on a relatively unindicated, mild deformity is not a happy outcome. Loss of PIP and/or DIP motion is a poor outcome, as the patient has traded a more functional crooked finger for a less functional, straighter, and stiffer one. Patient selection, parental education about risks and needs for aggressive therapy postoperatively, and performing the osteotomy between the ages of 5 and 10 years lessen this risk. Physeal arrest will limit the overall length of phalanx and affected finger. Thus, osteotomies need to be distal to physis. Similarly, the osteotomy cannot violate the joint(s) leading to stiffness, pain, or eventual arthrosis.

In camptodactyly, a major concern is flap necrosis or hypertrophic scarring that limits digital motion and thus outcomes. Decisions regarding the type of flap or use of full-thickness grafting influence this risk. The most alarming outcome would be digital ischemia from direct injury or correction beyond bounds of arterial excursion. Hopefully you identify that cliff edge with gentle correction in the operating room without going over it. Hypersensitivity and digital dystrophy can occur from neural stretch injury. Loss of PIP flexion and DIP extension are not uncommon and really should be expected in severe deformity correction. Preoperative education and aggressive postoperative therapy are mandatory.

CASE OUTCOME

Infantile camptodactyly is often bilateral and best treated with splinting. Although McFarlane advocated for early operative release or rerouting of an aberrant insertion of the lumbrical, the results have been limited, and recurrence has been high for most patients and surgeons. This infant was started on a passive extension stretching and forearm-based nighttime progressive extension orthoplast splinting, which was used effectively in this case. Correction to 0 degrees passive

A

B

C

FIGURE 6-10 **A:** Clinodactyly of thumb associated with Rubinstein-Taybi syndrome. **B:** Radial Z-plasty for thumb clinodactyly reconstruction. **C:** Pre-(patient's right) and post-(patient's left) operative result of bilateral thumb clinodactyly.

and active PIP extension on the left and 5 degrees active extension and 0 degrees passive extension on the right occurred over 3 months.

SUMMARY

Clinodactyly and camptodactyly are the most common forms of crooked fingers that present for evaluation. Both are autosomal dominant, exist in <1% of the population, are mild deformities, and usually do not have functional significance. In moderate, progressive cases of camptodactyly, splinting and stretching is the primary treatment. Severe forms of both camptodactyly and clinodactyly are candidates for surgery, but patient compliance is critical to successful outcome.

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CHAPTER

7

Macrodactyly

CASE PRESENTATION

A 3-month-old female infant presents with an enlarged middle finger. There are no other associated systemic or musculoskeletal malformations. There is no family history of congenital differences and, in particular, of macrodactyly, limb hypertrophy, or neurofibromatosis. At this stage, the middle finger is already the length of the mother's middle finger but wider. There is limited active motion present (Figure 7-1).

CLINICAL QUESTIONS

- What causes digital and limb enlargement?
- Is macrodactyly a genetic condition?
- Are there associated malformations with digital or limb hypertrophy?
- What is the evaluation of a child with macrodactyly or limb hypertrophy?
- How is the clinical course monitored?
- What are the surgical indications?
- Which procedures are performed at which time?
- What are the expected outcomes from natural history and/or surgery?

THE FUNDAMENTALS

You and I do not see things as they are. We see things as we are.
—Herb Cohen

Unfortunately, people continue to expect other people to fit in a perceived social norm. This is particularly true of the appearance of the hands and upper limbs. Digital enlargement or entire limb overgrowth, if profound or progressive, can be a psychosocial issue for affected children, their parents, and families. Even the pseudoscientific, descriptive term "gigantism" evokes perceived horror or a circus-freak quality for macrodactyly and limb overgrowth. Such stigma is unfair and detrimental to these children.

Enlargement of a limb does not necessarily make it less functional. If the motion and sensibility are normal, then the superhero-appearing limb functions quite well. However, if the enlarged digits or limbs are stiff, relatively insensate, painful, or weak, then function is impaired.

Etiology and Epidemiology

Increased vascular or neural supply will result in increased growth of all tissues (skin and soft tissues, muscles, and bones). Macrodactyly and limb hypertrophy are thus seen with lipofibrohamartomatous peripheral nerves (involving the median more commonly than ulnar nerves) and neurofibromatosis; vascular enlargement with arteriovenous fistulas, vascular malformations, and Klippel-Trenaunay syndrome; and lymphatic malformations. Increased bone and cartilage growth will result in macrodactyly, such as is seen with osteochondromatosis and Ollier enchondromatosis (see Chapters 47 and 49).[1–4] Hemihypertrophy is a regional form of enlargement that can include part or all of one limb or the entire half of the body including the face. Hemihypertrophy can be associated with Wilms tumor. Enlargement can be due to congenital muscular hyperplasia of a limb.[5] Limb hypertrophy can also be seen with more generalized syndromes such as Proteus or CLOVES.[6–8] Aside from neurofibromatosis, which has an autosomal dominant inheritance, all of these conditions are sporadic and rare. Macrodactyly due to lipofibromatosis of the nerve is rare in all races but less common in non-Caucasians. Blacks have more macrodactyly of the foot than of the hand.[9]

Clinical Evaluation

The principles of clinical evaluation involve defining (1) the form of macrodactyly or limb hypertrophy, (2) whether the postnatal growth is proportional or progressive, and (3) the width and length of the affected part compared to expected adult growth. These days, the diagnosis is often made in utero by ultrasound.[10] Otherwise, in most cases, it is obvious at birth. Serial exams with exact length and girth measurements are recorded yearly from diagnosis. Plain radiographs are obtained to assess osseous deformity,

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FIGURE 7-1 Macrodactyly of both the long and, less so, the index finger with divergence of the digits. An MRI of this patient revealed lipofibromatosis of the median nerve at the wrist extending distally to the common digital nerve and proper digital nerves of the index and long fingers.

length of each bone, and physeal maturity compared to the opposite side. The use of magnetic resonance imaging (MRI) and computed tomography scans[11–13] provides definitive diagnosis by assessing fatty infiltration of lipofibromatous peripheral nerves, vascular anomalies, congenital muscular hyperplasia or anomalous muscles, and lymphatic malformations. With hemihypertrophy, a screening ultrasound is obtained for Wilms tumor. Electrodiagnostic studies are more sensitive than clinical exam in children for compressive neuropathy, a common complication of macrodactyly and limb hypertrophy.[14,15]

Flatt classified macrodactyly as: Type I is lipofibromatosis, type II is neurofibromatosis, type III is polyostotic, and type IV is hemihypertrophy. Lipofibromatosis has also been named lipofibroma hamartomatosis, macrodystrophia lipomatosa, and macrodactylia fibrolipomatosis, among others. The name signifies digital enlargement due to fat and fibrous infiltration in a peripheral nerve distribution, much more commonly in the median than the ulnar nerve (Figure 7-1).[16,17] The index finger is most commonly involved, often in conjunction with the long finger or thumb. The dilation of the nerve often starts in the distal forearm and extends through the carpal canal and common digital nerve out to the proper digital nerve. The involved nerve has fatty infiltration and fibrosis. The bone often has altered architecture by biopsy with wide medullary canals and distorted trabeculae.[18] The subcutaneous tissue is fibrotic. The skin is expansile with volar greater than dorsal, and distal greater than proximal, enlargement of skin and subcutaneous tissues.

Multiple digital involvement is more frequent than single digit. Unilateral hand involvement is most common. Syndactyly occurs in about 10% of cases. Asymmetric growth of each involved digit with angular and rotational malalignment is common and corresponds to the degree of proper digital nerve lipofibromatosis. The involved digit(s) often hyperextend and radially deviate due to more palmar and ulnar involvement. Flatt called these "banana fingers." The growth can be progressive or proportional. With progressive enlargement, digital motion and function diminishes.

Sensibility by two-point discrimination and light touch measurements are, surprisingly, usually normal. However, compressive neuropathy can occur with loss of sensibility and motor function over time. This is usually due to a carpal tunnel syndrome[14,15] but also has been described with lipofibromatosis of the ulnar nerve and cubital tunnel compression.[19] Electrodiagnostic studies are often required due to limits of history and physical exam for carpal or cubital tunnel syndrome diagnosis in these children. There are children with lipofibromatosis of the median nerve who present with only a palpable mass in the distal forearm without macrodactyly. MRI and electromyography and nerve conduction velocity (EMG/NCV) studies are necessary for diagnosis. These lesions are usually monitored over time when the nerve is functioning normally since it is not a neoplasia. Neural decompression and carpal release are indicated if weakness and loss of sensibility develop.

Flatt's other types of macrodactyly include neurofibromatosis, hemihypertrophy, and polyostotic forms. A syndromic class should be included with Proteus, CLOVES, and Klippel-Trenaunay syndromes, among others. In addition, congenital unilateral muscular hyperplasia is seen separate from hemihypertrophy. Vascular and lymphatic malformations will result in limb and/or digital enlargement. With all digits involved, upper limb and even truncal involvement, these conditions are more likely. MRI scan is used to define pathoanatomy and aid in diagnosis and treatment. Genetics consultation and multidisciplinary clinic evaluation and care are important in these situations.

Surgical Indications

The presence of macrodactyly or limb hypertrophy alone is not an indication for surgery. There is wide variation in clinical presentation. Some minor increases in size can be near normal in appearance and function. Alternatively, there are many instances of limb and/or digital hypertrophy that cannot be resolved or "normalized" even by surgical intervention. Often, care for these children is a case of managing expectations.

In the cases of lipofibromatosis of a major peripheral nerve, progressive deformity and loss of function are

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FIGURE 7-2 X-ray of the index finger after debulking of radial-sided macrodactyly and corrective osteotomy of ulnar deviation deformity with pin fixation.

indications for surgical treatment. Options include (1) soft tissue debulking, (2) appropriately timed physeal arrests, (3) digital realignment (Figure 7-2), (4) bony reduction, (5) any combination of options (1) to (4), and (6) ray resection. Repeat surgery is common.[20]

In terms of congenital muscular hyperplasia and certain forms of hemihypertrophy, debulking of excessive and/or accessory muscles and soft tissues is indicated when digital malalignment becomes too problematic for proper hand function. Median nerve decompression in the carpal canal is indicated with loss of sensibility and thenar strength.

Neurofibromatosis and osteocartilaginous causes of macrodactyly and limb hypertrophy are discussed in Chapters 47 and 28.

SURGICAL PROCEDURES

◆ Nerve Decompression

When these children or their parents complain of loss of manual dexterity, carpal tunnel syndrome should be suspected. As mentioned in the clinical evaluation section, nerve conduction and electromyographic electrodiagnostic studies are important for accurate diagnosis. If confirmed, nerve decompression should occur before irreversible neuromuscular changes occur.

The incision extends from distal forearm across palm. The median nerve and the adjacent muscles and tendons are identified proximally and isolated. With lipofibromatosis, the nerve is inspected closely with loupe or microscopic magnification. Dissection of the nerve extends from proximal to distal across the palm. The transverse carpal ligament is incised longitudinally along the ulnar border while protecting the ulnar nerve and palmar vascular arch exiting from Guyon canal and transversing the palm distal to the transverse carpal ligament. If the carpal tunnel release is part of a digital debulking procedure, the nerve is followed distally through the bifurcation of the common digital nerve(s) into the proper digital nerves of the affected digit(s). If this surgery is for congenital muscle hyperplasia or hemihypertrophy, the extrinsic and intrinsic muscular anatomy is defined by direct inspection and isolation. Often there is increased bulk or accessory muscles present. The increased interosseous bulk may be splaying the digital metacarpals, and the dynamic muscle imbalance may be responsible for digital malalignment. Resection of this redundancy is performed as necessary. The exact amount of resection is difficult to quantify. Similar resection of excessive skin and soft tissues is performed before tension-free closure in all these conditions.

In children and adolescents, we close the transverse carpal ligament with a Z-plasty. A second, partial longitudinal incision from distal to proximal is made in the ligament parallel to the original ulnar longitudinal incision. This incision is carried proximally until the ligament can be rotated ulnarly for nonconstrictive coverage of the nerve. Care is taken to identify and protect the recurrent motor branch to the thenars during this incision. Remember, though this nerve is usually extraligamentous, it can course through the ligament. Also, though it usually branches from the median nerve distal to the transverse carpal ligament, it can also branch proximal to or under the ligament. The ligament is then rotated on its radial base adjacent to thenar muscle origins. It is repaired to the ulnar proximal base of the incised ligament for tension-free coverage. A Freer elevator should pass easily under the repaired ligament. This ligament reconstruction prevents bowstringing of the nerve and adherent scarring of the nerve directly to the skin and superficial subcutaneous tissues.

As mentioned, redundant skin and subcutaneous tissues are excised as necessary. The amount of resection is dependent on viability of the flaps with a tension-free closure. Deflation of the tourniquet is important to assess the vascularity of the soft tissues. A large compressive dressing is left in place for 2 weeks. Postoperative therapy is critical to regain full wrist and digital mobility.

If the nerve compression syndrome occurs in any other anatomic location, such as the ulnar nerve at the elbow, similar principles of nerve decompression are followed.

Debulking Procedures

Progressive macrodactyly can be disfiguring and dysfunctional. If the decision is made with the parents to preserve the digit, then repeated and/or sequential soft tissue debulking operations are usually necessary. Unfortunately, like a digital replant, once down that road, there is no turning back. Flap necrosis, digital ischemia, and neural impairment are risks with excessive resection in any one procedure. Long-term stiffness is possible from repeated surgeries. Remember, soft tissue debulking will reduce the circumference and width but not the longitudinal growth or size. Reduction in length will require timely restriction of growth by epiphysiodesis or acute shortening by bony reduction. Digital malalignment that affects function will require osteotomy. Bone and soft tissue reduction and realignment can be done in conjunction or separately. Remember, each surgical intervention carries an increased risk of loss of motion and scar problems, so more comprehensive surgical care in one setting is best as long as the complication risk does not increase. Complex combined soft tissue and bony reduction procedures cross over into the double black diamond category of surgeons, so beware. This section will cover debulking of soft tissues alone.

The optimal case for soft tissue reduction is marked increase in girth but equivalent length to the same digit of the contralateral hand and appropriate length for digital cascade of the affected hand (Figure 7-3A). The goal of the surgery is a more normal-appearing digit that maintains mobility. A Z-plasty midaxial incision is utilized over the involved digital nerve. This allows for appropriate resection and easy insetting of flaps (Figure 7-3B). Elevation of the redundant skin and subcutaneous flaps is performed while protecting the underlying neurovascular bundle (NVB). The nerve is generally quite large and tortuous. The artery is often compressed by the abnormal fibrous stroma. Preserving the digital artery is a delicate dissection. The amount of tissue resection is limited by concerns of digital and flap viability (Figure 7-3C). Like constriction ring excision and flap rotation, about 270 degrees of digital circumference is safe in one procedure. The opposite (NVB) is usually left in situ without dissection. A decision has to be made regarding the lipofibrohamartomatous digital nerve. It can be left in situ, carefully debulked under the microscope leaving longitudinal fascicles, or excised. Surprisingly, all options seem to leave normal digital light and two-point discrimination sensibility. At the first reconstruction, we usually leave it intact or debulk it. However, if it is clear that it is a large, convoluted bundle of scar and it distorts digital size, we boldly excise it leaving the artery intact. Excision of redundant skin and subcutaneous tissue is performed to allow for tension-free closure (Figure 7-3D). There may be some additional trimming of Z-plasty edges to get it right where you want it. This tinkering does count in finding the fine line between flap

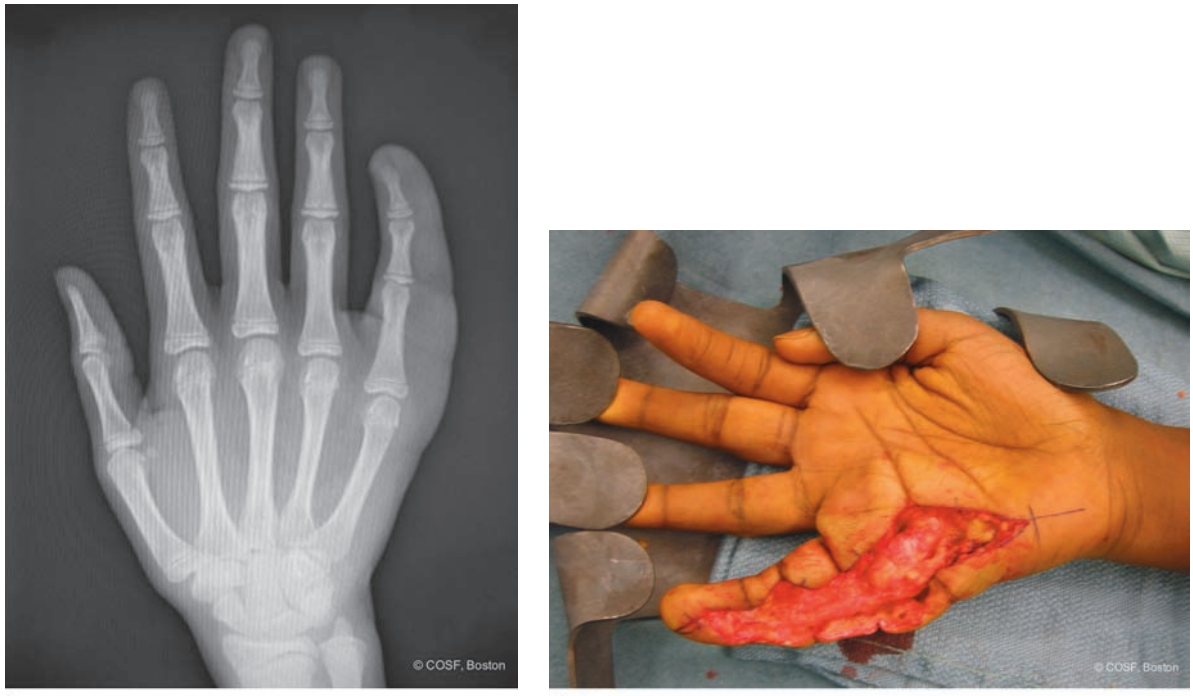

FIGURE 7-3 **A:** X-ray of macrodactyly of small finger with proportionate length but girth increased due to involvement of ulnar digital nerve lipofibromatosis. There is mild radial deviation of the digit present. **B:** Z-plasty midaxial incision for debulking procedure.

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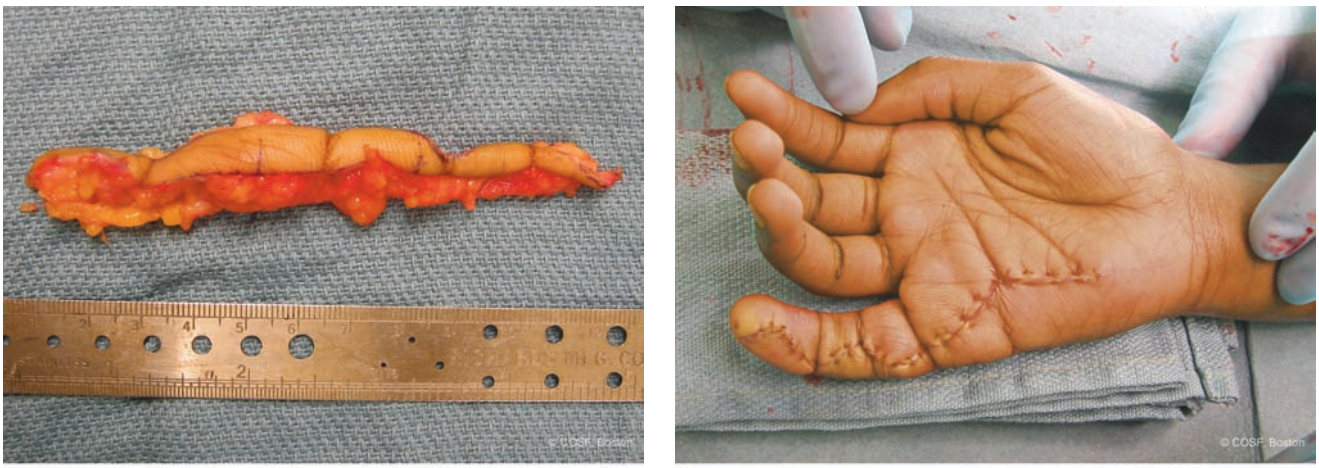

C D

FIGURE 7-3 (*continued*) **C:** Resected skin and fat. **D:** Z-plasty closure after debulking. In this case, the nerve was debulked and preserved.

necrosis and inadequate debulking. Postoperative casting is used for 2 weeks, followed by rapid mobilization and scar management with hand therapy. Preventing loss of digital motion is imperative.

Epiphysiodesis

Some people skate to the puck. I skate to where the puck is going to be.
—Wayne Gretzky

The technical aspects of this procedure are relatively straightforward. The patient selection and timing are more critical. The best indication is a mobile, straight macrodactyly that has slow progressive hypertrophy. Surgery should be performed when the affected digit achieves near adult length of the same digit of the same gender parent. Obviously, this is a bit of guesswork, and this timing method is not as comprehensive as a lower limb growth chart analysis. Epiphysiodesis of the metacarpal, proximal, middle, and distal phalangeal physes will stop longitudinal growth. However, circumferential growth will continue. This is the "rock in the pond" growth by outward waves that turns a long, thin osseous rectangle more square-like. The more skeletally mature the patient is, the less digital distortion occurs by this circumferential growth after epiphysiodesis.

Under fluoroscopic guidance, small incisions are made over each phalangeal physis in the midaxial line. The volar NVB, collateral ligaments, and dorsal extensor mechanism are preserved. Loupe magnification and bright lighting allow for identification of the physis at each level. Small curettes and, at times, an appropriate-size power drill, are used to completely remove the cartilage while preserving the metaphyseal and epiphyseal bone and soft tissue stability. Local bone, allograft, or bone substitutes can be inserted for epiphysis-to-metaphysis fusion.

Ray Resection

The truth of the matter is, we always know the right thing to do. The hard part is doing it.
—Norman Schwarzkopf

The decision for ray resection can be very difficult for many parents. It seems to be an easier decision when macrodactyly occurs in the foot. The best indication in the hand is a single, nonthumb macrodactyly in an infant in whom the digit is already adult size, relatively immobile, and of limited function (Figure 7-4). It is clear people do not count fingers on other people's hands. (How long did it take you to notice that Mickey Mouse and Bart Simpson only had three fingers?) If done well, this is a very cosmetic and functional result. It exceeds the parents' expectations and washes away their negative assumptions. However, you may have to gently guide them to this decision while respecting cultural and personal differences. And not everyone will agree with your opinion. That is the wonder of living in a society that allows freedom of choice and expression.

The reconstruction follows the principles outlined in ray resection for any reason in child or adult. Incisions around the base of the affected proximal phalanx are made to allow for web reconstruction at appropriate level and size (Figure 7-4B). Dorsal and palmar incisions can be longitudinal or with Z-plasties depending on closure needs and to avoid contracting scars with growth. The common digital NVBs are identified proximally to the affected and adjacent digits (Figure 7-4C). The flexor tendons are isolated proximal to the A1 pulley where they are transected. The extrinsic extensor is isolated dorsally out to the level of the metacarpophalangeal joint where it is transected. Longitudinal venous drainage for the adjacent digits is preserved with ligation of transverse vessels and veins to the affected digit. The proper digital nerves to the affected digit are dissected back into the palm by separating the epineurium where they are transected. This should be done in as

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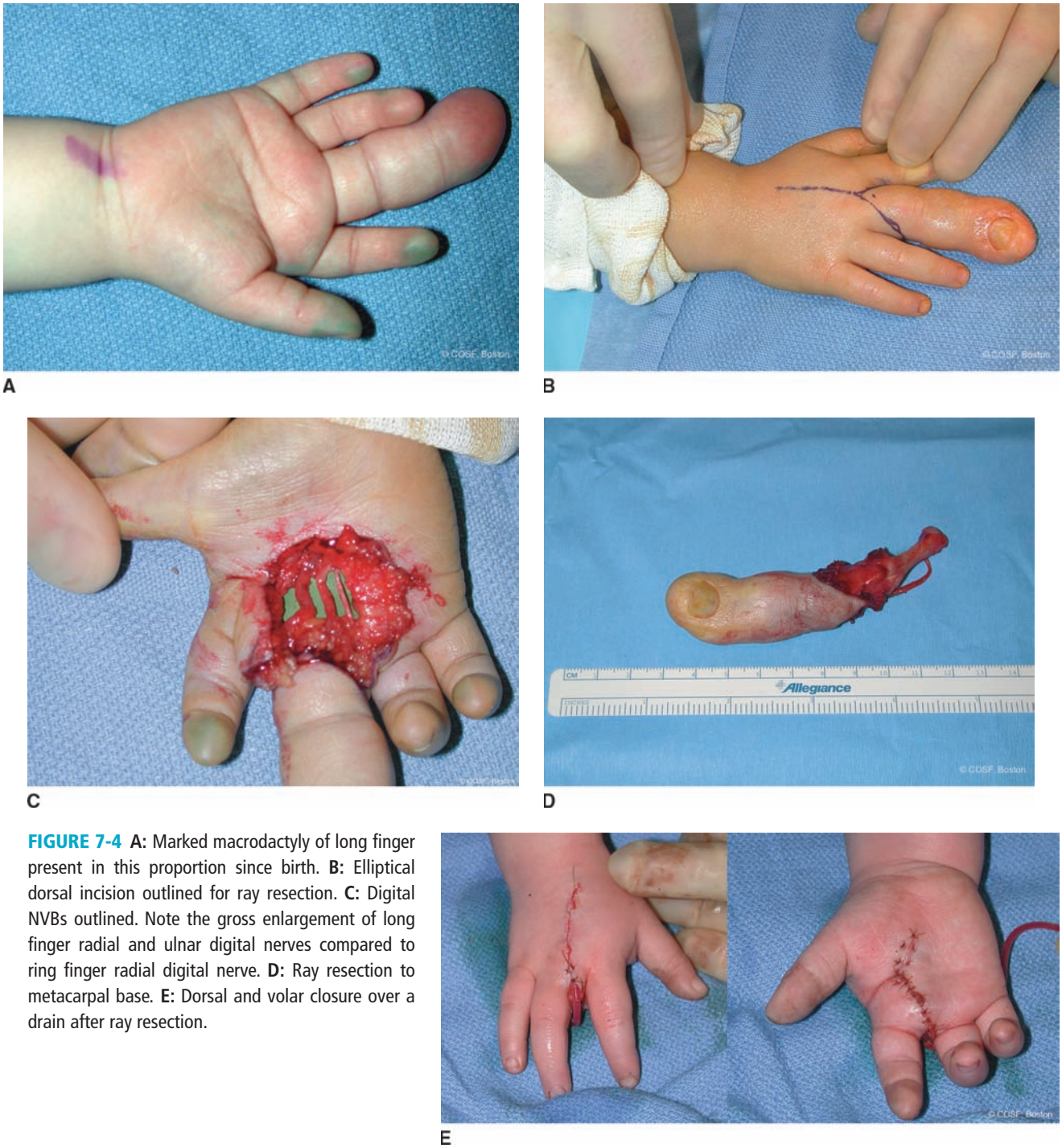

FIGURE 7-4 **A:** Marked macrodactyly of long finger present in this proportion since birth. **B:** Elliptical dorsal incision outlined for ray resection. **C:** Digital NVBs outlined. Note the gross enlargement of long finger radial and ulnar digital nerves compared to ring finger radial digital nerve. **D:** Ray resection to metacarpal base. **E:** Dorsal and volar closure over a drain after ray resection.

healthy neural tissue as possible and then nerve ends are placed in intrinsic muscle if possible. The proper arteries to the affected digit are ligated after the common digital bifurcation in each web space. The transverse metacarpal ligaments are incised on either side of the digit while preserving the length for subsequent reconstruction of the new transverse metacarpal ligament. The intrinsic muscles and tendons to the adjacent digits are preserved. The metacarpal is resected extraperiosteally through the carpometacarpal joint, and this completes the ray resection (Figure 7-4D).

Reconstruction is done by closing the gap between the unaffected digits. Proximal, middle, and distal periosteal nonabsorbable sutures will slide the two digits together. Care must be taken to avoid rotational or angular malalignment. Tenodesis is used to monitor alignment with this closure. The transverse metacarpal ligament is then repaired. Two transverse metacarpal smooth pins are often placed parallel to one another to maintain alignment. Excision of redundant skin and subcutaneous tissues is then performed for tension-free closure, usually with

curves and Z-plasties to prevent contractures with growth. The web-space flaps are repaired to maintain viability and normal contour (Figure 7-4E). Deflation of the tourniquet is used to assess skin and digital viability. Protective casting is maintained for 4 weeks, followed by splinting for 2 weeks. Mobilization starting at 4 weeks is imperative to prevent stiffness and loss of function long term.

◆◆ Bony Reduction with Soft Tissue Surgery

You must learn from the mistakes of others. You can't possibly live long enough to make them all yourself.
—Sam Levenson

Preserving a large, distorted digit requires a complex osseous and soft tissue reduction. The goal of both a functional and cosmetic finger affects surgical decisions. For example, the easiest way to achieve the desired length is to amputate the most distal aspect of the finger to match the opposite hand. However, this will result in a permanent loss of the nail, an unacceptable outcome for many patients and families. Partial or complete middle phalangectomy is a more cosmetic method of shortening.[21] This usually requires two stages to achieve both bone and soft tissue reduction while preserving digital viability and sensibility. Partial resection can be combined with an angular corrective osteotomy. Complete resection requires collateral ligament reconstruction for interphalangeal joint stability.[22] If more bony resection than the middle phalanx is required to achieve the desired length, then an arthrodesis will be necessary. This will result in loss of some motion. Longitudinal reduction in the bone may be required to achieve appropriate girth. Joint reconstruction for articular alignment and soft tissue stability is more complex. This may affect motion and alignment. Whenever the resection is in the middle of the finger, there will be redundant skin that will require a second operation to resect. Any residual digital malalignment can be corrected at the second stage with an osteotomy.

POSTOPERATIVE

The major concern postoperatively is restoration of passive followed by active motion. Therefore immobilization is performed only until tissue healing allows for initiation of therapy. In the soft tissue only procedures, this involves cast protection for 2 weeks to allow for flap healing, followed by therapy with intermittent splinting and Coban (3M, St. Paul, MN) compression dressings. When bony and joint procedures are a part of reconstruction, cast protection continues for 4 weeks until bone and ligament healing are sufficient to allow for mobilization. At that time, pins are removed in the office, and therapy with intermittent splinting and Coban compression wrapping is used. The goal is full restoration of motion by 6 to 12 weeks after cast removal.

ANTICIPATED RESULTS

With ray resection, the goal of a cosmetic hand with normal motion, sensibility, size, strength, and acceptable alignment is expected. There is some speculation that adjacent digits can be affected over time with macrodactyly due to lipofibromatosis neural involvement. Fortunately for us, that has not occurred thus far, but the parents are warned of this possibility.

Debulking of macrodactyly will result in an improved appearance to the digit(s). Multiple operations are anticipated. There will be residual limitations in motion and abnormal increased circumference to the digit. The pre- and postoperative sensibility should be equivalent. The digit should be better but not normalized.[23–25]

The more extreme the whole hand or limb involvement, the less likely there will be a marked cosmetic improvement. Reduction in pain and improvement in function with nerve decompression is achievable.

COMPLICATIONS

Flap necrosis from excessive single-stage resection is the most common surgical problem. Loss of motion and, therefore, digital or hand function can occur from natural history, multiple operations with residual scarring or deformity, and low patient compliance with therapy. Digital malalignment is common. Poor sensibility is not as common as expected. Poor outcome resulting in request for amputation has occurred in reported case series.[25]

CASE OUTCOME

This child underwent ray resection in infancy. Ten years later, she continued to have excellent motion, alignment, normal strength, sensibility, size, and hand function. There has been no alteration in growth in the adjacent digits. Her peers and strangers do not recognize she only has four digits on that hand (Figure 7-4).

SUMMARY

Marked hypertrophy of a digit, hand, and/or limb is a complex problem, especially when progressive. It is rare and variable enough that each case requires an individualized approach. Ultimately, the situation can be improved but not normalized. Ray resection is the most definitive procedure but has limited application. Debulking is the most common procedure but has its limitations in terms of expected outcomes. At the outset, these children and their parents want a normal-appearing and functioning digit, hand, and limb, and rarely can we provide that.

COACH'S CORNER

Vascular Anomalies

Vascular anomalies present with a wide clinical spectrum from minor skin lesions to focal enlargement to extensive limb hypertrophy. There is evidence that they are frequently misdiagnosed, and many patients receive inappropriate advice or treatment. Capillary malformations (port wine stains, nevus flammeus) are abnormal, fragile capillary beds and are different from vascular birthmarks ("angel's kiss" on the forehead/eyelids/nose or "stork bite" on the neck). Arteriovenous malformations (AVMs) are abnormal direct artery-to-vein connections without a normal intervening capillary bed. AVMs can be mistaken for infantile hemangiomas, the most common vascular tumor. Infantile hemangiomas will present in the first 2 weeks of life, grow rapidly, become bright red (thus, the "strawberry hemangioma" term) in the first 6 to 9 months, and then recede. Tremendous overgrowth can be seen with syndromic AVMs. Klippel-Trenaunay-Weber (KTW) syndrome patients have port wine stains, varicose veins, lymphatic malformations, and marked hypertrophy of the involved limb and trunk (Figure 7-5). They have frequent problems with blood clots, cellulitis, skin breakdown, pain, and difficulty with limb use. Parkes Weber syndrome involves enlargement of an entire limb from arteriovenous fistula(s) or malformation(s) and can be associated with high-output cardiac failure. Treatment for vascular and lymphatic anomalies depends on the extent of the lesion. The use of MRI scans is important for correct diagnosis and appropriate management decisions. The extent of the skin lesion is deceiving compared to the involvement in the deeper tissues. Conservative treatments with elevation and compressive garments are common but have their limits. Debulking procedures for KTW and Parkes Weber syndrome are at times necessary but have a high risk of bleeding, persistent lymphatic drainage, infection, and recurrence. Radiology-guided sclerotherapy (ultrasound and x-rays utilizing dye injections) is used often in our institution for complex anomalies. These patients require multidisciplinary care and double black diamond level expertise in all the subspecialties involved.

FIGURE 7-5 Lower limb enlargement associated with Klippel-Trenaunay-Weber (KTW) syndrome. Note the port wine stains, varicose veins, lymphatic malformations, and marked hypertrophy of the involved trunk, limb, and toes.

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CHAPTER

8

Central Deficiency and Symbrachydactyly

CASE PRESENTATION

An 18-week-pregnant mother is referred to the advanced fetal care center for ultrasound evidence of cleft hands (Figure 8-1). The father has cleft hands that had surgery as a young child. The ultrasound is otherwise normal for organ system development. The parents want to know how far medical science and surgical advances have come since dad's childhood.

CLINICAL QUESTIONS

- What are the genetic causes of cleft hands?
- What are the associated conditions, if any, with typical cleft hands?
- How are cleft hands classified?
- Is there nonoperative treatment?
- What are the surgical principles for typical cleft hands?
- What are the expected results of surgical treatment?
- What are the complications?

THE FUNDAMENTALS

Approach the game with no preset agendas and you'll probably come away surprised at your overall efforts.
—Phil Jackson

Functional grasp, pinch, and release are critical for independent activities of daily living. Less than the full complement of independent, aligned, mobile fingers and thumbs can limit function. Bilateral disorders, even in the presence of a normal-functioning brain, can compromise opportunities and choices in life. So can unilateral hand disorders, though less so. Cleft hands are usually bilateral and always have digital absence and deformities. The cosmetic and social concerns and implications of cleft hands are real and important for the child and family.

Typical (ectrodactyly) (Figure 8-2) and atypical (symbrachydactyly) (Figure 8-3) cleft hands are rare. With ectrodactyly, the basic principle is to close the cleft and deepen the first web space in order to preserve or enhance grasp, pinch, and release, as well as to improve cosmesis. This chapter mostly addresses typical cleft hands. Symbrachydactyly treatment is also covered in Chapter 9.

Etiology and Epidemiology

Cleft hands occur in 1:10,000 to 1:90,000 live births depending on phenotypic classification.[1,2] There is a clear genetic basis for typical cleft hands. Phenotypic expression is variable with approximately 70% of individuals with the genetic abnormality having clinical manifestations. Clefts can be present in one to four limbs. There is considerable variability in the degree of hand and foot abnormalities, but central deficiencies are always present.

The genetic basis for cleft hands is well founded in scientific research. Split hand–split foot malformations (SHFMs) are autosomal dominant disorders with variable penetrance. There are five distinct SHFM types with Dlx homeobox gene abnormalities. Ectrodactyly-ectodermal dysplasias-cleft lip/palate (EEC) syndromes are due to p63 mutations, an ectoderm-specific transcription factor. The p63 and Dlx proteins colocalize in the nuclei of the apical ectodermal ridge (AER). There is increasing scientific evidence of a transcriptional cascade of events that contributes to ectodermal

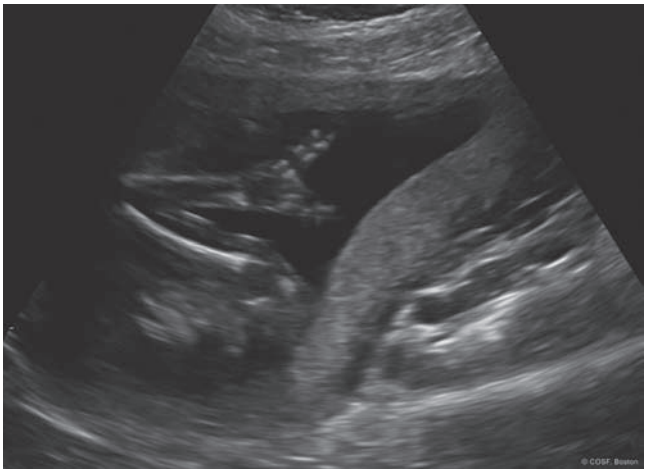

FIGURE 8-1 Prenatal ultrasound depicting central deficiency of the hand.

FIGURE 8-2 Radiograph of middle finger metacarpal present supporting index finger phalanges and a part of index MCP joint. Index is super digit.

FIGURE 8-3 Atypical cleft hand, symbrachydactyly. This is usually unilateral with negative family history.

development with p63 mutations affecting Dlx homeobox gene regulation.[3] A reduction in dactylin transcription is another contributing factor in some cleft hands.[4,5]

Cleft hands have been described as a longitudinal central deficiency (type IB International Federation of Societies for Surgery of the Hand [IFSSH] classification).[6] Symbrachydactyly has been classified as an undergrowth (type V). More recently, the Japanese Society for Surgery of the Hand proposed a modification to the IFSSH classification[7] with (1) all forms of symbrachydactyly being reclassified as type I (longitudinal [1B] or transverse [1A] deficiency) and (2) a new category of failure of ray induction to include typical cleft hand (previous type I), central polydactyly (previous type III), and bony syndactyly (previous type III). This is based on experimental work with embryonic rats treated with a chemotherapeutic agent (busulfan). In this animal model, cleft hands, central polydactylies, and osseous syndactylies were all created from defects in the central hand plate due to failure of induction.[8] The experimental data indicate there is diffuse cell death in the central ectoderm and mesoderm with regression of fibroblast growth factor in the AER and bone morphogenetic protein-4 and sonic hedgehog in the mesoderm. A similar pattern of interdigital apoptosis and cartilage condensation leads to abnormal induction of digital rays in cleft hands, central polydactylies, and osseous syndactylies.[9,10] There is one clear case of maternal chemotherapy for breast cancer in the first trimester resulting in cleft hands.[11]

Clinical Evaluation

There is never trouble diagnosing a cleft hand at birth. In fact, many are now diagnosed by prenatal ultrasound. The basic anatomy of four longitudinally aligned metacarpals, supporting four sets of longitudinally aligned, independent triphalangeal digits, with stable, mobile joints, is not present in centrally deficient hands. In addition, the thumb ray is rarely normal. So, evaluation begins by examining every anatomic structure of the hand and determining what is present or absent, what is normal or abnormal. This includes detailed soft tissue specifics, which can be overlooked (such as metacarpophalangeal joint [MCP] ligament stability in the index finger). These hands are so different that you truly need to start at the beginning and move precisely and methodically through clinical and radiographic exam features, ending ultimately with an intraoperative assessment of the anatomy. The surgeon can feel like an airplane pilot doing his or her exacting preflight checks: "Mobile thumb present … Check … Middle finger metacarpal present … No … Small finger normal size … No …" and so on. A high level of detail matters. Surgeons often focus only on the bony structures, which limits the precise understanding and treatment of these unique hands.

Clefts can be central, radial, less commonly ulnar, or in various combinations.[12,13] The central cleft is usually V shaped with absent middle finger phalanges. In the mildest clefts, the middle finger phalanges are merely hypoplastic. The middle finger metacarpal can be absent, hypoplastic, bifid, or duplicated. The degree of involvement of the

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Table 8.1

Manske and Halikis based their classification of central deficiency on the status of the first web space[17]

Type	Clinical Features
I	Normal first web space
IIA	Mildly narrowed first web space
IIB	Severely narrowed first web space
III	Syndactylized thumb and index rays and first web space
IV	Merged first web space and cleft, index ray suppressed
V	Absent web, thumb suppressed, ulnar rays present

cleft may extend beyond the absence of the middle ray to include adjacent index and ring finger rays. The ultimate cleft is the presence of the small finger only, adhering to Maisels' digital suppression sequence.[14]

There are general clinical and radiographic patterns used to classify cleft hands. Nutt and Flatt used the number of digits absent (one, two, or three) as the basis of their classification. Ogino used a similar method but has five subtypes. There are also unusual subsets such as hands with six metacarpals[15] or with transverse bones across the cleft.[16] Manske and Halikis based their classification of the more common central and radial deficiencies on the status of the first web space (Table 8-1). The spectrum of first web-space changes extends from a normal (I), to narrowed (IIA mild, IIB severe), to syndactylized (III), to merged (IV absence of both index and long finger rays), to an absent first web space (V absent thumb, only ulnar ray[s]). This classification helps surgical planning as closure of the cleft requires a functional thumb and adequate first web space to obtain equivalent or better grasp and pinch function.

Clefts may be unilateral, bilateral, or include one or both feet. The more deficient the first web space (types IIIB–V), the more likely there is to be bilateral hand and foot involvement (23% in Nutt, Flatt study).[18] Often there is fourth web-space syndactyly and hypoplasia of the small finger. Clinodactyly, bracketed epiphyses, joint malalignment, and instability are common. Bilateral hand and foot clefts are the most common presentation in SHFM; ulnar clefts are rarer. The ring finger ray may be hypoplastic, partially or completely absent. With complete absence of the small finger or small and ring finger rays, it may be hard to determine if the clinical presentation is a part of mild ulnar dysplasia or an ulnar cleft hand.

Increased incidence of congenital heart disease has been observed in SHFM 1 and SHFM 5 genetic variations.[19] EEC by definition has ectodermal dysplasia, cleft lip/cleft palate, and dental anomalies. In addition, EEC has an increased incidence of genitourinary abnormalities.[20] Patients with cleft hands and feet have also been shown to have an increased incidence of encephalocele.[21] Cleft hands have been described in Cornelia de Lange syndrome.[22] There have been rare reports of associated deafness.

Surgical Indications

If you've got nothing to do, don't do it here.
—Brenden "Buff" Blackler

Simple clefts are highly functional;[23] more severe clefts have greater functional impairment. Since the brain is normal in these individuals, adaptive function can be high even in the presence of bilateral, marked anatomic variations. Surgery therefore needs to maintain or improve hand function over what is expected from natural history.

Surgical excision of a transverse bone in the cleft with progressive deformity is clearly indicated.[16]

The psychosocial stigmata of the cleft can vary by individual, family, ethnic group, geographic location, and generations (Figure 8-4). There is no doubt that these

FIGURE 8-4 Children's Hospital Boston archive photograph from late 1880s reveals the appearance of the SHFM has not changed in more than a century.

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children and adults appear differently than noninvolved peers. How they feel about it and whether you can change that by surgery is unclear. However, most cleft operations are indicated to decrease deformity by cleft closure while maintaining or improving hand function by thumb and first web-space reconstruction.

SURGICAL PROCEDURES

My players understand that preparation is most important.
—Ben Jacobson, after Northern Iowa upset over number one seed Kansas in the 2010 NCAA men's basketball tournament

The principle of surgery for cleft hands is simple: close the cleft and optimize the first web-space and thumb function. This applies to Manske and Halikis types I to IV. It is more complicated in the complex deformities with malaligned, unstable, and/or stiff digits adjacent to the cleft. The best outcomes are in the best hands with the best thumbs. Makes sense, right? Even with the busy, referral- and tertiary-care–based practice, cleft hand surgery is rare. Even a high-referral pediatric hand surgeon will maximally see only about two patients and do up to four operations a year if there is bilateral involvement.[19] Tonkin and Wood, two senior, very practiced pediatric hand surgeons, presented jointly on their results of 12 Snow-Littler procedures. Experience is hard to come by and counts in these operations.

There is limited to no role for novice or intermediate-skill level surgeons in cleft hands except for (1) the simplest of clefts with near normal thumbs, (2) the gifted surgeon (by definition an immediate, expert surgeon), or (3) problems of patient access to expert surgeons. In any of those circumstances, we recommend case consultation before proceeding. With cleft hands, you need to work your way up to the black diamond level by gaining surgical expertise with other conditions and then applying prior experience to cleft surgery.

◆ Simple Z-Plasty Deepening of First Web Space, Barsky Closure of Cleft

Nobody's a natural. You work hard to get good and then work to get better.
—William James

The cleft closure in types I and IIA thumbs requires creation of a web commissure between the index and ring fingers. The Barsky flap (see Sidebar) is very useful in these circumstances (Figure 8-5). Similarly, simple, separate Z-plasty flaps (see Sidebar, Chapter 2) can be utilized to deepen the first web space and improve thumb function. Bilateral surgery can be done at the same setting in these relatively uncomplicated situations depending on the patient's age, family wishes, and surgeon's preference.

Patients are positioned supine with the affected limb(s) on an arm table(s). Fluoroscopy is helpful for the bony work. Incisions are marked with care taken to be certain that blood supply to the cleft and first web-space flaps will not be compromised by one another. The Z-plasty flaps of the first web space are raised while maintaining vascularity from the base of the triangles in these random pattern flaps. Two-part Z-plasty flaps are used most often by us with up to 2 cm limbs at 60-degree angles. Four-part Z-plasty flaps and rotation flaps are appropriate too. The adductor and first dorsal interosseous fascia are released. This includes aberrant fascial or ligamentous connections between the first and second metacarpals. Preservation of adductor and first dorsal interosseous muscle function is important. The flaps are rotated and closed without tension with 5-0 or 6-0 polyglactin sutures (Chromic, Ethicon, Inc., Somerville, NJ). Care is taken that the sutures are passed close to the edge of the flaps, so they do not impair blood supply to the apex of the flap, which is most at risk for necrosis.

The simple cleft closure is performed with Z-plasty incisions extending on both the palmar and dorsal

SIDEBAR

Barsky Flap

The distally based diamond or hexagon is outlined on the radial aspect of the ring finger in the midaxial line to dorsal aspect of the proximal phalanx. The level of the hexagon on the ring finger corresponds to the transverse portion of the T on the ulnar aspect of the index finger proximal phalanx. The flap is then at the desired level of the created web. The hexagon is broad based enough to prevent flap necrosis and have an adequate web. Elevation of the flap is done carefully from proximal to distal while protecting the underlying neurovascular bundle. The incision continues from the proximal square aspect of the hexagon across the rim of the cleft and up the ulnar aspect of the index finger. The incision ends in a T. The horizontal portion of the T is correspondingly set at the level of the planned web. The width of the T is broad enough to accept the square base of the hexagon. Similarly, dissection on the radial aspect of the proximal aspect of the index finger is performed while protecting the underlying neurovascular bundle. The ring finger hexagon insets into the index finger rectangular flaps without tension once the cleft is closed and transmetacarpal ligament reconstruction is completed. The palmar and dorsal flaps are repaired to the web flaps after excision of the redundant skin. All sutures are placed without tension and close to the edge to preserve vascularity to the random pattern flaps (Figure 8-5B).

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surfaces from the cleft proximally. These incisions allow full visualization of the soft tissue and bony anatomy. The commissure reconstruction is based on the Barsky flap[1] (see Sidebar). The V aspect of the cleft between the index and ring fingers is incised along the rim of the cleft. On the ring finger radial aspect of the proximal phalanx, a distally based diamond or hexagon flap is raised. On the ulnar aspect of the index finger proximal phalanx, the T aspect of the flap is opened. Dissection is carried proximally on both the palmar and dorsal surfaces. The proximal extent is dependent on (1) planned bony resection and/or reconstruction and (2) excision of redundant skin to achieve aligned digits and cosmetic closure.

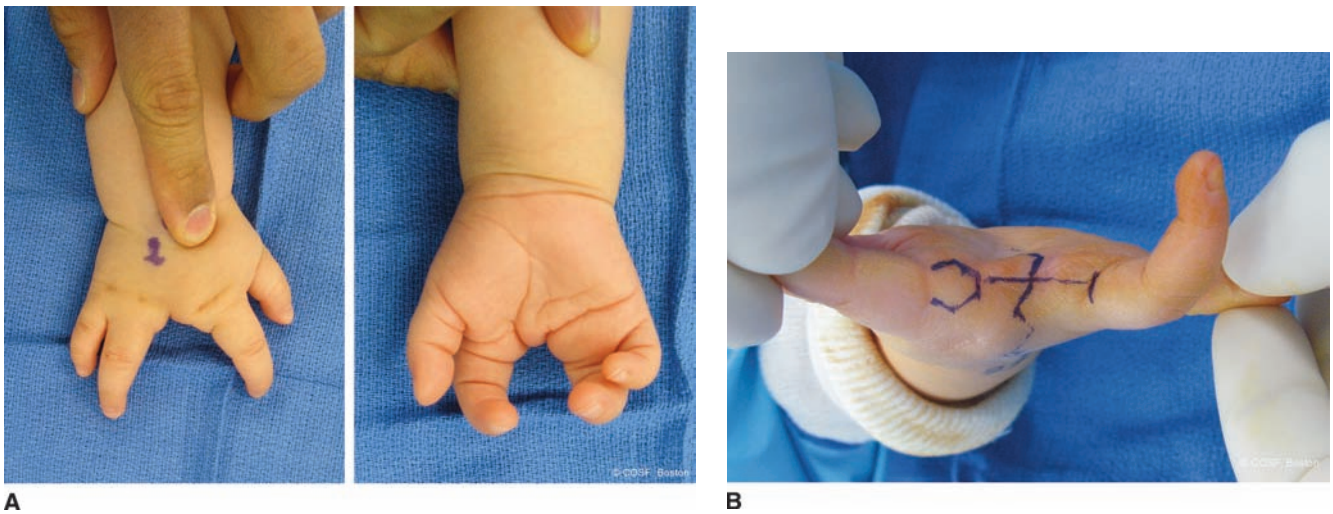
With a simple, aligned cleft, the middle finger metacarpal will be present, hypoplastic, or absent. A decision needs to be made about metacarpal resection or not. Maintaining the breadth of the hand by preserving the metacarpal may improve long-term grip strength. If present and straight, the cleft closure can be soft tissue–based distal to the metacarpal. However, distance between the index finger and the ring finger will be wider than normal. When there is absence of the entire middle ray either congenitally or postresection of an abnormal metacarpal, a transmetacarpal ligament reconstruction is necessary between the index and the ring fingers. The goal is to narrow the distance between two straight, stable rays. A carpal V wedge osteotomy may be necessary to approximate the digits without malangulation or malrotation.[24] Ligament reconstruction can be by local tissue (A1 pulleys), accessory index extensor, periosteal flaps, free grafts, or thick suture.[25,26] During reconstruction, the distally based metacarpal physis is protected while obtaining secure fixation. Placement and tensioning of the ligament repair is done to avoid malrotation of the digits during flexion. This is critical, as overtightening the intermetacarpal ligament reconstruction will result in malrotation and overlap of adjacent digits during fist formation. Intraoperative tenodesis is the best estimation of rotational alignment. The more dorsal the reconstruction, the more the tendency for the digits to supinate and the pulps to rotate away from one another; the more volar the reconstruction, the more they will pronate, and the digital tips will move toward one another. Central or equidistant volar and dorsal reconstruction is ideal.

In the absence of the middle ray, there is usually absence of the volar interosseous to the index and dorsal interosseous to the ring finger. This will affect the mobility and strength long term. It also promotes gap formation over time due to the limitations of dynamic closure of the index and ring fingers toward one another. Thus, periosteal nonabsorbable suture repair between the metacarpals is done in the proximal metaphysis, diaphysis, as well as distal transmetacarpal ligament reconstruction. Parallel transmetacarpal pinning is performed to protect the repairs, usually 0.035″ or 0.045″ C-wires.

After closure of the bony defect and deep soft tissue reconstruction, the Barsky flap reconstruction of the commissure is closed. The overlapping volar and dorsal skin of the palm is then excised. This is done in a nonlinear fashion to prevent contracture over time. Dimpling of the palm skin is avoided. The tourniquet is deflated to be certain the digits and flaps are viable. Bulking soft tissue dressings and a long-arm cast are applied (Figure 8-5).

◆ Fourth Web-Space Incomplete Syndactyly

The fourth web space frequently has an incomplete syndactyly and hypoplastic small finger. Web-space deepening is performed with five-part Z-plasties or a dorsal rectangular flap with corresponding Z-plasty flaps and full-thickness skin grafting (see Chapter 2). This is usually done as a second stage to the cleft closure and the first web-space deepening procedure.



A B

FIGURE 8-5 **A:** Typical cleft hand as a part of SHFM with dorsal and palmer views. **B:** Barsky flap outline for cleft closure in the same patient.

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C1 C2

FIGURE 8-5 (*continued*) **C1:** Dorsal view of cleft closure after intermetacarpal ligament reconstruction by local tissue and periosteal repair. **C2:** Palmar view photograph after redundant skin excision, Z-plasty closure of volar skin, web reconstruction, and pin fixation for postoperative stability.

◆ Closure of Ulnar Cleft with Parallel Digits

Closure of an ulnar cleft follows the same principles as noted above with a few potential differences. The small finger carpometacarpal (CMC) joint is inherently more mobile. The cleft can extend proximal through the carpus. The small finger can be hypoplastic creating length discrepancies between the small and middle fingers. The simplest surgery for these children is cleft closure with transmetacarpal ligament reconstruction and Barsky flap similar to central cleft closures. This will leave the small finger shorter and potentially malrotated in certain patients. The more complex closure, as outlined by Tonkin et al.,[27] involves a fifth metacarpal osteotomy and lengthening along with cleft closure. At times, a second-stage small finger proximal phalangeal osteotomy may be necessary.

◆◆ Complete Complex Syndactyly First Web Space

Digital Transposition with Complex Flaps to Reconstruct First Web Space

Type IIB and III thumbs in cleft hands require a more complex reconstruction. The operative plan is the same: close the cleft and optimize the first web space and thumb function. However, the size of a viable flap necessary to open and maintain the first web in these circumstances is considerable. Fortunately, the cleft itself has sufficient skin, especially after ulnar transposition of the index finger. Snow-Littler[20,28,29] (Figure 8-6), Miura and Komada[31] (Figure 8-7), Ueba[32] (Figure 8-8), and Upton (Figure 8-9) have all described transposition flaps to mobilize the cleft skin and insert into the first web space. Supplemental full thickness may be necessary. Broader flaps decrease the risk of necrosis of the leading aspects of the flaps.

In widely divergent metacarpals, the cleft often extends into the carpus. There may be flexor-to-extensor extrinsic tendon connections across the cleft. Transection and transfer of those tendons is appropriate. Foucher proposed a radial shift of the ulnar digits by carpal osteotomy to optimize results.[24] If a cross bone is present, most advocate removal. Care must be taken not to disrupt the MCP joint stability with removal. The capsule and ligaments must be left intact. At times, partial resection is necessary.[16]

◆◆ Snow-Littler Procedure

Surgical preparation and setup is the same as outlined above. The commissure closure between the index and the ring fingers is similar to a Barsky flap with the diamond or hexagonal flap raised from the index for inset into the ring finger. The rest of the cleft is raised as a palmar-based flap

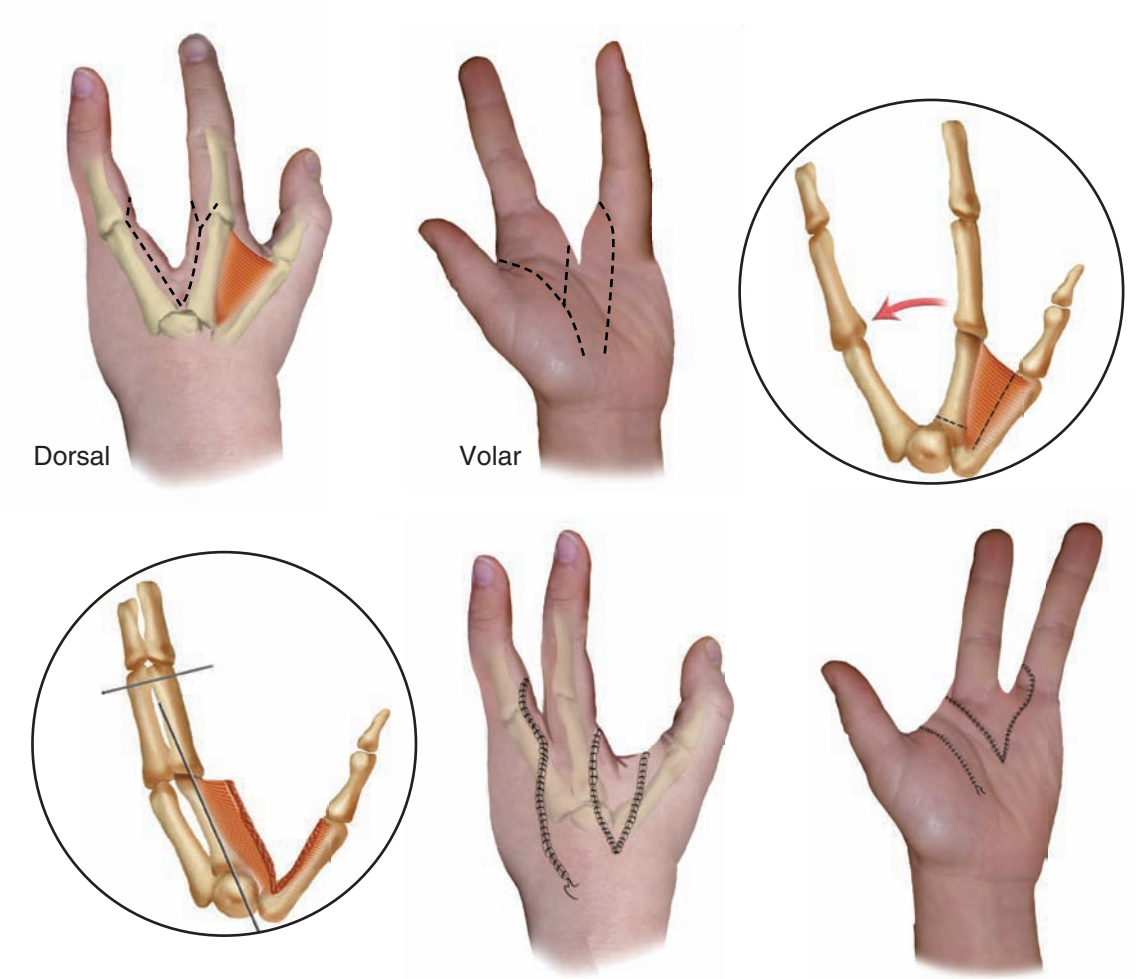

FIGURE 8-6 Illustration of the Snow-Littler technique of cleft hand reconstruction, using a palmar-based flap to reconstitute the first web space.

(apex on the dorsum and base in the palm) (Figure 8-6). The first web space is opened with a slightly curved incision. The palmar aspect of this incision is the radial base of the cleft flap, and the dorsal aspect determines the flap inset in the first web. The index finger is mobilized on the volar neurovascular pedicles with care taken to preserve venous outflow. On rare occasions, it can be raised on a dorsal flap. The first dorsal interosseous muscle is elevated off the thumb metacarpal as a muscle slide down to the base of the metacarpal near the CMC joint. Preservation of the neurovascular pedicle is important for future function. The radial artery is protected near the base. A transverse osteotomy is performed at the base of the second metacarpal if a middle finger metacarpal resection has been performed. If there is an absence of a middle finger metacarpal, the entire metacarpal is mobilized from the CMC joint distally. The index finger is mobilized on its neurovascular pedicles for transposition into the cleft. Vascularity and neural supply to both the thumb and index finger need to be preserved. One of the proper digital arteries in the web may need to be ligated, and the epineurium of the common digital nerve may require dissection proximally similar to a pollicization. This assures full ulnar transposition of the index into the desired location without neurovascular compromise. The index metacarpal is positioned adjacent to the ring finger and pinned with crossed smooth C-wires (range 0.027″ to 0.045″). Care is taken to avoid malrotation or malangulation. This is tested by tenodesis. Deep soft tissue repair continues with periosteal sutures and transverse metacarpal ligament reconstruction. The ligament reconstruction can be with A2 pulley turnover,[25] free graft, or osseous suture.[28–30] Retesting of potential malalignment is performed throughout reconstruction. Pin fixation includes not only crossed fixation at the base of the metacarpal but transversely as well. If there is MCP joint instability or bony malalignment, surgical correction is desirable at this setting. Local tissue or free grafts are used for MCP joint stabilization. Corrective wedge osteotomies are used for metacarpal or phalangeal malalignment. Excised middle finger metacarpal bone can

FIGURE 8-7 Schematic diagram of the reconstruction technique of Miura and Komada.

be used for opening wedge corrections. All osteotomies are pinned. The extent of surgery in one setting is dependent on the risk of digital or skin necrosis. Our preference is to do a single-stage correction but never at the expense of tissue necrosis.

The central flap is then inset in the first web space. Direct, tension-free closure is performed. If the first web-space syndactyly was complex and complete, additional full-thickness skin grafts may be necessary on the borders of the thumb and index fingers. This may be obtained from the central defect closure with trimming of palmar and dorsal flaps or from the groin. Completion of the central flap closure is performed.

◆◆ Miura and Komada Flaps

The flaps in this procedure are less at risk of necrosis (Figure 8-7). The cleft and index finger flaps are bilobed on the dorsal hand from the leading edge of the cleft and then around the index finger. The principles of the index ray transposition are the same as outlined in the Snow-Littler procedure. First web-space resurfacing is by rotation or Z-plasty flaps. Miura's technique is less complex, and there is a lower risk of flap necrosis.[31]

◆◆ Ueba Flaps

The flaps in this procedure are also less extensive (Figure 8-8). There is a palmar-based rectangular flap off the ulnar aspect of the index finger and a dorsal-based transverse flap off the radial aspect of the ring finger. Both have modifications for commissure reconstruction of the new web space between index and ring fingers. The dorsal-based ring finger flap is used to resurface the first web after index ray transposition. The disadvantage of these flaps is that dorsal skin ends up in the palm and vice versa. This is a small price to pay if the flaps do not become necrotic but more significant in darker-skinned patients.[32]

◆ Type IV Merged First Web

Since there is already a first web space, the goal of surgery is to position the thumb in alignment for better pinch (Figure 8-10). This may include (1) removing a transverse

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FIGURE 8-8 Illustration of Ueba's technique of cleft hand reconstruction.

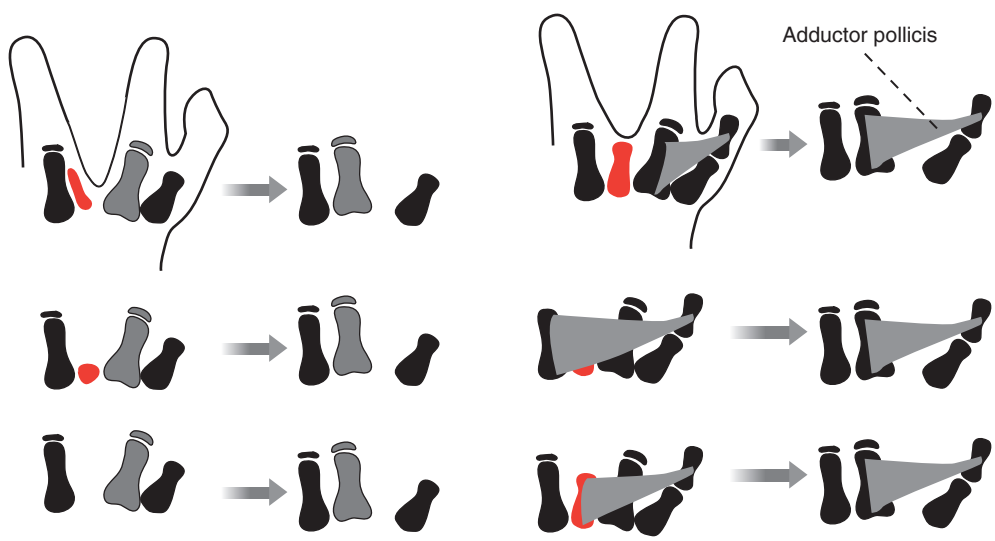

FIGURE 8-9 Upton's technique of cleft hand reconstruction.

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FIGURE 8-10 Radiograph of Manske classification type of merged web with absent index and long fingers, delta thumb metacarpal, and hypoplastic small finger. This patient was treated with thumb realignment osteotomy and first web reconstruction to improve pinch.

bone, (2) performing a thumb metacarpal osteotomy, or (3) closing the first web of thumb to ring or small finger to optimize spacing. Most often when a cross bone is present, it is removed. However, Wood advocated that on rare occasions, the transverse bone may actually help keep the web space open and should be left behind. We have yet to face this situation.[16] Generally, an osteotomy of the thumb with rotation and Z-plasty flaps will improve thumb positioning for grasp and pinch.

Type V Absent Thumb

Bidactylous Hand

The goal of care here is to provide pinch function by separation and realignment. Local flaps and full-thickness skin grafting may be all that is necessary to start with side-to-side pinch. However, rotational osteotomy and more advanced flap coverage from the groin or radial forearm may be required to achieve opposition.

◆◆ Free Toe Transfer for Pinch in Monodactylous Hand (See Chapter 46)

This is a very complicated procedure with limited published results. The consensus is that the anatomy of both the foot and hand are unpredictable and deficient in a bilateral SHFM. Utilizing the toe for transfer to the hand usually does not impair ambulation and may improve shoe wear. However, that toe is not normal and can have marked limits in its function as a hand digit.[33,34]

POSTOPERATIVE

Long-arm cast immobilization with pin stabilization is maintained for 4 to 6 weeks depending on the extent of bony reconstruction and the age of the patient. Cast and pin removal is performed in the office setting without sedation. Orthoplast splinting is utilized at nighttime to maintain alignment and help with scar reduction for several weeks. Occupational therapy is performed until supple active motion and developmentally appropriate use is achieved. Patients are followed monthly until this occurs and then annually until skeletal maturity is reached.

ANTICIPATED RESULTS

The quality of the thumb and digits is very dependent on the severity of the original malformation. Active, functional grasp, pinch, and release should be expected. An improvement in the cosmetic outcome should occur. Goldfarb and Chia described improvements in radiographic and clinical alignment, as well as parent and surgeon satisfaction by visual analog scale.[22] Mild residual divergence of the metacarpals and phalanges along with proximal interphalangeal joint flexion contracture of the ring finger was the most notable clinical finding at longer term follow-up.

COMPLICATIONS

Flap necrosis is the most significant immediate problem. If marginal, it can be treated with dressing changes. If more severe, debridement and revision surgery with skin grafts or even radial forearm or groin flaps may be necessary.

Revision of the first web-space flaps can be necessary due to web-space creep with growth. In addition to local flaps, full-thickness skin grafting is required at times.

Progressive deformity can occur with growth in the presence of bracket epiphyses, joint malalignment, or muscle imbalance. Corrective osteotomies, joint stabilization, or muscle rebalancing procedures are not uncommon in adolescents in the more severe cleft hands (Figures 8-11 and 8-12).

Gap formation is not uncommon. Frequently it does not need to be addressed as there is no functional deficiency. In the initial surgery, extensive closure of the gap may cause digital malrotation.

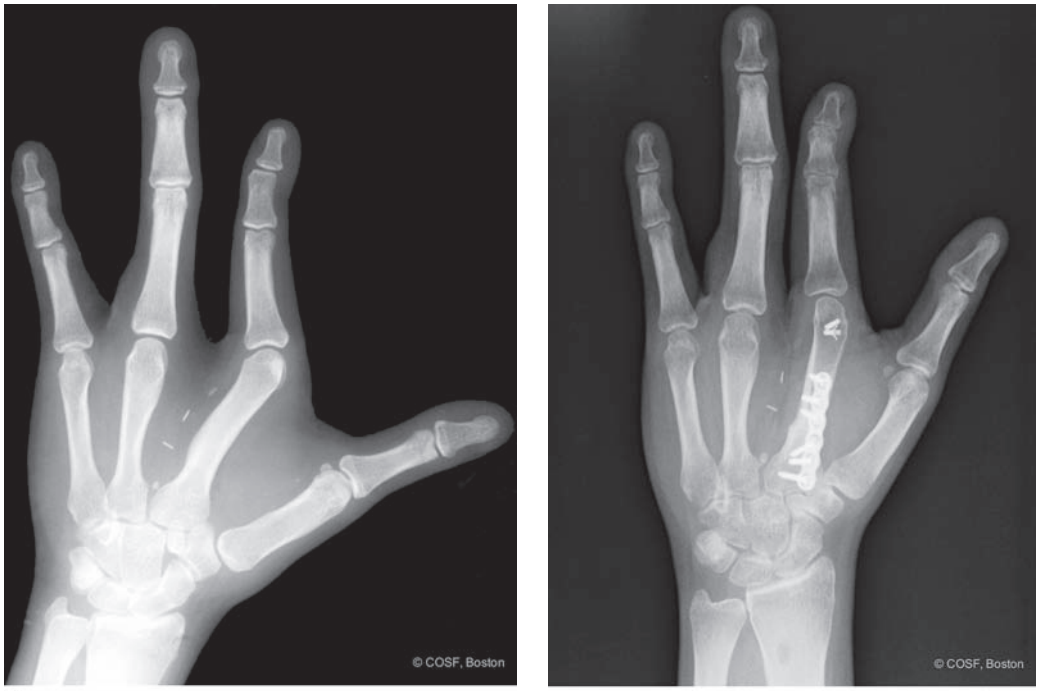

FIGURE 8-11 **A:** Preoperative anteroposterior x-ray of adolescent cleft patient (initial reconstruction as infant) with malrotated and malangulated index finger and MCP joint instability. **B:** After ligament reconstruction MCP joint and metacarpal corrective osteotomy to realign index finger.

FIGURE 8-12 Radiograph of bifid metacarpal after osteotomy by outside surgeon to realign digits.

CASE OUTCOME

Consultation with parents during pregnancy was quite extensive. Father wanted to know what had changed since his childhood care for cleft hands. Mother wanted to know the psychosocial implications from our perspective and treatment options. The prenatal consultation brought both reassurance and relief. Postnatal care involved surgical reconstruction of clefts at 9 months of age (similar to Figure 8-5).

SUMMARY

Cleft hands have a clear genetic basis with failure of induction of the central digital rays due to p63, Dlx homeobox and dactylin mutations, regulation, and deficiencies. There is a wide spectrum of phenotypic expression from unilateral minor clefts (types I, IIA) to bilateral SHFM and EEC (types IIB, III–V). Surgical principles are based on cleft closure and optimization of the first web space and thumb function. Flap design varies, dependent on the unique malformation. The surgeon needs all the tools of bony and soft tissue reconstruction to treat these patients.

COACH'S CORNER

Advanced Fetal Care Center

Prenatal consultation is now commonplace for us in our Advanced Fetal Care Center (Figure 8-1). Ultrasound diagnostic imaging of the fetus is standard in prenatal care.[35,36] The technology is so advanced that we have had parents tell us that a 20-week fetus "looks like Dad." This technologic progress clearly leads to prenatal diagnoses of congenital differences. With the wealth of information available on the Internet, parents want to know more about the diagnosis and the implications for them and their child. A consultation with the pediatric subspecialist is very helpful to bring perspective to the complexity of what they have read and heard. The consultation can make the delivery of their child more joyful as they have had the time to grieve the loss of their "normal, perfect" child and bring love and attention to their newborn with a congenital difference. Prenatal consultation can alleviate the anxiety and fear of the unknown that occurs with a diagnosis of a congenital difference made immediately at birth. This interaction also builds a relationship with the subspecialist early on in pregnancy that makes surgical decision making later more trusting and informative.

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CHAPTER

9

Aphalangia and Amniotic Band Syndrome

CASE PRESENTATION

A 1-month-old infant presents for evaluation of a "hand defect." At birth, the child was noted to have congenital differences of the hand, including "extra skin creases" and the absence of the digital tips (Figure 9-1). Despite the abnormal appearance, the digital tips have always appeared pink. No obvious abnormalities have been noted in the proximal hand or remainder of the affected upper limb. The other three limbs are normal by exam as is a complete organ system exam by the pediatrician.

CLINICAL QUESTIONS

- What is amniotic band syndrome (ABS)?
- What is the etiology of ABS?
- What are the clinical features of ABS, and how is it distinguished from symbrachydactyly?
- How is ABS classified?
- What are the treatment principles?
- What are the surgical techniques utilized for aphalangia?
- What are the treatment principles for congenital below-elbow amputations?

THE FUNDAMENTALS

Etiology and Epidemiology

Also known as constriction band syndrome, constriction ring syndrome, Streeter dysplasia, and limb-body wall malformation complex, ABS is thought to affect 1:1,200 to 1:15,000 live births.[1–5] Males and females are equally affected. In some series, up to 60% of cases have an associated identifiable event during pregnancy.[3] No hereditary predisposition has been identified.

There are two theories regarding etiology. Streeter first proposed the intrinsic theory, suggesting that ABS results from an abnormality in the germplasm differentiation and development.[6] Accordingly, a defect in differentiation—perhaps from teratogenic exposure, viral infection, or vascular disruption—causes necrosis and band formation.[7–9] Torpin was among the first to advocate an extrinsic cause of ABS.[10] In this theory, the amnion ruptures and free-floating strands of membrane entangle, constrict, deform, and/or amputate affected parts. At the same time, the exposed chorion absorbs the amnionic fluid and induces a transient oligohydramnios, resulting in even further external compression on the developing limb. (This may in part explain the association of ABS with other "packing" disorders, such as congenital clubfoot.) Experimental studies have demonstrated the ability to reproduce similar phenotypes, supporting the extrinsic theory.[3,11–14] We, like most authorities, subscribe to the extrinsic theory of causation.

FIGURE 9-1 Clinical photograph of a hand with amniotic band syndrome. *Arrow* points to the second web-space sinus tract with distal syndactyly. Congenital amputation and constriction band noted on third and fourth digits, respectively.

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Clinical Evaluation

Patients with ABS may present with a wide spectrum of clinical manifestations. Hand findings range from subtle dimpling or indentations of the skin, constriction bands with distal lymphedema, and acrosyndactyly to absence of distal amputations. Despite the range of findings, a number of clinical features are characteristic.[3,15,16] First, the bands typically lie transversely, orthogonal to the longitudinal axis of the digit or limb. Second, central digits tend to be more affected than border digits due to their natural increased length. Third, the majority of constriction bands affect the digits; forearm or brachium involvement is much less common. Level of involvement may depend upon the timing of amnionic disruption and entrapment.[13] These clinical findings are consistent with the extrinsic theory of causation.

In cases of ABS where the band is severe enough to cause "autofusion" of adjacent digits but not so deep as to result in amputation of distal parts, acrosyndactyly may occur.[17] While the exact mechanism is unknown, distal hemorrhage, superficial tissue loss, and scarring and fusion of distal segments have been theorized.[12] Unlike complex syndactyly due to failure of differentiation, the acrosyndactly of ABS usually occurs without bony fusion and typically exhibits a sinus tract at the base of the affected digits that passes from dorsal to volar (Figure 9-2). This sinus tract lies distal to the level of the normal web commissure. Often the digital tips are closely apposed and collectively resemble a "bunch of grapes." In these situations, the orientation of the digits is confusing, and it is often difficult to ascertain which digital tip belongs with each digit. In cases like these, the long finger tip is usually most palmar.[18,19]

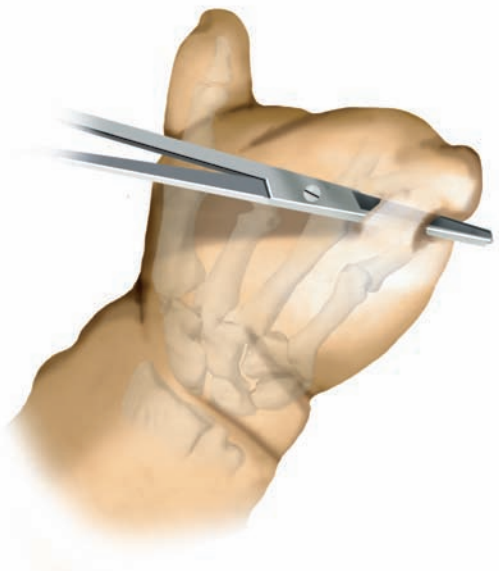

FIGURE 9-2 Illustration of the interdigital sinus tract typical of the acrosyndactyly seen in amniotic band syndrome.

Although ABS is thought to represent a deformation of a normal digit with therefore normal underlying anatomy, there may be distal nerve dysfunction and/or vascular insufficiency. Nerve dysfunction and distal sensory defects may be due to neurapraxia. Furthermore, in some cases, a temperature gradient may be noted across the band, with the distal segment having lower temperature, diminished capillary refill, and edema. This is due to vascular insufficiency related to the band. There are rare situations in which the band is still present at birth and causes acute vascular compromise. These bands should be removed or incised in the nursery.

Associated conditions have been noted in up to 80% of patients. Concomitant congenital hand differences include syndactyly, hypoplastic digits, camptodactyly, and brachydactyly. Other congenital differences, including cleft lip, cleft palate, clubfoot, and craniofacial defects, are similarly seen in patients with ABS.[10,20]

While a number of classification systems have been utilized, that of Patterson is the most descriptive and commonly utilized[7] (Figure 9-3). Type 1 denotes simple amnionic bands with superficial skin involvement only. Type 2 refers to bands with distal deformity or lymphedema. Type 3 ABS is associated with acrosyndactyly. Type 4 is the most severe and denotes congenital amputations.

Surgical Indications

Learn to differentiate between what is truly important and what can be dealt with at another time.
—Mia Hamm

Given the broad spectrum of clinical findings and/or associated conditions, the treatment of ABS remains highly individualized from patient to patient. However, a number of guiding treatment principles are proposed. Superficial bands with aesthetic differences but no functional impact may be treated electively with band release using skin and soft tissue rearrangement (e.g., Z-plasties). Deeper bands resulting with lymphedema or distal deformity are treated accordingly with similar soft tissue techniques, though this is often pursued when the patient is younger, to maximize function and eliminate distal changes. Syndactyly or acrosyndactyly is treated with surgical releases with web-space reconstitution, skin rearrangement, and/or skin grafting. Finally, patients with distal ischemia due to the tourniquet-like effect of a very deep amnionic band are treated emergently to avoid tissue loss and secondary complications such as infection. Interestingly, Flatt[19] has reported that the effect of bands may not be static, as the underlying granulation tissue may cause progressive constriction and late vascular insufficiency.

Similar to the principles of syndactyly release, caution is advised whenever both sides of the digit are operated upon in a single setting. While single-stage circumferential releases may be considered for superficial bands,

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FIGURE 9-3 Schematic representation of the Patterson classification of amniotic band syndrome. Type 1 denotes simple amnionic bands with superficial skin involvement only. Type 2 refers to bands with distal deformity or lymphedema. Type 3 ABS is associated with acrosyndactyly. Type 4 is the most severe and denotes congenital amputations.

two-staged releases (50% band release at first procedure, followed by completion of the release 6 weeks to 3 months later) may be more judicious in patients with deep bands to avoid vascular embarrassment.[16,19,21,22]

SURGICAL PROCEDURES

Removal of Band in Office or Nursery

The only potential emergency in infancy is vascular compromise from an amnionic band acting like a venous tourniquet. In this situation, the band will be a darkened ring around the finger. It can be teased off the digit(s) with a surgical pickup. Alternatively, a longitudinal incision may be made through the constriction, releasing the tourniquet-like effect of the amnionic band. This situation is rare but important. The procedure may be performed in the nursery without anesthesia and can lead to immediate improvement in vascularity if performed early enough.

Acrosyndactyly can be due to bands that forced the connection of all digits. These are usually associated with congenital amputations. Early in infancy, separation back to the sinus tracts of all digits is not a risk for vascular compromise. The result can be very dramatic, especially with liberation of the thumb. Release from each sinus tract distally will mobilize the first, second, and fourth web spaces. Often the long and ring fingers need to stay initially conjoined. Later reconstruction is usually necessary, but this procedure in the first few months of life allows for more refined active use of the hand.

Simple Band Excision and Z-Plasties or Rotation Flaps

Under general anesthesia, tourniquet control, and loupe magnification, simple bands may be excised with 60-degree Z-plasty flaps to confer soft tissue coverage without inducing secondary scar contractures. Z-plasties in series or excision of constriction band with careful elevation of skin flaps is performed (Figure 9-4). While the subcutaneous fat is kept on the flaps in an effort to preserve vascularity, any identifiable deep veins or superficial nerves are longitudinally preserved during the initial, careful dissection. This is especially critical for deep bands on the volar aspect of the digit, as the neurovascular bundles may be closely apposed to the constriction band and underlying bone and difficult to visualize. Plans should also be made to excise the constriction band, rather than incorporating this abnormal tissue into the rotating flaps. To restore a smooth, more normal contour to the affected digit, subcutaneous fat is mobilized to provide adequate soft tissue coverage, and excess tissue at the leading edge of the flaps is judiciously debulked.[23] Simple band excision and circumferential skin closure is not recommended as it will result in subsequent scar contracture and "recurrence."

Nonvascularized Toe Phalangeal Transfer

Hit the shot you know you can hit, not the one you think you should.
—Dr. Bob Rotella

In cases of aphalangia—due to ABS, symbrachydactyly, or transverse deficiency—nonvascularized toe transfers may be considered. In these situations, a toe phalanx with its surrounding periosteum is taken from the foot and transferred to the soft tissue "nubbin" or pocket of the affected digit(s). By increasing the length of the affected digit, function of the hand may be improved. This procedure takes advantage of the general principles that all sensate digits will be utilized by the child, more digits provide better function than fewer digits, and digital length is important for digital function.

Indications for nonvascularized toe transfers include (1) aphalangia of the thumb with absent digits at the metacarpophalangeal (MCP) level, (2) bilateral hand/finger involvement, or (3) intercalary bone defects, particularly of the thumb. Relative contraindications include absence of the metacarpals and single digital involvement. A soft tissue "nubbin" of adequate size that can accommodate the transferred bone is a prerequisite to surgery. Furthermore,

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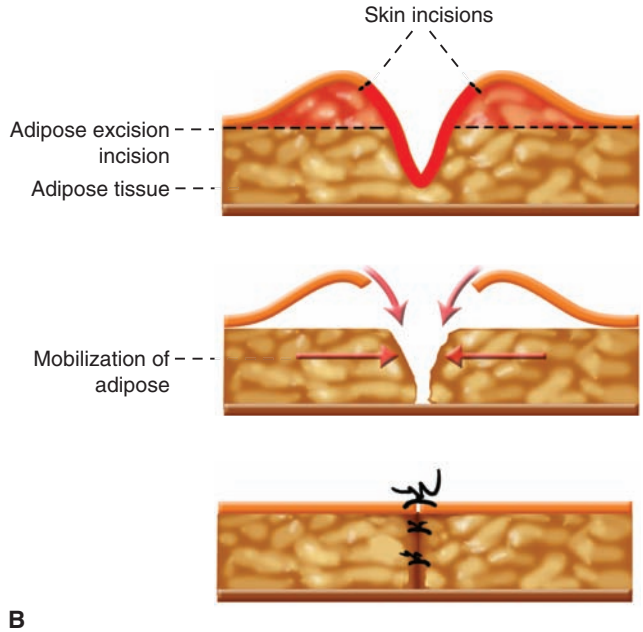

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FIGURE 9-4 Clinical photographs of simple band release and Z-plasties. **A:** Preoperative appearance depicting superficial bands of the index, long, ring, and small fingers. Note the varying degrees of band depth and relative "ballooning" or lymphedema of the index. Skin incisions are created along the bands in the fashion of Z-plasties in series. **B:** Schematic cross-sectional representation of skin flap elevation, band excision, and subcutaneous fat debulking and mobilization. **C:** Postoperative appearance following band excision, flap rotation, and primary skin closure.

early surgery is advocated, preferably before 12 months of age; multiple studies have demonstrated higher rates of physeal growth in transplanted phalanges when surgery is performed in younger patients.[24,25]

Surgery is performed under general anesthesia and tourniquet control (Figure 9-5).[26,27] Dorsal zigzag or chevron incisions are created on the affected digit. Soft tissue dissection is performed down to the level of the extensor mechanism, which is incised longitudinally. Usually, the extensor and flexor tendons may be conjoined and confluent. Care is made to preserve the soft tissue "cap" at the distal aspect of the nubbin, to avoid devascularizing the digital tip. Blunt dissection is then performed via gentle longitudinal spreading, creating a soft tissue pocket or cavity to accept the toe phalanx. The dimensions of this recipient site are then measured.

Direction is then turned to the foot. Typically, the proximal, less commonly middle, phalanges of the second, third, and/or fourth toe(s) are harvested depending on how many phalangeal transfers are planned. Bilateral foot harvesting can occur for later symmetry of appearance. Ultimately, the choice of the extraperiosteal bone(s) to be transferred is based upon parental preference, careful preoperative planning, and intraoperative measurements of the recipient soft tissue pocket. (It is helpful to measure the length and width of the toe phalanges on a preoperative foot radiograph and have these measurements readily available during surgery.) A dorsal chevron incision is created over the desired toe phalanx. The toe extensor mechanism is also split longitudinally. With care being made to preserve the periosteum, the collateral ligaments are released, preserving length proximally for transfer and revascularization. Once the distal articular surface is liberated, distal-to-proximal extraperiosteal dissection is performed. The plantar plate and then pulleys must be released, with preservation of the underlying flexor tendons and neurovascular bundles of the toe. The toe phalanx is then released from the more proximal joint, allowing for transfer. The collateral ligaments and plantar plate attachments are preserved at the proximal end of the phalanx for attachment to the metacarpal during transfer. In the donor toe, the extensor may be sewn to the flexor tendon to close the defect and preserve length and alignment prior to wound closure.[28]

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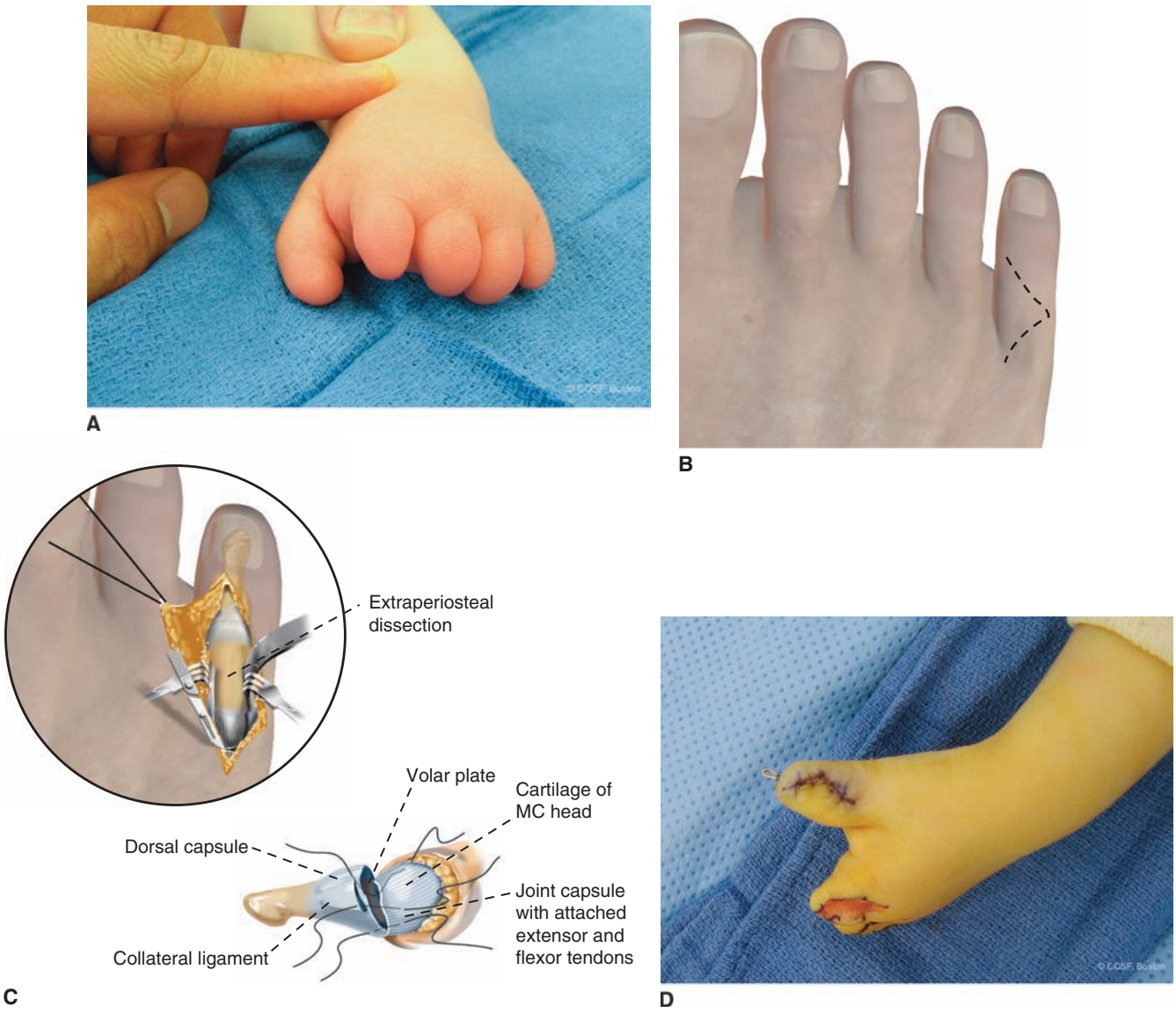

FIGURE 9-5 Technique of nonvascularized toe phalanx transfer. **A:** Clinical photograph of a patient with aphalangia depicting the structural deficiencies. Note the substantial soft tissue nubbins at the end of the digits, which are prerequisites for this technique. **B:** Schematic diagrams depicting incisions over the hand and foot. Usually the middle toes (2nd, 3rd, 4th) are used for non-vascularized phalangeal transfer. **C:** Schematic diagram depicting the manner of soft tissue reconstruction. **D:** Completed nonvascularized toe phalangeal transfer after pin fixation and primary skin closure to the thumb. Note the open soft tissue pocket at the recipient site of the index finger.

A longitudinal smooth pin (0.028″ to 0.035″) is then placed down the longitudinal axis of the toe phalanx. After the toe phalanx is placed in the soft tissue recipient site, the pin may be passed antegrade out the tip of the soft tissue nubbin, followed by retrograde passage from the phalanx into the metacarpal head. In cases where an MCP joint is being reconstructed, the collateral ligaments and plantar plate of the toe phalanx are reattached to the longitudinally split MCP joint capsule. After pin fixation is achieved, the extensor mechanism is reapproximated to the transferred phalanx. Skin is closed using interrupted absorbable sutures. This procedure is performed as often as indicated in a single setting. It is not rare to transfer two to four toe phalanges to a hand in the appropriate situation. A long-arm mitten cast is applied over a bulky soft dressing.

◆◆ Free Toe-to-Hand Transfer

Hand function is severely compromised in cases of total or near-total digital loss. In general, at least two digits (or a thumb and a digit) are needed to perform rudimentary grasp and pinch. At least one of these digits should be mobile yet stable, under volitional motor control.

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Sensibility is critical, as the insensate digit or hand will not be utilized.

Free toe-to-hand transfers have been advocated in special situations for either thumb or single-digit reconstruction (Figure 9-6). In cases where the thumb is preserved, as is common in ABS, toe transfer to the ulnar side of the hand may facilitate grasp and pinch. Similarly, in ABS cases of thumb aphalangia where the thenars are preserved, toe transfer may be preferred over pollicization. Fortunately, in amniotic band syndrome, the anatomy proximal to the amputation is normal. Also, there frequently are foot and toe deformities that make sacrifice for transfer an easier decision for parents.

Free toe-to-hand transfers offer a number of theoretical advantages. By definition, the transfers bring additional functional units to the deficient hand. No sacrifice of a functional or adjacent digit is required, which is particularly important in the hand without the normal complement of digits. Technically, transfers are facilitated by the similar surgical and functional anatomy shared between toes and fingers. And finally, the aesthetic and psychological benefits of a more normal-appearing hand should not be underestimated.[29,30]

Indications remain controversial. In congenital cases, free toe-to-hand transfers may be considered in thumb aplasia without normal adjacent digits to pollicize, ABS, symbrachydactyly, and other transverse failures of formation. Aphalangia with bilateral hand involvement is also considered an indication.

More important than indications, however, are the factors that would portend a greater functional gain following toe-to-hand transfer compared with simpler, less technically demanding reconstructive strategies (Table 9.1).[31,34,35] Patient characteristics favoring toe-to-hand transfer include bilateral hand involvement, absent thumbs, younger age, presence of normal metacarpals, and normal proximal anatomy (e.g., ABS). Unfavorable factors include unilateral hand involvement, absent metacarpal heads, and older age in the setting of symbrachydactyly.

Timing of surgery is similarly controversial. Although Lister described successful transfer in patients as young as 6 months of age,[32] free toe-to-hand transfers are generally

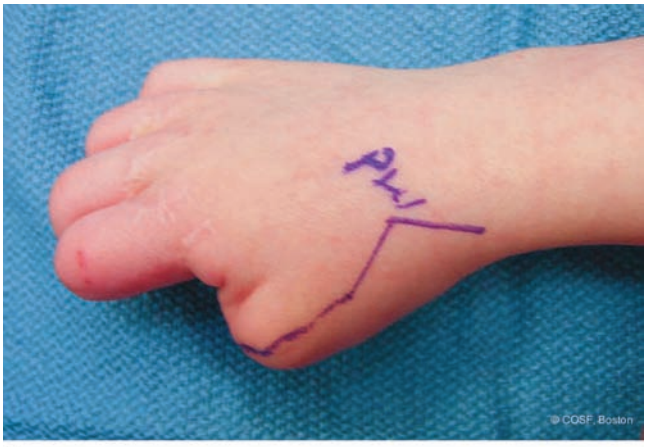

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FIGURE 9-6 Technique of free toe-to-hand transfer. **A:** Clinical photograph of a hand with absent distal thumb, index, long, and ring digits in the setting of amniotic band syndrome. The dorsal incision over the thumb is depicted. Previous syndactyly releases noted on the other digits. **B:** Corresponding radiograph; note the normal skeletal and vascular anatomy proximal to the sites of tissue loss, characteristic of amniotic band syndrome. **C:** Hand after completed toe-to-hand transfer.

Table 9.1

Factors "for" and "against" free toe-to-hand transfer for congenital hand differences

	For	Against
Etiology	Amniotic band syndrome	Symbrachydactyly
Laterality	Bilateral	Unilateral
Age	<2 years	>2 years
Function	Absent thumb	Metacarpal hand
Thumb metacarpal	Present	Absent
Thenar muscles	Present	Absent
Finger MCP joints	Present	Absent

Adapted from Eaton CJ, Lister GD. Toe transfer for congenital hand defects. *Microsurgery*. 1991;12:186–195.

recommended between 18 and 24 months of age. The earlier the transfer is performed, the faster and more easily the child will learn to incorporate the new digit in hand use. Similarly, in unilateral cases, earlier transfer may be preferred, to maximize function and prevent the child from using the normal hand to compensate for the affected hand. In bilateral hand involvement, particularly in the setting of symbrachydactyly where the proximal neurovascular anatomy is likely to be abnormal, later surgery can be entertained. (see Chapter 46 for full technical details of microvascular toe-to-hand transfer).

Following free vascularized tissue transfers, we routinely use intravenous dextran for thrombosis prophylaxis for 5 postoperative days, followed by oral aspirin for a total of 3 weeks postoperatively. Serial examinations to assess for color, turgor, and warmth of the toe transfer are performed in the immediate postoperative period. At present, we do not utilize implantable or invasive monitoring of the anastomoses, nor do we routinely use postoperative bone scans, Doppler examinations, or surface temperature monitors to assess viability (Sidebars 1 and 2).

SIDEBAR 1

Fetoscopic Release of Constriction Bands: A Glimpse of the Future?

With advanced imaging technologies, greater understanding of prenatal and perinatal physiology, and increasing expertise in minimally invasive procedures, the potential for prenatal surgery for congenital differences of the hand and upper limb is great. Once a pipe dream among pediatric surgeons, prenatal intervention is now becoming a reality. To date, most fetal procedures have been performed for life-threatening conditions (such as twin-twin transfusion syndrome, twin reversed arterial perfusion sequence, obstructive uropathy, congenital cystic adenomatoid malformations, and diaphragmatic hernia).[45–50] However, increasingly there has been an interest in developing techniques for treating limb-threatening conditions such as ABS.

In theory, release of constriction bands in utero may prevent hand and upper limb deformation and ultimately tissue loss.[51,52] Keswani et al. previously reported the successful intrauterine release of constriction bands in two patients using fetoscopic techniques, with documented restoration of blood flow to the distal extremity. Sentilhes et al. similarly reported attempted release of a constriction band with an ultimately favorable outcome, though complications were encountered during the fetoscopic procedure. These fetal interventions take advantage of properties of fetal tissue, which heals without scar formation.[53–58]

Despite these exciting developments, a number of limitations exist. Fetal monitoring and access continue to be difficult. Preterm labor and its accompanying complications remain almost an expectation following current fetal interventions. Scientific investigation and experimentation are challenging given the dearth of appropriate animal models of congenital hand conditions and fetal surgery. Finally, a host of ethical implications must be debated, most notably the utility of performing an intervention for the benefit of one patient (the fetus) at the risk of two patients (fetus and mother), particularly for a nonlethal condition for which a number of viable postnatal treatment options exist. Stay tuned, sports fans.

SIDEBAR 2

Transverse Deficiency (Congenital Below-Elbow Amputations)

I learned you can learn to do things differently, but do them just as well.
—Jim Abbott, former professional baseball pitcher and congenital below-elbow amputee

Aside from amniotic band syndrome and symbrachydactyly, the pediatric hand and upper extremity surgeon will encounter a number of other congenital "amputations" affecting the upper limb. The most common transverse deficiency is the so-called congenital below-elbow amputation, occurring in 1:20,000 live births (Figure 9-7).[59]

Congenital below-elbow amputations are typically unilateral, sporadic, and rarely associated with other congenital differences. Traditionally, these congenital differences were thought to be due to vascular insufficiency during embryonic development, perhaps distinguishing them from symbrachydactyly. More recent investigation suggests that congenital below-elbow amputations may be a more proximal manifestation of symbrachydactyly.[60] Abnormalities in fibroblast growth factor expression from the apical ectodermal ridge have been implicated in animal models, though the exact etiology in humans has yet to be clearly defined.[61–63]

Historically, the teaching has been that patients with congenital below-elbow amputations should be fitted with prostheses as they approach 6 months of age.[64–66] Developmentally, this is when children typically begin to perform bimanual tasks in the midline and also acquire the ability to sit independently. (Hence the phrase, "sit to fit.") The rationale was that children would require increased working length of the affected limb to adequately perform bimanual tasks, tripod sit, and attain the balance needed to sit and ambulate. Over time, with increasing growth, strength, and functional demands, prostheses with passive terminal devices ("hand paddles") are exchanged for those with active terminal devices. While distraction osteogenesis and other surgical treatments have been advocated to address the limb deficiency, these have been reserved for special situations (e.g., excessively short forearm amputation stump precluding prosthetic fitting) and do not represent the standard of care.[67–69]

More recent information has challenged the traditional tenets regarding prosthetic fitting. First, often children and adolescents with transverse deficiencies of the upper limbs do not wear their prostheses, even when fitted. Buffart et al. reported that while children could use their prostheses for two-thirds of activities, they did so only 30% of the time.[70] These findings have been corroborated by others, suggesting the children and adolescents do not wear their prostheses.[59] This is particularly true in patients with more distal amputation levels. While upper limb prostheses can provide length and even an active terminal device, they do not provide any sensibility. This lack of sensation, combined with the burden of their application, weight, and often more conspicuous aesthetics, frequently drives patients to abandon their prostheses in favor of a lighter, more mobile, sensate—though shorter—amputation stump. Despite advances in myoelectric prostheses, issues regarding weight, battery life, and durability remain; to date, no clinically important advantages have been demonstrated with myoelectric over body-powered prostheses.[71,72]

Furthermore and perhaps more importantly, multiple studies looking at patient-derived outcome measures have demonstrated that prosthetic use is not necessarily associated with increased function or quality of life. James et al. evaluated 489 children with unilateral congenital below-elbow amputations, of which 321 wore prostheses.[73] There were no differences in multiple outcome measures (PODCI "Pediatric Outcomes Data Collection Instrument," PedsQL "Pediatric Quality of Life Inventory") between prosthetic wearers and nonwearers. Indeed, nonwearers performed as well if not better than prosthetic users on standardized functional assessments (the Unilateral Below Elbow Test [UBET] and Prosthetic Upper Extremity Functional Index [PUFI]). Other studies support these findings.[70] At present, the available evidence suggests that prostheses may help with social acceptance and/or are useful for specific activities but are not advantageous for the general activities of daily living.[70,73,74]

Given the spectrum of individual patient's wishes and demands, combined with ever-evolving technology, we currently offer prosthetic fitting to patients with congenital below-elbow amputations at the age of 6 months, understanding that many will choose not to wear their prostheses as they grow older. Furthermore, as functional demands and self-awareness change over time, continued discussion is made regarding the utility of body-powered terminal devices or even myoelectric prostheses on a case-by-case basis.[75]

FIGURE 9-7 Clinical photograph of a patient with a congenital below-elbow amputation.

POSTOPERATIVE

Following simple Z-plasties and soft tissue rearrangement, postoperative casts are removed after 2 weeks, followed by scar management and range-of-motion exercises. Cast immobilization in cases of nonvascularized toe phalangeal transfer and free toe-to-hand transfers is not removed until 4 weeks postoperatively, when pins are removed in the office, and hand therapy is initiated for splint fabrication and scar management.

ANTICIPATED RESULTS

Successful band release is expected after appropriate Z-plasties and constriction band excision. Serial clinical examinations are performed throughout childhood, particularly during the first 3 to 6 years of life, to monitor growth and ascertain that there is no band recurrence.

When nonvascularized toe phalangeal transfers are performed at a young age (certainly prior to 18 months of age and ideally earlier than 12 months of age), the transferred bones will maintain open physes and exhibit both longitudinal and appositional growth.[25,28,33] Little aesthetic or functional foot deformity is typically seen, particularly when the donor toe length is preserved by suturing the flexor to extensor tendons. These children are followed periodically until skeletal maturity to be certain of digital growth and functional use.

With meticulous surgical technique, successful free toe-to-hand transfer is achieved in greater than 95% of cases, if "success" is defined as viability of the transferred tissue.[36,37,38–42] In most cases, growth is preserved in the transferred part. Functional results, however, remain unpredictable.[39,43,44] Typically, passive motion exceeds active motion of the transferred digit. Often there is an extension deficit, leading to varying degrees of flexion contracture. While sensibility is preserved, careful testing reveals it to be abnormal. Typically, strength is about 50% less than normal. Surgical "tinkering" is common later to improve alignment.

COMPLICATIONS

Web-space creep and recurrent bands with growth are not rare. If significant, these are easily dealt with by repeat syndactyly release or amnionic band surgery. The most serious problem with nonvascularized phalangeal transfer is resorption, followed by failure of the transfer to grow. These complications are very rare if the soft tissue pocket is sufficient, the transfer is extraperiosteal, and the procedure is performed in infancy. Finally, loss of a vascularized transfer due to vascular compromise does occur in 1% to 5% of cases. Viability of the transfer but limited functional use is a more common problem.

CASE OUTCOME

This patient was diagnosed with amniotic band syndrome. After family discussion and observation, surgery was performed beginning at 9 months of age for constriction band release and performed in a staged fashion (similar to Figure 9-4). As there were inadequate soft tissue "pockets" at the tips of the affected digits, nonvascularized toe phalangeal transfers were not performed. Given the preserved thumb length and function, as well as a normal contralateral hand, no further surgical treatment was pursued.

SUMMARY

In cases of aphalangia, functional use of the hand may be improved with surgical intervention. Characterization of the underlying abnormality—amniotic band syndrome, symbrachydactyly, or transverse deficiency—is critical in these situations, particularly during surgical planning. In cases of ABS with tight bands or distal lymphedema, Z-plasties and band excision will allow for improved aesthetics and growth potential. In cases of deficient thumbs or digits, nonvascularized toe phalangeal transfers or free toe-to-hand transfers may be utilized to bring functional elements to the hand to improve pinch and grasp.

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COACH'S CORNER

Amniotic Band Syndrome versus Symbrachydactyly

Amniotic band syndrome affecting people with multiple digits and with distal amputations may appear similar to symbrachydactyly or atypical cleft hand. While at first glance these may appear to be similar conditions, there are clinical differences that aid in diagnosis, counseling, and surgical decision making.

Symbrachydactyly is embryologic failure of formation, likely due to vascular insufficiency or disruption during hand and upper limb development. The entire hand is affected, and bilateral hand involvement is rare.[3,76] In contrast, patients with ABS will often have more than one extremity affected.

In symbrachydactyly, distal digital structures are often present even in very underdeveloped hands, often exhibiting rudimentary finger nail plates, nail beds, and digital pulps. This is likely due to the fact that the mesodermal abnormality does not affect the development of distal ectodermal structures. In ABS, distal nail plates, nail beds, and digital pulps are not present.

Symbrachydactyly may occur with Poland syndrome and other conditions related to vascular insufficiency.[77] Amputations, if present, will typically occur at the level of the joints. Furthermore, the proximal musculoskeletal and neurovascular anatomy may be abnormal. In ABS, amputations tend to occur through the phalanges, leaving a remnant of tapered bone. The structures proximal to the bands or levels of amputation are normal! This distinction is critical, as many of the surgical interventions possible in ABS (e.g., toe-to-hand transfer) are predicated on the reliable presence of normal proximal anatomy. This is not true for symbrachydactyly.

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CHAPTER

10

Thumb Hypoplasia

CASE PRESENTATION

A 9-month-old child comes in for evaluation of a "weak thumb" (Figure 10-1). The parents report that this was noted at birth but have not yet sought orthopaedic consultation due to other medical issues. While at times the child uses the thumb for spontaneous grasp and pinch, at other times the child will attempt to hold and manipulate small objects between the index and long fingers.

CLINICAL QUESTIONS

- What are the characteristic clinical features of the hypoplastic thumb?
- What medical conditions and syndromes are associated with thumb hypoplasia?
- How is thumb hypoplasia classified?
- What are the treatment principles?
- What are the indications for surgical reconstruction?
- What types of operations are performed for the hypoplastic thumb? What factors determine which types of operations to perform?
- What is a pollex abductus?
- What is a chondrodesis?
- What are the expected outcomes and potential complications of surgical treatment?

THE FUNDAMENTALS

You don't need thumbs…My best friend is my brother's dog. He doesn't have any thumbs and he's doing fine.
—Pat Angerer, Iowa Hawkeyes offensive lineman

Etiology and Epidemiology

The upper limb develops during the fourth to seventh week of gestation (see Chapter 1). A number of signaling centers have been identified that contribute to upper limb morphogenesis, patterning, and differentiation. The apical ectodermal ridge (AER) is responsible for proximal-distal development, mediated by a number of fibroblast growth factors.[1] The zone of polarizing activity (ZPA) has been implicated in anterior-posterior pattern formation, mediated in part by sonic hedgehog and homeobox (HOX) gene products. Finally, the WNT7a signaling center directs dorsal-ventral development. While the exact mechanisms are yet unknown, it is believed that abnormalities in the AER and/or ataxic insult on the ZPA may result in thumb hypoplasia, with or without radial longitudinal deficiency.[2–4]

Thumb hypoplasia represents approximately 5% to 15% of all congenital hand differences.[5,6] Males and females are equally affected, and the right thumb is more commonly involved than the left.[7,8] In over half of cases, there is bilateral, though often asymmetric, involvement.

In up to 40% of cases, thumb hypoplasia may present in association with known syndromes (Table 10.1).[7–9]

FIGURE 10-1 Clinical photograph of a Blauth type IIIA hypoplastic thumb. Note lack of IP joint skin crease and thenar muscle bulk.

Table 10.1

Syndromes associated with thumb hypoplasia

Radial longitudinal dysplasia
VACTERRL
Fanconi anemia
Thrombocytopenia-absent radius
Holt-Oram syndrome

Awareness of syndromic associations is critical, as often the hand surgeon is the first medical care provider to evaluate the patient; in these situations, potentially life-altering diagnoses and lifesaving interventions can be made. The VACTERL syndrome denotes combined abnormalities of the vertebrae, anus, cardiovascular tree, trachea, renal system, and limb buds. (The classic "VACTERRL" syndrome involves Vertebral anomalies, Anal atresia, Cardiac defects, Tracheo-Esophageal fistula, Renal, and Radial Limb anomalies.)[10–12] Holt-Oram syndrome refers to thumb hypoplasia associated with congenital heart defects, typically atrial and ventricular septal defects. The genetic mutations for Holt-Oram syndrome have been identified as involving the TBX5 gene in over 70% of patients.[13] Fanconi anemia also has an autosomal dominant inheritance pattern. In infancy, there are usually characteristic facial features (microphthalmos, strabismus, and hearing deficits).[14] Pancytopenia often does not present until later in childhood. Fanconi anemia can be identified by a mitomycin C test, but it is now advocated that all infants with thumb hypoplasia and/or radial-sided defects be assessed early for Fanconi anemia with the diepoxybutane test, since a delay in diagnosis can have potentially life-threatening consequences.[15] Thrombocytopenia with absent radius is also from autosomal recessive inheritance. While no causative genetic mutations have been identified, patients demonstrated deletions on the long arm of chromosome 1[16]; both the c-mpl gene and the HOX genes have been implicated.[17,18] The thrombocytopenia is present at birth. The platelet count usually improves with growth, and hand surgery should be delayed until it is safe.[14–19]

Clinical Evaluation

Coaches have to watch for what they don't want to see and listen to what they don't want to hear.
—John Madden

Clinical evaluation begins with careful inspection and physical examination. To identify the underdeveloped thumb, one must understand what constitutes "normal." In a previous study of 546 hands in 243 patients less than 18 years of age, it was determined that the tip of the adducted thumb reaches to 70% of the length of the index finger proximal phalanx, measured proximal to distal,[20] and 32% of the length of the index finger from the metacarpophalangeal (MCP) joint to its tip. The widths of the thumb and thumb nail were found to be 133% and 105% that of the adjacent index finger, respectively. Interestingly, these comparisons between normal thumb and index digits remain relatively constant among patients of different ages.

Thumb hypoplasia is characterized by five distinct clinical features. First, the thumb is smaller, shorter, and narrower. Second, there may be interphalangeal (IP) joint stiffness with relative paucity of the flexion and extension creases, due to underdevelopment of the extrinsic muscles. Third, the MCP joint is typically unstable, due to ligamentous insufficiency. Fourth, the thenar muscles are underdeveloped and weak, resulting in absent palmar abduction of the thumb and a concavity of the normally prominent thenar eminence. Finally, there is often a first web-space narrowing, likely due to the imbalance between the robust adductor pollicis and weak or absent thenars. As there is a high frequency of bilateral involvement, comparison to the apparently normal contralateral thumb may often be misleading.

In situations in which there are absent or rudimentary flexion and extension creases of the IP joint, a pollex abductus should be suspected.[5] Defined as an abnormal connection between the flexor pollicis longus and extensor pollicis longus tendons, a pollex abductus may be seen in up to 35% of cases and will cause the thumb to rigidly abduct when the extrinsic flexors or extensors are activated. Pre- or intraoperative identification of a pollex abductus is critical, as failure to address this anatomic abnormality may result in suboptimal surgical outcomes.

Classification systems of thumb hypoplasia assist in surgical decision making and reflect the evolution in the understanding of this condition. While Müller was among the first to categorize thumb hypoplasia, it is Blauth's classification (and Buck-Gramcko's modification thereof) that has withstood the test of time and is most commonly used today (Figure 10-2).[21–23] A type I thumb is smaller and shorter than normal but still has all the elements that constitute a normal-functioning thumb. Type II thumbs have underdeveloped skeletal elements, MCP instability, first web-space narrowing, and intrinsic (thenar) hypoplasia. Type III thumbs have additional extrinsic deficiencies. The type IV thumb refers to the so-called pouce flottant, or floating thumb; in these situations, the rudimentary thumb is connected to the radial aspect of the hand by a narrow skin bridge without any meaningful musculature or bony connection. Type V denotes the complete absence of a thumb. Type V thumbs are thought to be most common, while type III are second most common.[7,8]

Two important modifications of the Blauth classification are worthy of note, as they guide surgical planning. Lister subdivided type II thumbs according to

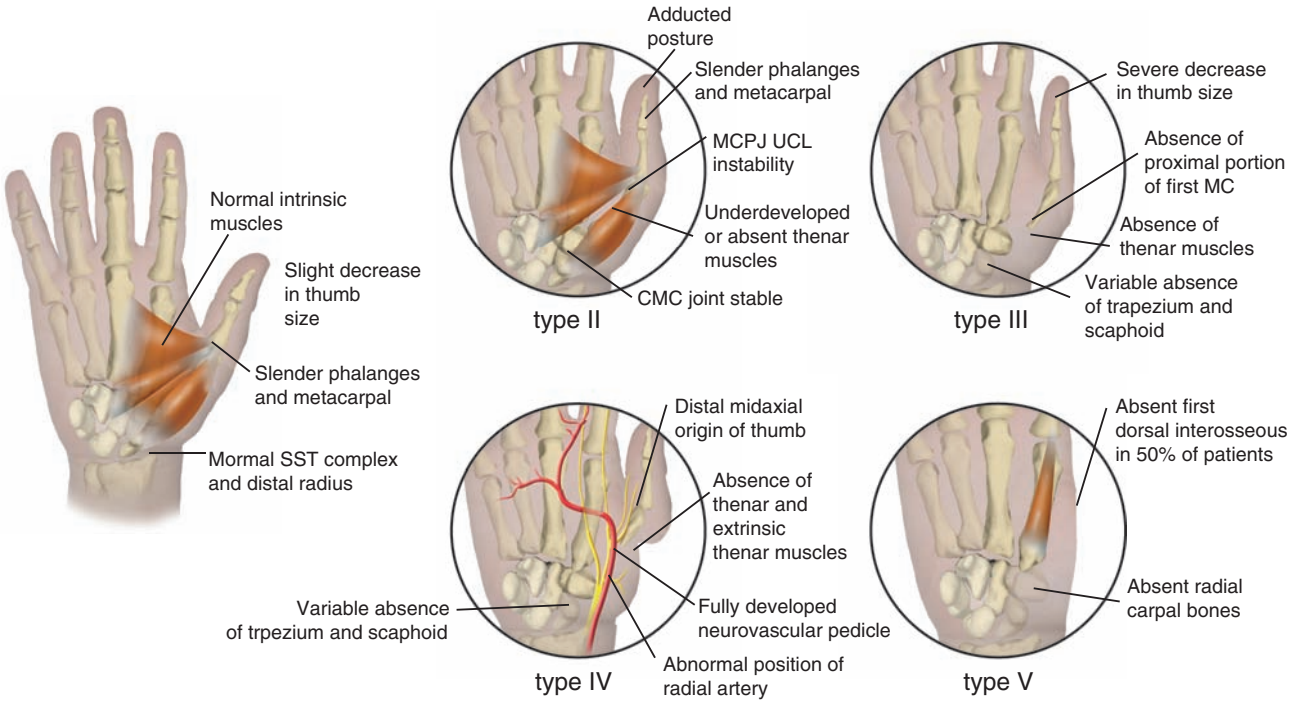


FIGURE 10-2 The modified Blauth classification.

MCP joint stability; type IIA thumbs have uniaxial instability, whereas type IIB thumbs demonstrate global MCP joint instability.[24] Furthermore, Manske and McCarroll subdivided type III thumbs into those with a stable carpometacarpal (CMC) joint (type IIIA) and those with unstable CMC joints (type IIIB).[25] While the difference between type IIIA and IIIB thumbs is readily apparent in texts and schematic diagrams, the clinical distinction is often more challenging, particularly in the young child in whom there is incomplete ossification of the skeletal structures.

Plain radiographs may assist in the diagnosis and guide appropriate classification, typically demonstrating hypoplastic thumb phalanges or metacarpal, often with a tapered or absent metacarpal base. Initial radiographic evaluation should include the wrist and forearm, given the high association with radial longitudinal dysplasia and radial carpal involvement.[26]

Given the common syndromic associations, genetic consultation with appropriate cardiac, renal, and hematologic testing are critical in the evaluation of any child with thumb hypoplasia. This includes chromosomal challenge (or chromosomal fragility) testing to rule out Fanconi anemia.[27] Furthermore, thorough evaluation of the spine and lower extremities should be done to identify associated VACTERRL or other conditions.

Surgical Indications

Given the importance of the thumb in all aspects of hand function, surgical reconstruction is recommended in all but type I thumb hypoplasia.[28–30] While the decision to proceed with surgery is easy for patients, families, and care providers alike, it is the type of operation to be performed that remains critical for success. In general, type II and IIIA thumbs are reconstructed, while type IIIB, IV, and V thumbs are treated with thumb ablation and index finger pollicization (see Chapter 11).

The principle of hypoplastic thumb reconstruction is simply to address each abnormal clinical element. The first web space should be deepened, the MCP joint stabilized, and opposition power restored. Little can generally be done to address size differences and thumb IP joint stiffness; for this reason, families should be counseled preoperatively that the thumb may remain smaller in appearance and stiff at the IP joint, even with successful surgical reconstruction.

First web-space deepening is typically achieved with two- or four-part Z-plasties. Alternatively, the Brand rotation flap can be utilized (Figure 10-3).[31] While pedicle or random pattern rotation or advancement flaps have been described, these are rarely needed.[32,33] Opponensplasties typically utilize either the abductor digiti quinti (ADQ) (Huber opponensplasty)[34–36] or the flexor digitorum superficialis (FDS) to the ring finger (see Coach's Corner).[37–40] In cases of uniaxial MCP joint instability (type IIA), the ulnar collateral ligament may be reconstructed with free tendon graft, excess FDS tendon from the opponensplasty, or local fascial tissue from the adductor pollicis. In global MCP instability, chondrodesis of the thumb metacarpal and proximal phalanx is performed and may provide the most reliable and functional outcome (Figure 10-4).[41]

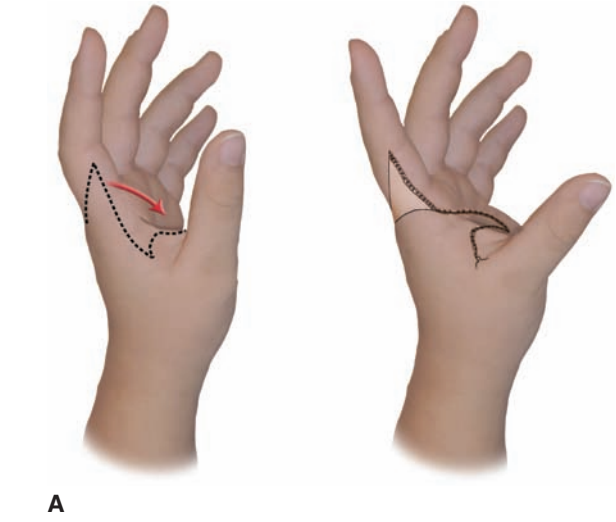


FIGURE 10-3 The Brand flap. **A:** Schematic diagram. **B:** Clinical photograph of incisions used in Brand rotation flap. **C:** Intraoperative appearance after rotation completed.

The optimal timing for surgery remains unclear. Surgery at or shortly before 12 months of age seems to be ideal, as the anatomic structures are large enough for easy surgical manipulation and fine motor development, and cortical representation of the thumb has not yet become ingrained.[42,43]

SURGICAL PROCEDURES

Reconstruction of the Type II Thumb (First Web-Space Z-Plasty, FDS Opponensplasty, and MCP Stabilization)

Under general anesthesia and tourniquet control, the limb is exsanguinated with an Esmarch bandage and tourniquet inflated to 250 mm Hg. Z-plasty incisions are created in the first web space with the dorsal limb along the dorsoulnar aspect of the thumb. Incisions are designed in this way to facilitate later exposure to the ulnar collateral ligament of the thumb MCP joint. Care is made to incise the dermis only, to avoid iatrogenic injury to the dominant vascular pedicle to the thumb. The vessels may be reliably protected by incising the dorsal and volar incisions first, followed by gentle spreading of the tenotomy scissors to elevate the adipocutaneous flaps. The scissors may

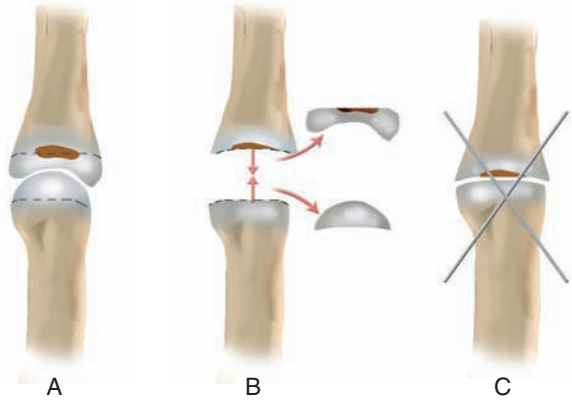


FIGURE 10-4 Schematic diagram depicting chondrodesis.

then be used to protect the underlying structures as the transverse incision is made in the web commissure. The first dorsal interosseous and adductor pollicis may then be easily identified. To maximize first web-space deepening, the fascia overlying the intrinsics is then released. If local tissue is to be used to stabilize the MCP joint, the proximal or distal origin of the fascia may be preserved to allow for subsequent ulnar collateral ligament reconstruction or reinforcement.

Following this, opponensplasty is performed (Figure 10-5).[44] An oblique or zigzag incision is created at the level of the distal palmar crease overlying the A1 pulley to the ring finger. Longitudinal spreading is performed and the flexor tendon sheath identified. The A1 pulley is incised and the FDS isolated. Proximal traction on the tendon will allow for visualization of the FDS decussation, which is transected proximal to its rejoining at Camper chiasm and insertion on the middle phalanx in efforts to avoid secondary hyperextension deformity. A second longitudinal incision is then created radial to the flexor carpi ulnaris (FCU) and proximal to the wrist flexion crease. The FCU and FDS tendons are identified, with care made to avoid injury to the ulnar neurovascular bundle. Once the FDS to the ring finger is identified, proximal traction will allow for delivery of the distal stump into the more proximal forearm wound. The oblique/zigzag incision at the base of the ring finger is then closed with interrupted absorbable 5-0 suture (Chromic, Ethicon, Inc.,

A

B

C

D

FIGURE 10-5 Surgical reconstruction of a type IIIA hypoplastic thumb using the FDS opponensplasty. **A:** Preoperative appearance of the hypoplastic thumb, illustrating thenar absence. **B:** Surgical incisions allowing for access to the FCU and FDS in the distal forearm, FDS to the ring finger, APB insertion over the radial aspect of the thumb MCP joint, and first web-space deepening via Z-plasty. **C:** The FDS to the ring finger has been harvested and withdrawn into the forearm wound, allowing closure of the ring finger wound. **D:** A pulley is created using a distally based strip of FCU tendon sewn to itself.

E

F

G

FIGURE 10-5 (*continued*) **E:** The FDS tendon is passed through the FCU pulley, and there is always adequate length for transfer and ligament stabilization. **F:** Using the radial incision over the thumb MCP joint, a subcutaneous tunnel may be created proximally and ulnarly to the distal forearm wound along the path of the anticipated transfer. **G:** The FDS tendon is brought into the radial thumb wound and sewn into the base of the proximal phalanx and APB insertion, completing the transfer. If ulnar collateral ligament reconstruction is needed for thumb stability, one slip of the FDS may be used for tendon transfer and the other slip passed to the ulnar side of the thumb for ligament reconstruction.

Somerville, NJ). The distal radial half of the FCU tendon is then incised longitudinally, with care being made to preserve its distal attachment to the pisiform. A transverse cut is made radially, creating a free limb of FCU. The proximal end of this limb is then sutured back to the pisiform or distal FCU using nonabsorbable braided polyester sutures (Ethibond, Ethicon, Inc., Somerville, NJ) creating a pulley. The FDS is then passed through the FCU pulley. A traction suture is then passed through the FDS stump in preparation for transfer.

An additional incision is created along the radial midaxial line or dorsoradially on the thumb centered on the MCP joint. The rudimentary insertion of the thenars, as well as the extensor apparatus of the thumb, is identified. With proximal extension and dissection, anatomic abnormalities such as the pollex abductus may be identified.[45] Using a blunt hemostat or Kelly clamp, a subcutaneous tunnel is then created connecting the distal forearm wound to the dorsoradial thumb wound; care is made to make the tunnel subcutaneous but superficial to the palmar aponeurosis. Using a hemostat passed from the thumb distally to the forearm proximally, the previously placed traction suture is then grasped and the FDS tendon passed through the subcutaneous tunnel. Adequate tendon length and tension-free excursion are then confirmed. The distal forearm wound may then be irrigated and closed with a running subcuticular or simple interrupted absorbable suture.

At this time, the thumb is fixed in an appropriate position of palmar abduction and extension with a percutaneous 0.028″ smooth stainless steel pin, entering the thumb tip and passing retrograde down the skeletal axis of the thumb, engaging the trapezium. With adequate tension on the flexor tendon, one slip of the FDS is then sewn into the radial or dorsoradial aspect of the thumb proximal phalanx and extensor mechanism in the anatomic site of abductor pollicis brevis (APB) insertion.[46] This typically requires trimming excess length of FDS tendon. Drill holes through the proximal phalanx, while previously described, are not utilized.

If ulnar collateral ligament reconstruction is desired, the slip of the FDS not previously utilized may then be

passed subcutaneously from the radial to ulnar thumb wound, superficial to the extensor mechanism.[47] The FDS slip may then be secured using 4-0 braided nonabsorbable polyester sutures (Ethibond, Ethicon, Inc., Somerville, NJ) to both the head of the metacarpal and base of the proximal phalanx, completing the collateral ligament reconstruction. The Z-plasty flaps are then rotated into position and closed with interrupted absorbable 5-0 sutures (Chromic, Ethicon, Inc., Somerville, NJ). Tourniquet is released and confirmation is made of vascularity to the thumb and skin flaps. A sterile bandage is applied, followed by a long-arm thumb spica cast.

◆ Reconstruction of the Type IIIA Thumb (First Web-Space Z-Plasty, Huber Opponensplasty, MCP Chondrodesis)

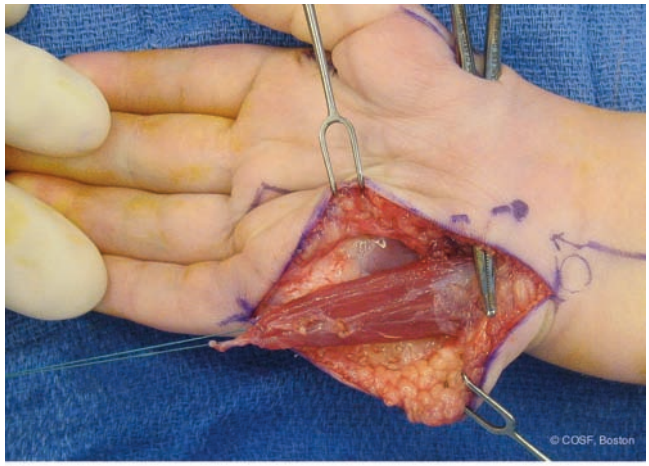
After adequate induction of general anesthesia, limb exsanguination, and tourniquet inflation, Z-plasty incisions are performed as described above. Following first

A

B

C

FIGURE 10-6 Surgical reconstruction of a type IIIA hypoplastic thumb using the Huber opponensplasty. **A, B:** Preoperative clinical appearance demonstrating the shortened thumb, narrow first web space, and absence of thenar musculature. **C:** Clinical incisions utilized for Huber opponensplasty.



D

E

FIGURE 10-6 (*continued*) **D:** Intraoperative photograph depicting the mobilized ADQ. Note is made of a strip of periosteum harvested with the distal tendinous portion of the ADQ, increasing length. A hemostat can be seen passing subcutaneously from the dorsoradial incision on the thumb to the base of the ADQ; this passage must be dilated to accommodate the girth of the muscle transfer. **E:** Final intraoperative appearance after transfer and wound closure.

web release, direction is turned to exposure of the ADQ (Figure 10-6).

A curvilinear incision is created beginning at the pisiform, following the hypothenar crease, joining the ulnar midaxial line of the small finger at the level of the distal palmar crease, and extending distally to the level of the proximal interphalangeal joint. Adipocutaneous flaps are carefully raised, identifying and protecting superficial sensory branches of the ulnar nerve, which are typically retracted with the radial skin flap. The hypothenar eminence is exposed, and the superficial ADQ identified. Distally, the insertion of the ADQ is elevated off the base of the proximal phalanx with a strip of distal periosteum; this step in ADQ harvest is critical, as often there is insufficient length of the ADQ tendon alone to allow for easy transfer. Once the tendinous insertion with its periosteal extension is elevated, the ADQ may be easily raised from distal to proximal all the way to the level of the pisiform. While Lister states that "it is necessary to liberate the abductor origin from the pisiform bone, retaining an attachment to the tendon of the flexor carpi ulnaris," dissection radial or proximal to the level of the pisiform is to be avoided, as this may result in inadvertent compromise of the neurovascular pedicle to the muscle![48]

After the ADQ has been elevated and its neurovascular pedicle preserved, a second incision over the dorsoradial aspect of the thumb MCP joint is made. The base of the proximal phalanx and extensor apparatus is identified. A subcutaneous tunnel is then bluntly created connecting the ulnar and thumb wounds with a hemostat or Kelly clamp. Given the girth of the ADQ muscle (in contrast to the narrow FDS tendon), it is important to spread and expand the subcutaneous passage to allow for easy passage of the donor muscle; failure to do so will result in insufficient length or inadequate excursion of the transfer.

In cases of global MCP joint instability, chondrodesis is then performed. Via the Z-plasty incision, an arthrotomy of the MCP joint is created, and the cartilaginous surfaces of the proximal phalanx and metacarpal exposed. Using a No. 67 Beaver blade, small rongeur, or narrow osteotomes, the articular cartilage and underlying subchondral bone are removed until the epiphysis is seen; meticulous technique is required at this stage, as often the small bony epiphysis appears only as a blush of pink beneath the surrounding cartilage. Failure to preserve the adjacent physeal cartilage will result in growth disturbance of an already hypoplastic thumb. Once the bleeding surfaces of the epiphyses have been exposed, the phalanx and metacarpal may be apposed and fixed using percutaneously placed smooth pins, typically 0.028″ or rarely 0.035″ in diameter, stabilizing the joint and holding the thumb in the desired position of abduction, extension, and radial deviation.

The end of the ADQ may then be passed from the ulnar wound to the thumb. Attention is made to rotate or "fold over… like the page of a book" the ADQ muscle belly as it is passed to prevent kinking of the neurovascular pedicle.[35] After adequate excursion is ascertained, the ulnar wound is irrigated and closed primarily with absorbable 5-0 sutures (Chromic, Ethicon, Inc., Somerville, NJ). The ADQ is then sewn into the dorsoradial periosteum of the thumb proximal phalanx, completing the tendon transfer. Thumb and Z-plasty incisions are then closed in the standard fashion. The prior pin(s) are cut and left outside the skin for later removal. Tourniquet is deflated,

and vascularity of the thumb confirmed. The limb is then immobilized in a long-arm thumb spica cast.

◆◆ Vascularized Joint Transfer

Thumb reconstruction for type IIIB hypoplasia has been performed using free microvascular metatarsophalangeal (MTP) joint transfers to reconstruct the deficient thumb CMC joint.[49–53] In these situations, the MTP joint from the second toe is taken with varying amounts of adjacent metatarsal and proximal phalangeal bone to recreate the base of the thumb. A dorsal elliptical skin paddle is created, centered on the second toe MTP joint, and the skin incision is extended proximally in a curvilinear or zigzag fashion. The vascular pedicle arising from the dorsalis pedis/first dorsal metatarsal artery and the saphenous vein and accompanying distal branches are meticulously isolated. There are numerous anatomic variations that may be encountered (see Chapters 9 and 46). Osteotomies are created at the desired level through both the second metatarsal and proximal phalanx, preserving the joint capsule and collateral ligaments. Tendinous stumps of the extensor digitorum longus (EDL) and extensor digitorum brevis (EDB) are taken with the joint for subsequent tendon transfers; the second toe flexors are typically left in situ after pulley release. The pedicle is then sacrificed and joint transferred to the hand. The donor site may be closed primarily or with the assistance of dorsal skin grafting.

The recipient site is exposed via a radial incision centered over the CMC joint as well as a dorsal incision, the latter of which will be used for exposure of the subsequent tendon transfers. The hypoplastic CMC joint is exposed, excising the rudimentary fibrous tissue and preparing the thumb metacarpal and radial carpus to receive the vascularized joint transfer. The MTP joint is then placed into the CMC region, and K-wire fixation is used to reapproximate the metatarsal to the radial carpus and the toe phalanx to the distal thumb metacarpal. Vascular anastomoses can then be performed to the radial artery—which is often absent in cases of thumb hypoplasia—or to the ulnar artery or second common digital artery with or without interpositional vein grafting. Tendon transfers may then be performed to obtain abduction, adduction, flexion, and extension power, dependent upon the availability of donor tendons. For example, the abductor pollicis longus may be transferred to the EDB, and the extensor indicis proprius may be transferred into the EDL. The need for subsequent staged opponensplasties or chondrodeses is common to restore adduction, opposition, and thumb stability.

While free vascularized MTP joint transfer has been successfully performed for type IIIB hypoplastic thumbs, we do not perform these procedures, due to their technical complexity, need for additional reconstructive procedures, and suboptimal results compared with index pollicization (see Sidebar).

SIDEBAR

What to Do for the Type IIIA or IV Hypoplastic Thumb When the Family Refuses Pollicization?

When in doubt, punt!
—John Heisman

Surgical options include phalangization, distraction lengthening, "on-top plasty," and toe-to-hand transfer.[24] *Phalangization* refers to soft tissue procedures in which the metacarpal is made more phalanx-like.[55] Prerequisites include adequate soft tissue envelope, a mobile CMC joint, and appropriate motors for the affected digit; in cases of thumb hypoplasia, the opposition power must be provided via tendon transfers. *Distraction lengthening* technically refers to increasing the (distal) soft tissue envelope about the thumb tip via gradual distraction techniques to allow for subsequent nonvascularized toe phalangeal transfer.[56] Despite the theoretical advantages and experience with nonvascularized toe phalangeal transfer in cases of symbrachydactyly and amniotic band syndrome, distraction lengthening has not proven to be a reliable strategy for thumb hypoplasia. Metacarpal lengthening via distraction osteogenesis may provide increased length but does not address the other characteristic features seen in thumb hypoplasia.[57] While the experience in dealing with posttraumatic loss of thumb length has proven beneficial, its applicability to congenital situations remains undefined. *On-top plasty* refers to transferring the distal portion of a lesser digit to the base of the thumb. This is not typically desirable in thumb hypoplasia, given that an imperfect thumb persists and a functional element of the hand is sacrificed. Finally, free vascularized toe-to-thumb transfers have been proposed in cases of hypoplastic thumb. Despite the theoretical appeal, toe transfers have been demonstrated in multiple studies to provide inferior clinical results compared with pollicization procedures.[58] Similarly, free vascularized toe joint transfers to provide CMC stability to a type IIIB thumb are also inferior to the well-performed pollicization.[49,50]

Given the limitations and disadvantages of these alternative treatment strategies, the question remains: What to do for the patient with a type IIIB thumb who refuses pollicization? Continued education through informed discussion in a mutually respectful fashion is the play to make. Often in these cases, referral for second or third opinion can be extremely helpful, as can introduction of the patient/family to other patients who have previously undergone pollicization procedures.

POSTOPERATIVE

The thumb is immobilized in a long-arm thumb spica cast for 4 weeks postoperatively. At that time, the pin is removed, and the patient is fitted with a forearm-based thumb spica orthosis, worn full time for an additional 2 weeks except for bathing, scar management, and gentle range-of-motion (ROM) exercises. Following this, ROM and strengthening are advanced as tolerated, and the splint is worn at nighttime until there is voluntary control of the opposition transfer and softening of the web-space scar.

ANTICIPATED RESULTS

With adherence to the above-stated principles and using meticulous surgical technique, excellent outcomes may be expected following reconstruction of the hypoplastic thumb. Stability of the MCP joint may be reliably achieved, opposition restored, and increased pinch/grip strength and thumb use attained.[7,45,54] While the ultimate power and size of the thumb may not be "normal," hand function is markedly improved with increasing stability and opposition strength.

COMPLICATIONS

What to do with a mistake—recognize it, admit it, learn from it, forget it.
—Dean Smith

Hypoplastic thumb reconstruction is among the most rewarding and most challenging procedures in pediatric hand surgery. While hand function can be markedly improved, a number of complications may be encountered. Some of these are due to inherent deficiencies in the thumb; others may be due to technical or strategic errors.

The first and most important decision is whether to reconstruct or pollicize the congenitally deficient thumb. While most agree that type IIIA thumbs may be reconstructed and type IIIB thumbs should be pollicized, often this distinction can be challenging. This is particularly true given the incomplete ossification of the developing carpus, as surgical treatment is often decided upon before the CMC joint can be truly assessed radiographically. While delays in treatment may offer greater insight, clinical observation may yield the best information. If a patient is not utilizing the thumb in any meaningful way—instead pinching and grasping between adducted index and long fingers—reconstruction may be unsuccessful; in this situation, the child (and thumb) has already determined that the thumb is not salvageable.

Even after appropriate reconstruction, there may be unexpected outcomes. Persistent MCP joint instability, despite attempts at ligament reconstruction, may occur, due to either inadequate ligament reconstruction or global laxity of the MCP joint. In these situations, secondary chondrodesis of the MCP joint may be required. Weak opposition may be seen after opponensplasty. In cases of Huber transfers, care must be made to avoid devitalizing the ADQ during the proximal dissection. Excessive dissection or release of the ADQ from its origin at the pisiform may compromise the neurovascular pedicle, resulting in suboptimal function of the transfer. Finally, persistent stiffness and inadequate flexion extension may be seen if a pollex abductus is unrecognized. Careful preoperative evaluation—as well as intraoperative inspection—is needed to detect this relatively common anatomic variant.

CASE OUTCOME

This patient was diagnosed with thumb hypoplasia. Upon further query, this was found to be associated with Holt-Oram syndrome. Additional genetics evaluation was pursued, and there was no evidence for Fanconi anemia or any other associated systemic conditions. Given the functional limitations, the patient underwent first web deepening, MCP joint chondrodesis, and Huber opponensplasty (Figure 10-6). Postoperatively, there was good MCP stability and active opposition function, allowing for thumb use.

SUMMARY

Thumb hypoplasia is characterized by small size, narrowed first web space, IP joint stiffness, MCP instability, and weakness or absence of the thenar muscles. Initial examination requires evaluation for associated syndromes, and genetics consultation is recommended in all cases. In patients with a thumb metacarpal base and stable CMC joint (type II-IIIA), surgical reconstruction in the form of web-space deepening, MCP stabilization, and opponensplasty may improve hand function. A host of surgical strategies are available, and the pediatric hand surgeon should be familiar with all operative techniques to ensure maximal functional benefit.

COACH'S CORNER

ADQ versus FDS for Opponensplasty

Fastball or changeup? Fullback dive or quarterback sneak? Slam dunk or layup? Sugar or plain? While we are confronted with seemingly simple choices, the decision between performing a Huber opponensplasty versus an FDS opponensplasty is dependent upon a number of patient and surgeon factors, with each option possessing theoretical advantages and disadvantages over the other.

Advantages of the Huber opponensplasty are several. First, an intrinsic muscle is used to restore intrinsic function,

(*Continued*)

and the ADQ is more similar in resting length and tension to the APB. Second, the hypothenar muscles are almost always present and available for transfer, even in cases of extensive radial longitudinal dysplasia. Third, the action of the ADQ is synergistic to that of the APB, and the young child can intuitively learn how to fire the transfer. In addition, little donor morbidity is noted after ADQ transfer. Finally, the bulk of the ADQ reconstitutes the contour of the deficient or absent thenar eminence, restoring more normal aesthetic appearance to the thumb.

Conversely, the FDS opponensplasty has several appealing characteristics. The FDS is strong and provides more than adequate power for thumb opposition, despite its vector of pull. The additional length provided by the FDS is quite useful for ligamentous reconstruction of the ulnar collateral ligament of the thumb MCP joint. Furthermore, there is little risk of injury to the neurovascular pedicle during harvest and preparation of the transfer.

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CHAPTER

11

Pollicization

CASE PRESENTATION

A 6-month-old female infant presents for a third opinion regarding treatment of a unilateral hypoplastic thumb. Of note, the child has a ventricular septal defect of the heart that is not hemodynamically compromising and that the cardiologist predicts will close on its own. The infant has undergone repair of a tracheoesophageal fistula and is gaining weight and height on oral feeds now. Her thumb has been nonfunctional so far. Radiographs reveal absence of the proximal thumb metacarpal. The index finger has full total passive and active range of motion (Figure 11-1).

CLINICAL QUESTIONS

- What systemic conditions are associated with a hypoplastic thumb?
- How are hypoplastic thumbs classified?
- Which thumbs are best treated with amputation and index finger pollicization?
- How does pollicization compare to microvascular reconstruction in a Blauth type IIIB thumb?

THE FUNDAMENTALS

Prehension distinguishes human hand function. Sophisticated pinch develops as children progress from rake grasp to rudimentary pinch to tip-to-tip pinch over the course of the first 1 to 2 years of life. Strong thumb intrinsic and extrinsic muscles, along with joint stability and mobility, are vital for normal pinch function.

A hand with a congenital thumb aplasia or a pouce flottant (floating thumb) (Figure 11-1) will be permanently devoid of tip-to-tip pinch function without operative intervention. A pollicization of the index finger is still the procedure of choice for these hands. However, the expected outcomes for a floating thumb with mild radial dysplasia and a near-normal index finger (Figure 11-2) are much better than a floating thumb with marked radial dysplasia and limited index finger function (Figure 11-3).

A hypoplastic thumb without a proximal metacarpal and carpometacarpal (CMC) joint (Blauth type IIIB) similarly will never develop prehension with that thumb without surgery. There are societal and surgical differences of opinion about whether the best treatment for function and appearance is (1) amputation of the hypoplastic thumb and index finger pollicization or (2) microvascular metatarsal-phalangeal joint transfer for CMC joint reconstruction with tendon transfers.[1–7]

Etiology and Epidemiology

The specifics are discussed in more detail in the thumb hypoplasia and radial longitudinal deficiency chapters (see Chapters 10 and 13). Suffice it to say, any thumb deficiency can be associated with malformations or deficiencies of other organ systems. In particular, vertebral, anal, cardiac, tracheoesophageal, renal, lower limb (VACTERRL), and hematopoietic abnormalities are common. Specific syndromes include Holt-Oram (autosomal dominant cardiac septal defects and radial deficiency), TAR (autosomal recessive thrombocytopenia absent radius), and Fanconi anemia (FA) (autosomal recessive bone marrow failure).

Clinical Evaluation

It is imperative that a thorough evaluation of the cardiac, renal, musculoskeletal, hematopoietic, and gastrointestinal organ systems occurs before care for the hand begins. Clearance of each system by physical exam and additional testing is done in conjunction with primary care pediatrics and multiple medical and surgical subspecialists. Of note, early diagnosis of a FA is one of the rare situations in which a hand surgeon can truly save a life (see Sidebar).

In terms of hand and arm evaluation, simply, the quality of the index finger determines the quality of the pollicization. The presence of index finger metacarpophalangeal (MCP), proximal interphalangeal (PIP), and distal interphalangeal (DIP) skin creases with easy, full passive motion of those joints is reassuring that the index finger is well developed (Figure 11-2). Thin, shiny skin

FIGURE 11-1 **A:** Clinical photograph of pouce flottant. **B:** Radiograph of same patient without proximal metacarpal, no CMC joint. This was treated with a pollicization.

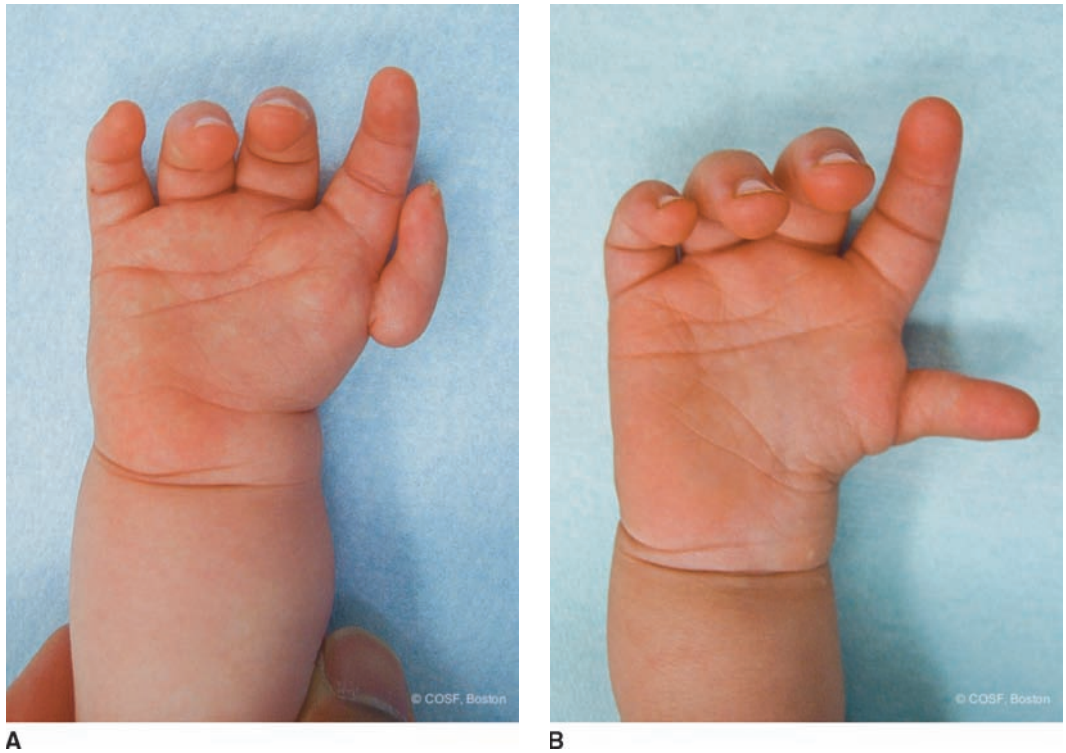


FIGURE 11-2 **A:** More defined type IIIB. **B:** This pouce flottant represents even more complex decision making for the parents of this child with another type IIIB. These thumbs make it very difficult for parents to accept amputation and pollicization rather than reconstruction.

SIDEBAR

Fanconi Testing and Bone Marrow Transplantation

FA is a rare, autosomal recessive genetic disorder (rarely X-linked recessive) with an incidence of about 1:350,000 live births. The incidence is much higher in the Ashkenazi Jewish population. The genetic deficiency is in core proteins (FANCA) responsible for DNA repair. Eight of these FANCA proteins assemble in the nucleus when DNA failure occurs. Failure of these proteins to effectively repair DNA accounts for the high risk of cancer, especially acute myelogenous leukemia, and/or progressive bone marrow failure in untreated patients with FA. These children can have associated congenital differences with hearing loss, short stature, and renal abnormalities, among others. At present, any infant, especially those without typical phenotypic features of FA, with radial longitudinal deficiency should have a chromosomal fragility challenge test (with mitomycin C or diepoxybutane [cross-linking agents]). Early identification of FA allows for HLA-type testing of family members looking for an identical match for hematopoietic stem cell transplantation. If no matches exist, genetic counseling can assist the family in deciding about a savior sibling with preimplantation genetic diagnosis. Early survival rate after identical HLA matching bone marrow transplantation can be as high as 90% and significantly exceeds transplantation from unrelated donors. Bone marrow stem cell transplantation has the best results in the first decade of life and before any bone marrow failure begins. Macrocytosis and nonmegaloblastic anemia occur at an average age of 7 years. Thus, early identification of FA and genetic counseling are critical to survival rates with bone marrow transplantation. The pediatric hand surgeon needs to be very knowledgeable about FA and well connected with skilled genetic counseling and care to help save or prolong a life.

without creases is a grave concern about future function (Figure 11-3). Similarly, the more radial deficiency, the less likely there is adequate musculature and joint mobility to provide desired pinch postoperatively. It is clear that outcomes from simple thumb aplasia without radial deficiency are far superior to pollicization in the presence of marked radial club hand. Therefore, a thorough clinical and radiographic assessment is critical in realistic planning and discussions with parents and families. They will not be able to discriminate their child's situation from others they have read about or discussed with other families. You can, and you must, in your exam of the child, engage parents in discussions and surgical decision making.

FIGURE 11-3 Severe radial longitudinal deficiency (type IV) with pouce flottant. Pollicization results will have a more limited outcome due to stiffness (note no skin creases at IP joints) and muscle limitations of index finger.

Surgical Indications

About the only thing that comes to us without effort is old age.
—Gloria Pitzer

The indications for pollicization include (1) absent thumb, (2) floating thumb, (3) hypoplastic thumb without a CMC joint, and (4) a well-developed, mobile index finger to become a high-quality thumb. Parental, social, religious, and personal considerations are major factors. Central nervous system integration is important, but, so far, no one has determined an IQ level required for pollicization.

SURGICAL PROCEDURES

A teacher is one who makes himself progressively unnecessary.
—Thomas Carruthers

Pollicization is an operation for the experienced and dedicated pediatric hand and upper limb surgeon. There are many different techniques of pollicization outlined in the peer review and textbook literature.[8–12] Mostly they differ on skin flap design and rotation. However, the underlying anatomic principles are the same. In order for an index finger to become a functional and cosmetic thumb, you

need (1) more skin for a first web space that is deeper and more mobile than the second web space; (2) less bone for a biphalangeal thumb rather than a triphalangeal index finger; (3) more thenar abduction and opposition power; (4) a new CMC joint in the proper orientation for tip prehension to the middle finger, the new index so to speak; and (5) survival of the pollex, all skin flaps, and adequate mobility and strength for functional use. You can use the flap design of your choice. You cannot violate the principles and be successful (see Figure 11-6).

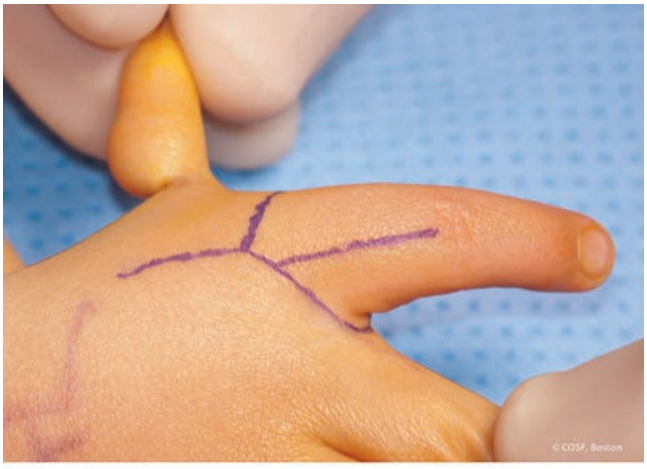
Specific unique anatomic features of a well-developed, mobile index finger that allow it to work as a pollex are (1) two extensor muscles and tendons, extensor indicis proprius (EIP) and extensor digitorum communis (EDC) that can be used to provide both extrinsic extensor and abductor function, (2) a strong first dorsal interosseous that can provide adequate thenar intrinsic muscle function, (3) a distal metacarpal epiphysis that can be converted into a thumb carpal bone, and (4) abundant dorsal skin that can be rotated into the first web space when the index metacarpal is excised.

Pollicization, like most operations, is a series of technical steps. Like many congenital hand operations, the flap design and incision outline with a marking pen is one of the most critical steps. As mentioned, there are many published and unpublished flap designs. We follow a series of modifications from the Buck-Gramcko pollicization technique that Lister modified and then Waters modified further (Figure 11-4).

The important part of the Lister modification was to extend the volar index finger incision out to the PIP joint level to ensure better first web-space inset. The Waters modification allows for better visualization of the CMC joint reconstruction through proximal extension of the dorsal incision over the metacarpal. The case outlined will follow those flaps (Figure 11-4A).

There is a difference between a pollicization with or without a pouce flottant (Figure 11-4B). Do not get seduced into making your volar curvilinear incision inclusive of your pouce flottant amputation. This will place your thumb in the plane of the digits and not in enough palmar abduction and opposition (Figure 11-4B).

After skin incisions, the next critical step is identification and preservation of the dorsal veins (Figure 11-5). Lack of venous outflow will result in venous congestion and potentially digital ischemia due to "no-reflow" phenomenon. To prevent this requires careful dissection as the dorsal flaps are elevated and mobilized.



A

B

C

FIGURE 11-4 **A:** Dorsal skin incision. **B, C:** Volar and radial skin incisions with floating thumb. **C:** Dorsal and radial skin incision without floating thumb.

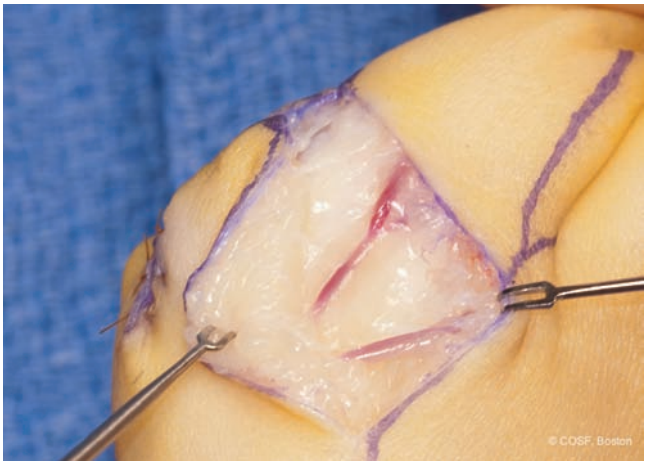


FIGURE 11-5 Venous outflow needs to be preserved with dorsal dissection of flaps.

Transverse venous connections to the long finger and dorsal ulnar hand are ligated while maintaining and mobilizing longitudinal venous outflow to the index finger. This allows for index finger transposition without kinking the veins.

Next, the volar flaps are elevated and mobilized while preserving arterial inflow and the radial and ulnar digital nerves to the index finger. The radial neurovascular pedicle can be hypoplastic or absent. You want to know this early on. If there is a pouce flottant, then the neurovascular bundle to the segment is identified and mobilized. Later a decision is made regarding ligation and amputation or utilizing part of the skin and soft tissues as a vascular flap.

In sequence, the flexor tendons are identified and the A1, A2, and A3 pulleys are released. This is in preparation for the A4 pulley to act as the oblique pulley of the thumb and the flexor digitorum profundus and flexor digitorum superficialis to become the equivalent of the flexor pollicis longus.

On the dorsal side, the EIP and the EDC are isolated. Hopefully both are present and robust enough to function independently as the extensor pollicis longus (EPL) (former EIP) and the abductor pollicis longus (former EDC II). The EDC is detached at the sagittal band insertion. The distal stump is secured to the EIP to prevent ulnar subluxation of the eventual EPL (Figure 11-6C). Absorbable suture is placed in the EDC, and it is mobilized to the base of the index finger metacarpal for eventual attachment to the new thumb metacarpal base (the former proximal phalanx).

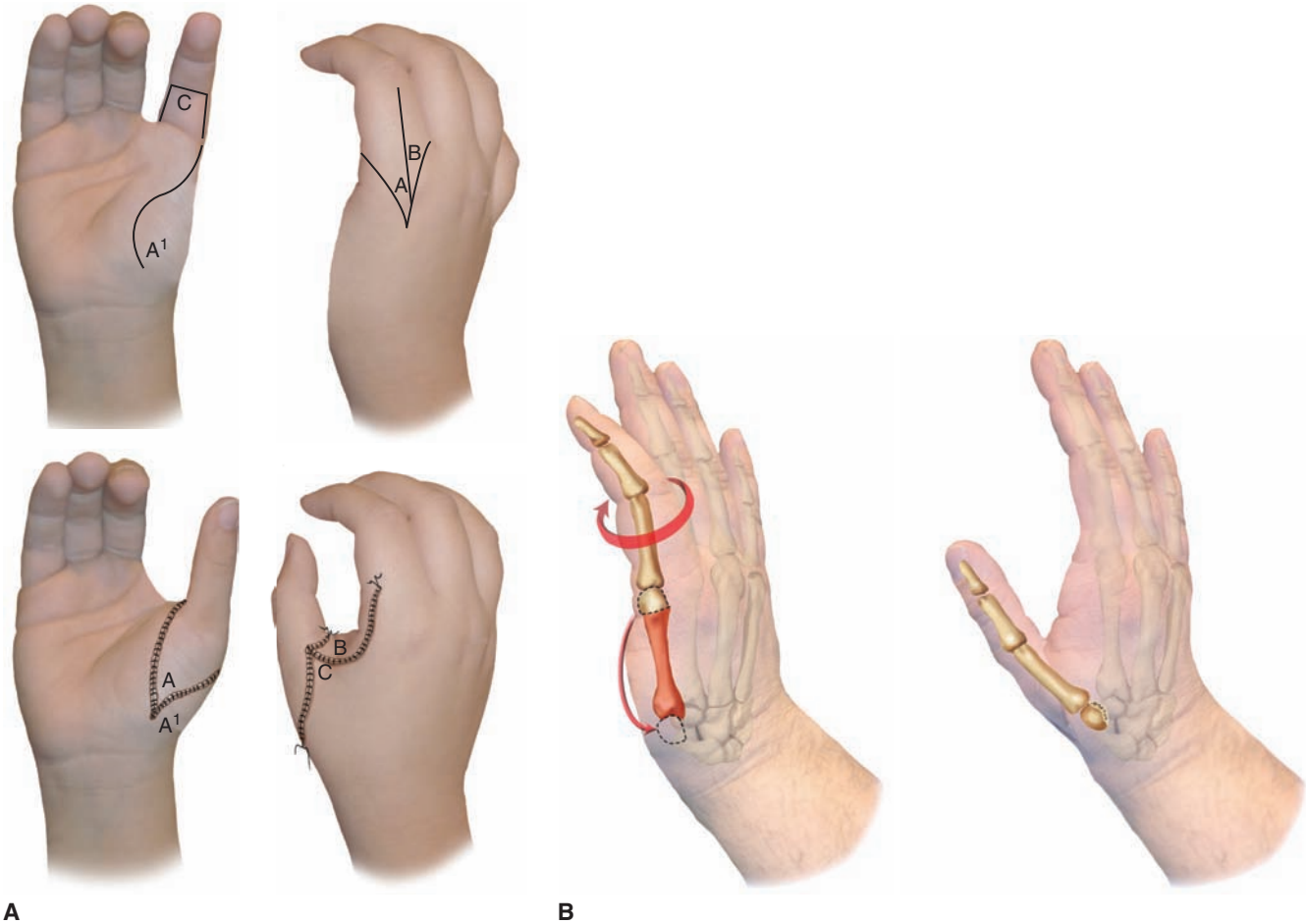
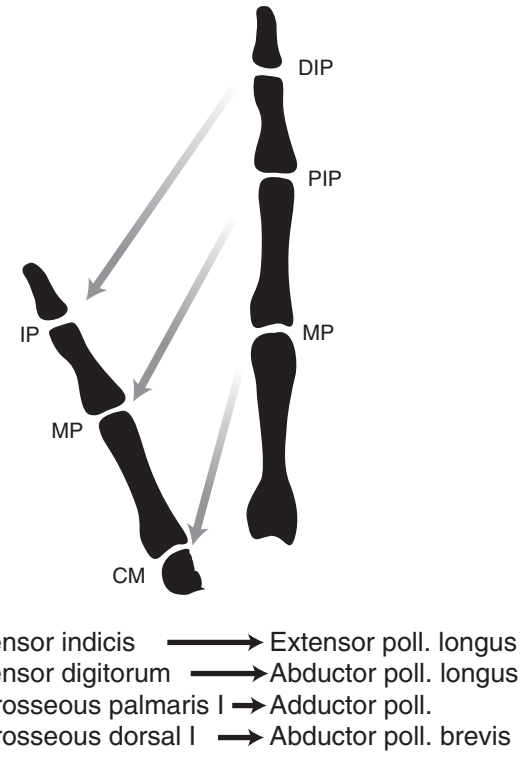


FIGURE 11-6 **A:** Illustration of Lister's modications of the classic Buck-Gramcko surgical incisions. **B:** Illustration of bony reduction from triphalangeal digit to biphalangeal thumb. Rotation of metacarpal epiphysis to become carpus.



C

FIGURE 11-6 *(continued)* **C:** Extension tendon realignment for thumb intrinsic and extrinsic function.

The second web space is carefully dissected to identify the bifurcation of the common digital neurovascular bundle into the index ulnar and long finger radial neurovascular bundles. The transverse metacarpal ligament is divided while protecting the bundles. The radial digital artery to the long finger is isolated and ligated. This is the point of no return. It is necessary for mobilization of the index finger to properly position the thumb in opposition. The epineurium of the radial middle and ulnar index digital nerves is separated into the palm, again for digital mobilization and transposition. Look out for an epineural ring[11] in which the digital artery passes through the nerve. This needs to be delicately opened without transecting the nerve or injuring this vessel. Otherwise it will kink the artery to the thumb in its new position.

The lateral bands, volar and dorsal intrinsic muscles, are isolated (Figure 11-7A). The lateral band is detached at the level of the MCP joint for both the volar and dorsal interosseous. This is a delicate dissection. The neurovascular bundles are volar and need protection. You have to always keep in mind preservation of the dorsal veins. Elevation of the intrinsics off the MCP joint without violating the tendon, collateral ligaments, or joint requires precise positioning of the Beaver blade. Distally the lateral bands are separated from the extensor mechanism to the level of the PIP joint on each side. This is in preparation for insertion of the new abductor and adductor at the level of the thumb MCP joint. Proximally the intrinsics, muscle belly, and distal tendon are mobilized while protecting their neurovascular pedicles (Figure 11-7A).

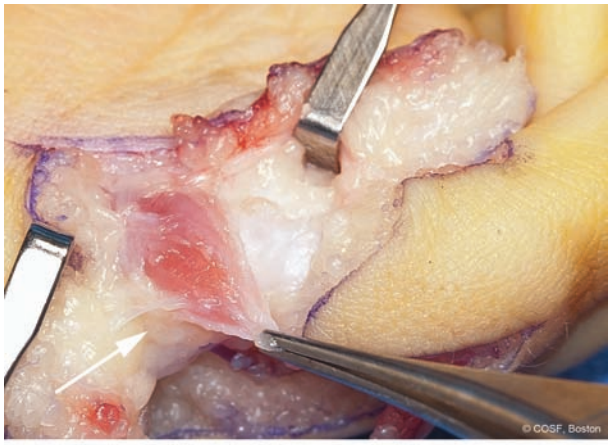
Now, you are nearing conversion of the index finger into a thumb. Resection of the metacarpal while retaining the distal epiphysis makes this possible. A longitudinal incision is placed in the index metacarpal from the base to the distal physis. Separation of the distal metaphysis and epiphysis is performed with sharp knife and elevator while protecting the volar neurovascular bundles and flexor tendons. The metacarpal is excised subperiosteally all the way to the base. The distal epiphysis is mobilized and rotated dorsally 90 degrees to prevent hyperextension of the new thumb CMC joint (Figure 11-7B).

The epiphysis is now the new thumb trapezium. The thumb is now ready for proper positioning and stabilization. As Riordan pointed out, the best position for the thumb CMC joint is volar to the middle finger metacarpal base. Dissection in that area clears a space for placement of the thumb carpus and metacarpal. Stabilization can be by peripheral sutures, a C-wire, or both. The delicate part is to get the rotation, angle and length correct. This is usually 100-120 degrees of opposition, 40-50 degrees of palmar abduction, and length just proximal to the middle finger PIP joint. All similar to a normal thumb. Once positioned and stabilized adequately, it is imperative to check that there is no kinking or compression of arterial inflow or venous outflow. Thumb muscle and tendon reconstruction is performed next. The former EDC, now APL, is attached to the radial aspect base of the metacarpal (the former proximal phalanx of the index finger). The first dorsal interosseous becomes the thenar intrinsics by attachment through the radial lateral band loop (Figure 11-7C) to the new proximal phalanx (the former middle phalanx) Similarly, the volar interosseous becomes the thumb adductor through the ulnar lateral band loop.

The thumb should now be dynamically balanced. Although many do, we do not foreshorten either the extensor or flexor tendons. We think the child's body will dynamically rebalance with better excursion than we will by our shortening and tendon repairs. This appears to have stood the test of time.

Flap rotation and skin closure is a great aid in setting the thumb in the correct position. We start with the placement of the most volar apex at the base of the thenars and secure that region. The first web space flap is then sutured down, including coverage of the volar proximal phalanx without tension (Figure 11-7D). Final closure is performed dorsally. We rotate extra skin and fat into the radial region to give the appearance of thenar bulk.

If present, amputation of the ponce flottant needs to occur before final decisions about flap rotation and closure. The simple floating thumbs can just be excised through a small elliptical incision. Coagulation of the digital artery and veins is performed with excision and then



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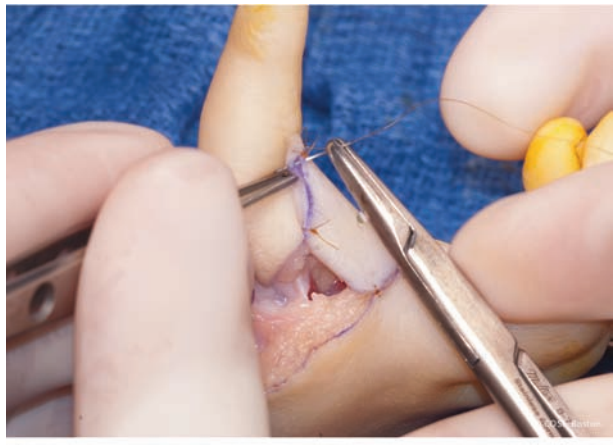

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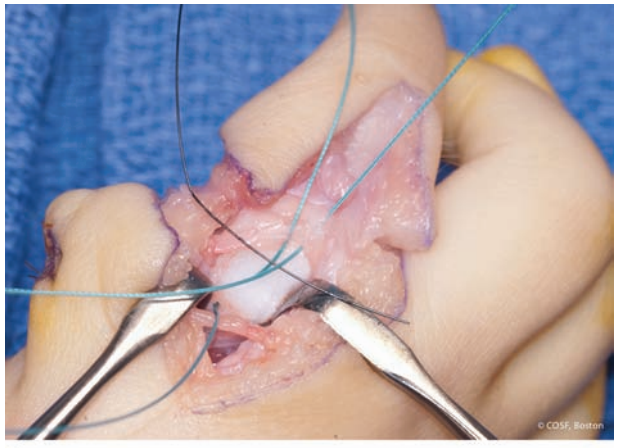

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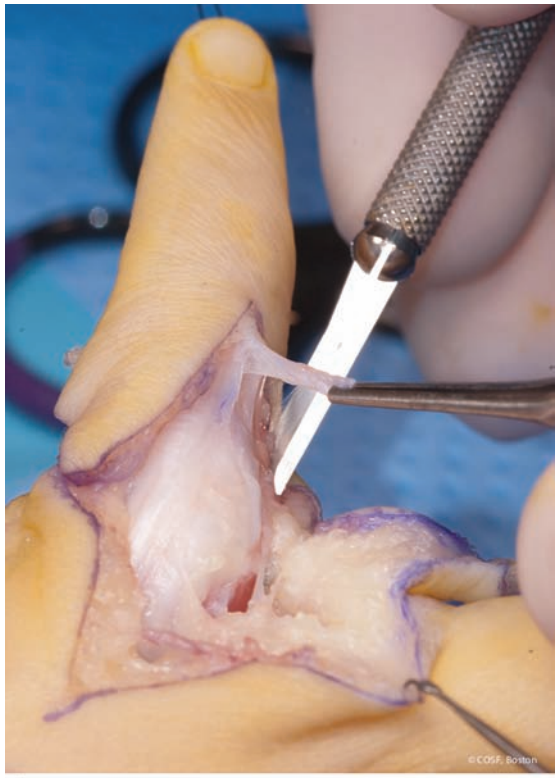

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F

FIGURE 11-7 **A:** Intraoperative photograph of mobilized first dorsal interosseous muscle for opposition reconstruction. **B:** After metacarpal resection, the epiphysis is rotated 90 degrees dorsally and secured to capsule with sutures. **C:** Lateral band elevation from extensor mechanism for loop insertion of new abductor and adductor pollex muscles. **D:** Suture repair of dorsal aspect of first web space flap **E:** In OR result after tourniquet deflation. Note pin placement. **F:** Different patient who required skin graft from amputated ponce flottant to avoid compression of vascular pedicle with flaps due to vascular malformation at base of long finger and in palm.

G

FIGURE 11-7 *(continued)* **G:** Long term result of pollicization.

the skin is closured directly. If there is a more developed floating thumb, the skin can be used a pedicle flap. This can improve bulk and appearance of the thumb if fat is included. Trimming of redundant skin is required to get the appearance right for the long term.

The tourniquet is released. There should, be instantaneous capillary refill (Figure 11-7E). Suture and flap adjustments are made if there are any issues. If necessary skin graft is applied to be certain there is a tension free closure without compromise (Figure 11-7F). The dressing is applied without any pressure on the flaps or digits. We obsess about this, checking and rechecking. A long arm thumb spica cast is applied while rechecking for vascular compression. Discharge to the recovery room occurs when the surgeon is completely assured all is well with inflow and outflow (Figure 11-7G).

POSTOPERATIVE

The long-arm cast and pin immobilization are continued for 4 weeks, with removal in the office. A long open splint is fabricated by the occupational therapist to maintain desired opposition, palmar abduction, and wide first web-space positioning. This is worn nearly full time except for bathing and therapy for 4 weeks and then nighttime for an additional 4 weeks. A web-space scar mold is often incorporated in the splinting. If there is an element of radial longitudinal deficiency, the splint is appropriately molded to correct for the wrist radial deviation and is worn longer for treatment of that part of the condition.

Passive motion is stressed right from the beginning of therapy. Long term, the best thumbs are the ones that achieve full IP, MCP, and CMC passive motion. Active motion will follow later.

ANTICIPATED RESULTS

The outcome is influenced by the initial quality of the index finger and the degree of radial longitudinal deficiency. Normal index fingers without much or any radial dysplasia will make excellent thumbs. Stiff, weak index fingers will make stiff, weak thumbs. In general, a pollicization will achieve 50% of the strength of a normal thumb.[8,13–18]

COMPLICATIONS

The most worrisome complication is loss of the index finger. We are almost afraid to write that we have never had this happen and jinx ourselves. You have to obsess every step of the way about your venous outflow; arterial inflow; and the design, rotation, and tension of your flaps. Do not compromise at all on this part of the surgery.

Limited motion and strength can be an issue. This can lead to disuse and bypassing the thumb for side-to-side pinch. In these situations, the small finger followed by the ring finger becomes the dominant digit. The weakness may improve with opponensplasty transfers, but the concern is weakening the best digit(s) of a limited functioning hand. Long-term motion loss may be due to web-space creep and will improve Z-plasty flaps, potentially with skin grafts. Ossification at the CMC joint from incomplete periosteal resection can also limit motion. Resection arthroplasty can help this. Finally, some of the pollicized thumbs can look dysvascular, which worsens with temperature and emotional changes. Parents need to be reassured that there will not be loss of the thumb due to lack of blood supply. However, except for waiting this out, we do not know how to make it go away.

CASE OUTCOME

Fortunately, this family was very accepting of the recommendation for an amputation of the type IV hypoplastic thumb and a pollicization. With cardiac anesthesia care, the patient underwent a pollicization at 9 months of age without complications. The postoperative therapy was aggressive, and she achieved full passive motion at the IP, MCP, and CMC joints by 4 months. Her active motion and strength improved over the next 6 months. She has an active, useful thumb, and the parents are pleased with their decision for a pollicization (Figure 11-8).

FIGURE 11-8 **A–D:** Clinical photographs of long-term pollicization with functional activities; opening door (**A**), preparing to catch basketball (**B**), holding ball (**C**), and doing gymnastics (**D**).

SUMMARY

Pollicization is a technically demanding operation that converts a functional index finger into a useful thumb. There are different flap designs, but all techniques are based on converting a triphalangeal digit into a biphalangeal thumb; excising the index metacarpal and converting the metacarpal epiphysis into a carpal base; utilizing the dual extrinsic extensors and intrinsics to reconstruct the thumb motors; and repositioning and deepening the new thumb-long finger web. Since people do not regularly count fingers, in Western cultures, it is accepted and often not noticed. The thumb usually achieves 50% or greater strength of a normal thumb.

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CHAPTER

12

Trigger Digits

CASE PRESENTATION

An 18-month-old child presents for evaluation of bilateral "thumb deformities" (Figure 12-1A). The patient's grandmother noticed "deformities" after examining the child's hand after a fall down stairs. Both thumbs have fixed interphalangeal (IP) joint flexion contractures; they are not spontaneously or manually reducible but are not painful or tender. Physical examination demonstrates a palpable nodule at the volar aspect of the metacarpophalangeal (MCP) joints and mild hyperextension laxity of the MCP. No treatment has yet been instituted.

CLINICAL QUESTIONS

- What is a "congenital trigger thumb"?
- Is it congenital? Hereditary? Acquired?
- What is the natural history of pediatric trigger thumbs?
- Is there a role for splinting, stretching, or occupational therapy?
- What are the surgical indications for trigger thumb release?
- How is pediatric trigger thumb release performed?
- What are the anticipated results and potential complications?
- Are trigger fingers similar to trigger thumbs?
- What are the indications for surgical release of trigger fingers?
- How is a trigger finger release performed? Does A1 pulley release suffice?
- What are the anticipated results and potential complications?

THE FUNDAMENTALS

First master the fundamentals.
—Larry Bird

Etiology and Epidemiology

The estimated prevalence of pediatric trigger thumbs is thought to be 3:1,000 live births at the age of 1 year.[1]

While the exact etiology is unknown, several studies evaluating thousands of newborns for the presence of trigger thumbs have clearly demonstrated that this condition is not present at birth.[2–5] Therefore, the term "congenital trigger thumb" is a misnomer and its use discouraged.

Triggering or locking is due to a size mismatch between the flexor pollicis longus (FPL) tendon and the tendon sheath, typically at the level of the first annular (A1) pulley. It has been speculated that the constant flexed position of the thumb IP joint during the pre- and postnatal periods results in collagenous degeneration, fibrosis, and synovial proliferation, leading to thickening of the FPL tendon and subsequent constriction.[6–8] Prior histopathologic studies have demonstrated no degenerative or inflammatory changes in the tendon or sheath; therefore, trigger thumbs are not likely due to an inflammatory, infectious, or degenerative process. To date, the true cause of pediatric trigger thumbs remains unknown.

Fingers are not thumbs, and triggering of the lesser digits should be considered an entirely different clinical entity, with its own set of clinical considerations and pitfalls. Trigger fingers are approximately 10 times less common than trigger thumbs. While the etiology is even less well understood, they are likely due to anatomic abnormalities of the flexor mechanism.[8–17] Most commonly, a proximal decussation of the flexor digitorum superficialis (FDS) slips or aberrantly distal lumbrical muscle origin leads to triggering as the digits move from flexion to extension. Nodular tendon thickening and intratendinous calcification or granulation tissue have also been described. Finally, deposition diseases such as the mucopolysaccharidoses are known to cause secondary triggering.

Children are not small adults. While the temptation can be great, adult rules should not be applied to the pediatric game. Inflammatory or overuse etiologies should not be implicated, nor should treatment modalities such as corticosteroid injections be utilized.

A

B

C

D

E

FIGURE 12-1 Surgical technique of trigger thumb release. **A:** Clinical photograph of a pediatric trigger thumb. **B:** Prior to surgical release, marks are made on either side of the palpable Notta nodule in the MCP flexion crease, marking the extent of the transverse skin incision. **C:** After spreading and retraction of the soft tissues and neurovascular bundles, the tendon sheath is exposed. **D:** The A1 pulley is incised. Note the IP joint hyperextension following pulley release. **E:** A bulky soft dressing is applied after wound closure.

Clinical Evaluation

Patients with *trigger thumbs* typically present during the first 18 months to 3 years of life with either triggering or a fixed flexion contracture of the IP joint. Often the abnormality is noted incidentally by family, teachers, or other medical care providers. There are times when it is recognized with some sort of trauma; then, it can be mistaken by parents, primary and emergency room physicians, and caregivers as an acute dislocation. They can be further mislead by a flexed posture on the lateral radiograph with unossified epiphysis of the distal phalanx; the sense of "joint reduction" with manipulation of the nodule distal to the first annular (A1) pulley; and frustration of almost immediate recurrent "dislocation" in their postreduction splint. When locked, the thumbs are not painful, nor do patients inhibit spontaneous use of the thumb and hand. When spontaneously or manually reducible, abrupt extension of the thumb IP joint may be

associated with transient pain, which may alert the family to the condition. One-third of patients will demonstrate bilateral thumb involvement, though this may be metachronous with variable severity.[18] Careful inspection and palpation will identify the Notta nodule within the FPL tendon, which will demonstrate excursion with passive IP joint motion. Often in long-standing cases, the MCP will demonstrate compensatory hyperextension laxity or instability, as the child attempts to open the first web space during cylindrical grasp. Nodules and triggering are not seen in the index through small fingers in the typical trigger thumb.

In *trigger fingers,* there too will be characteristic triggering or less commonly fixed flexion contractures, typically at the proximal interphalangeal (PIP) joint and associated with what feels like a Notta nodule (Figure 12-2). Both single and multiple digital involvements occur commonly, and bilateral hand involvement is not uncommon. Care should be made to identify associated medical conditions; in cases of associated mucopolysaccharidoses, evaluation for carpal tunnel syndrome and/or median neuropathy should be performed.[19]

Natural History

Say you were standing with one foot in the oven and one foot in an ice bucket. According to the percentage people, you should be perfectly comfortable.
—Bobby Bragan

Definitive statements about the natural history of pediatric *trigger thumbs* cannot be made. Most information comes from retrospective case series, with inherent biases and inadvertent interventions in the course of "clinical observation." The "spontaneous resolution" rate has been reported to be 0% to 66% of cases.[5,20–22]

FIGURE 12-2 Clinical photograph of a pediatric trigger digit of the long finger. Note the increased flexion posture with tenodesis and in the resting position. There is a trigger thumb present as well.

In what is often considered a classic paper on the subject, Dinham and Meggitt published a retrospective case series of 131 thumbs in 105 patients. In this investigation, 30% of patients presenting soon after birth demonstrated spontaneous resolution, whereas only 12% spontaneous resolution was seen when patients were observed or presented after 6 months of symptoms.

More recently, Baek et al.[23] reported on 71 thumbs in 53 patients, and 63% achieved full IP joint extension at a mean age of 5 years. It should be noted, however, that mean flexion contracture was 26 degrees at presentation, and no information was provided regarding the indications or number of patients undergoing surgical release during the study period. Furthermore, while a majority of patients attained full extension, given the ability for young children to hyperextend the IP joint, it is unclear whether full extension can be equated to spontaneous resolution. Similarly, there was no information about the degree of thumb flexion; unresolved trigger thumbs can present with an extension contracture rather than flexion contracture as expected.

Limited information also exists regarding the role of splinting or formal therapy and stretching on the natural history of the symptomatic pediatric trigger thumb. While some reports have cited "success" or "satisfactory results," many of these patients had abnormal final motion, and questions of compliance and duration with splinting therapy remain.[24–26]

Even less is known about the natural history of pediatric *trigger fingers*. Indeed, the natural history may never be truly established given the infrequency with which these occur and the heterogeneity of etiology and clinical presentation. While anecdotal reports exist of improvements with observation, stretching, or nighttime extension splinting, most of the smaller retrospective case series suggest that surgical treatment is required to eliminate the triggering.

Surgical Indications

Surgical indications for trigger thumb release continue to evolve, particularly given changing information regarding natural history. At present, we recommend surgical release for fixed flexion contractures or symptomatic and functionally limiting triggering in patients >18 months of age. We usually wait up to 6 to 12 months in the new presenting trigger thumb if the parents desire extended observation. We always closely examine the contralateral thumb and perform simultaneous bilateral releases if indicated (see Sidebar).

For patients with trigger fingers, surgical release is recommended after 6 months of failed observation and/or nighttime splinting or if the digit is locked. We obtain a preoperative x-ray of the trigger digit(s) to check for calcific tendonitis.

SIDEBAR

The Argument for Early Surgery

I watched the Indy 500, and I was thinking that if they left earlier they wouldn't have to go so fast.
—Steven Wright

Despite published information that many cases of trigger thumbs may spontaneously resolve over time, a number of disadvantages of observation bear notice. First, in the most recent prospective evaluation on the natural history of pediatric trigger thumbs, spontaneous resolution (as defined as full extension of the IP joint) occurred over 4 years. Therefore, if observation is chosen, patients/families should be aware of the long duration prior to expected resolution. Second, during the time that IP joint flexion contractures persist, compensatory hyperextension laxity of the MCP joint may secondarily develop due to the patient's efforts to increase the first web space in cylindrical grasp. This MCP laxity may not completely resolve after A1 pulley release.[31] Third, these patients may just exchange a flexion contracture for an extension contracture at the IP joint.

While there are a number of potential disadvantages to extended observation, there is relatively little downside to earlier operative release. The procedure is simple, straightforward, and associated with near universal success. Patients and families will see immediate improvements in IP joint motion and thumb use, leading to high patient satisfaction. Finally, secondary soft tissue or bony abnormalities may be avoided. For these reasons, compelling arguments can be made for earlier surgical release.

SURGICAL PROCEDURES

A1 Pulley Release for Pediatric Trigger Thumb

A hot dog at the ballgame beats roast beef at the Ritz.
—Humphrey Bogart

Trigger thumb release is performed in the operating room under general mask anesthesia. Esmarch bandage is utilized to exsanguinate the limb, and the bandage is wrapped around the proximal forearm or distal humerus three times to provide tourniquet control. The Notta nodule is palpated and marked with a marking pen at the level of the MCP flexion crease. Additional marks are made on either side of the nodule, defining the extent of the surgical incision (Figure 12-1). A transverse incision is then made through the dermis only in line with the MCP flexion crease. Great care is made to avoid incising too deeply during the skin incision, as the radial digital nerve and artery lie immediately below the skin and are at risk for iatrogenic injury. Longitudinal spreading is performed on either side of the flexor tendon sheath, allowing the adjacent neurovascular structures to fall away and exposing the tendon sheath. Under direct visualization, the A1 pulley is then incised longitudinally. Its attachment to the periosteum and origin of the oblique pulley is released.[27] The proximal flexor tendon sheath is released with spreading only to avoid injury to the crossing radial neurovascular bundle. The tendon is examined for abnormalities beyond the nodule by lifting it out of the wound with a retractor. If a cyst is present, it is excised. The nodule, however, is allowed to reabsorb on its own. Full passive stretching of the IP joint is performed, including the contracted volar plate. This resolves the trigger and IP joint contracture.

Although cast immobilization is not required, a durable, sterile bandage that will provide adequate wound coverage is needed. This may be reliably accomplished with the use of multiple layers of bandage material. A circular gauze covered by an ace bandage and stockinette is our bandage of choice; care is made to secure with adhesive tape all free edges that might allow the patient to remove the dressing. While Coban (3M, St. Paul, MN) may similarly accomplish these goals, caution is recommended when applying tight elastic bandages to any digit under anesthesia, particularly in the very young or nonverbal child.

Trigger Finger Release

Baseball is the only field of endeavor where a man can succeed three times out of ten and be considered a good performer.
—Ted Williams

Release of the A1 pulley is not sufficient in the treatment of pediatric trigger fingers. In up to 44% of cases, isolated A1 pulley release will result in persistent triggering.[28] For this reason, a number of expanded surgical strategies have been proposed, including incision of the A3 and part of the A2 pulley as well as widening of the FDS decussation.[29]

Trigger finger release is performed under general anesthesia (Figure 12-3). Because more extensive release may need to be performed, an extensile zigzag Bruner incision is made. With retraction and protection of the adjacent neurovascular bundles, the A1 pulley is incised. Intraoperative proximal traction on the flexor tendons proximal to the A1 pulley allows for visualization of a proximal decussation of the FDS or a hypoplastic slip of the FDS tendon. A single slip of the FDS is then excised, taking care not to leave a prominent oblique stump that might lead to subsequent triggering. If a hypoplastic slip is identified, it is the one excised; if both are normal in appearance, the ulnar slip is excised. The digit is passively flexed and extended, and the flexor tendons are pulled proximally to confirm no residual triggering exists. Simple wound closure is then performed. The digit/hand is immobilized similar to trigger thumbs until the surgical wound heals, followed by early range of motion.

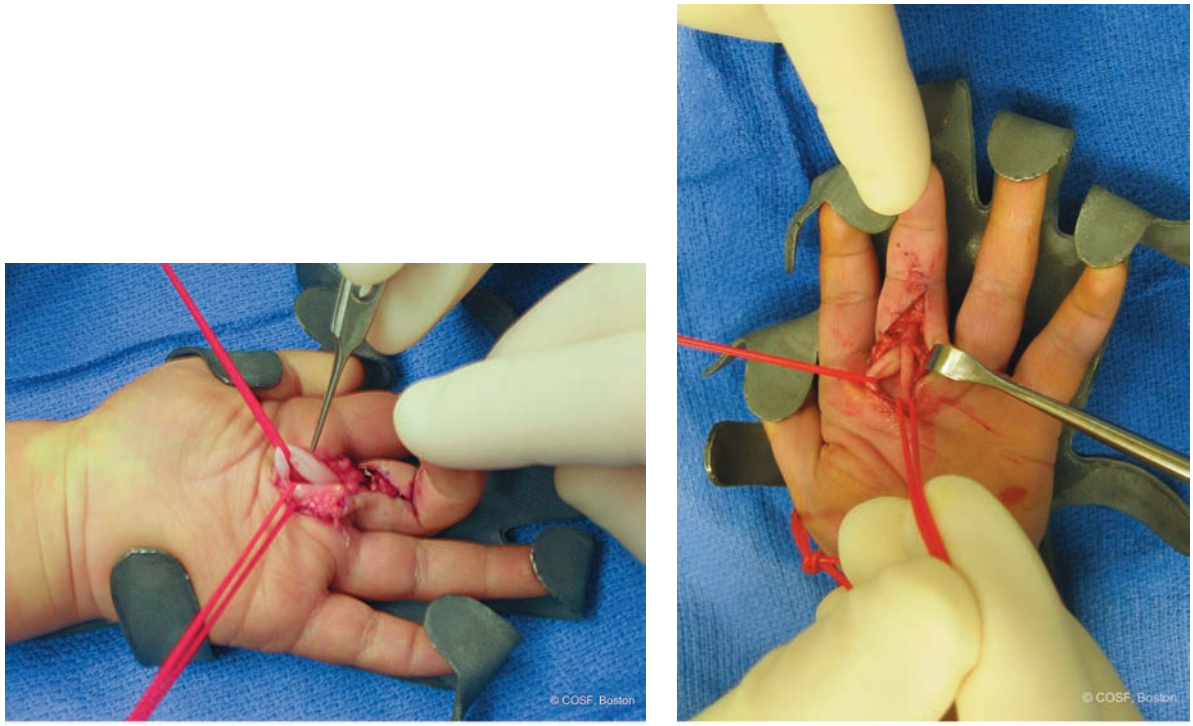

FIGURE 12-3 Surgical technique of trigger digit release. **A:** After extensile Bruner zigzag incisions, nodularity in the FDP tendon is seen adjacent to the FDS decussation. **B:** Triggering is resolved after excision of a single slip of the FDS.

◆ Multiple Releases for Mucopolysaccharidoses

Release of multiple trigger digits follows the same principles and surgical techniques as the single trigger finger with a few additional considerations.[19]

First, surgical incisions must be designed to allow for extensile exposure of the digits while creating vascularized skin flaps that will not lead to subsequent scar contractures. In addition, these incisions must allow for a concomitant carpal tunnel release, as is often seen in cases of Hurler and Hunter syndromes. Often this can be performed with an oblique incision in the distal palmar crease that extends from small to index finger. Furthermore, these children are almost always undergoing a simultaneous carpal tunnel release. We utilize a curvilinear palmar incision and perform a Z-plasty lengthening repair of the transverse carpal ligament after release.

In addition to the surgical incisions, often debridement of the tenosynovial deposits must be performed to allow for unrestricted gliding of the flexor apparatus. Judicious and meticulous technique is needed to avoid compromising tendon function.

Finally, realistic expectations must be conveyed to patients/families regarding the results of surgical release. While in early stages in younger patients, trigger releases may result in near-normal digital extension, older patients will demonstrate bony changes—including flattening of the articular surfaces of the PIP joint—that will result in persistent IP joint stiffness despite adequate soft tissue releases. This demonstrates yet another example of the pediatric orthopaedic principle is that soft tissue procedures alone will not correct established bony abnormalities.

POSTOPERATIVE

In trigger thumbs, the bulky soft dressing is removed 1 to 2 weeks after surgery, followed by advancement of thumb use as tolerated. No formal therapy is recommended, nor is any follow-up clinical evaluation necessary. We advise parents that if their child is not back to normal by 3 weeks postoperative, they should return for evaluation. They almost never do.

In trigger fingers, dressings are removed and digital motion allowed at 2 weeks postoperatively. Therapy may be considered for scar management and/or range-of-motion exercises, though this is again rarely necessary in simple trigger digits. However, with mucopolysaccharidosis releases, it is always necessary.

ANTICIPATED RESULTS

Recurrent triggering following trigger thumb release is so rare as to be case reportable, and recurrence is not an expected complication from surgical care.[30] While published reports have highlighted the potential for IP joint motion loss, MCP hyperextension laxity, and/or scar-related complications, adherence to the surgical principles and techniques here will result in excellent long-term outcomes.[9,31]

When trigger fingers are addressed with A1 pulley release and resection of a single slip of the FDS tendon, restoration of digital motion without recurrence may be expected in >95% of cases.[32]

CASE OUTCOME

This patient was diagnosed with bilateral trigger thumbs. After discussion with the family about the natural history and potential treatment options, decision was made to proceed with surgical release. Under general mask anesthesia, bilateral A1 pulley releases were performed with resolution of the IP joint contracture (Figure 12-1). There was full return of passive and active IP joint motion postoperatively, with no recurrence. Aesthetically, the family was quite pleased with the appearance of the thumbs, and the surgical scars were hardly visible within the MCP flexion crease.

SUMMARY

Trigger digits are common in the pediatric patient. While unlocked trigger thumbs may occasionally resolve spontaneously, surgical release is safe, efficacious, and carries little risk of recurrence. It is recommended for locked trigger thumbs shortly after presentation and for failure of reducible trigger thumbs to resolve with time. The less common trigger finger requires more extensile surgical exposure and aggressive release including release of one of the FDS tendon slips. Patients and families should be counseled regarding the small but real risk of recurrence. Mucopolysaccharidoses patients will have multiple trigger digits, and early carpal tunnel and trigger digit releases with FDS slip resections may prevent long-term weakness.

COACH'S CORNER

Trick Plays in Trigger Thumbs

A couple of technical tips may assist in winning at the game of trigger thumbs. First, transverse incisions through the flexion crease of the MCP joint should be utilized; zigzag or linear incisions are not used due to their inferior aesthetics and risk for scar contractures. Second, as in adults, the radial neurovascular bundle lies immediately beneath the dermis at the site of the skin incision. Delicate incision and dissection must be performed to avoid injury to the radial neurovascular bundle on the radial sesamoid "chopping block." Finally, in long-standing cases of IP joint flexion contractures, after A1 pulley release there may still be a tendency for the IP joint to posture in a flexed position. In these situations, passive hyperextension stretching of the IP joint may help release joint contracture and volar plate tightness.

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CHAPTER

13

Radial Longitudinal Deficiency

CASE PRESENTATION

A 3-month-old female infant presents with bilateral radial longitudinal deficiency (Figure 13-1). She has absent thumbs with a simple skin tag on the left and complete aplasia on the right. Both upper limbs are foreshortened, the left more so than the right. There are no associated malformations. Her father has less severe bilateral wrist and thumb involvement, treated surgically as a preschool and adolescent child.

CLINICAL QUESTIONS

- What is the incidence of radial longitudinal deficiency?
- What syndromes and malformations are associated with radial deficiency?
- How is radial deficiency classified?
- What is the initial treatment?
- What are the surgical options?
- How does one choose the appropriate treatment for the patient?
- What are the long-term results?

THE FUNDAMENTALS

A stable wrist is necessary for power grip. Normal digital motion and strength are necessary for sophisticated pinch function. Normal elbow motion is necessary for full hand-to-mouth and hand-to-groin activities. Normal limb length allows for full placement of the hand in space. Children with severe radial deficiency are lacking in all these areas. If bilateral, activities of daily living are compromised and require marked adaptive behavior. As Flatt pointed out, "Radial club hand … is a profoundly abnormal hand joined to a poor limb by a bad wrist."[1]

When you add in the significant aesthetic differences from unaffected limbs and hands, severe radial deficiency tests the resiliency of the human mind and spirit.

Etiology and Epidemiology

Also known as radial club hand or radial dysplasia, radial longitudinal deficiency occurs in approximately 1:30,000 live births.[2] It is associated with many other malformations as the timing of in utero preaxial upper limb development coincides with cardiac, hematopoietic, musculoskeletal, renal, gastrointestinal, and craniofacial, among others, organ system development.

These associated conditions include VACTERRL (V = vertebral, A = anal atresis, C = cardiac, TE = tracheoesophageal fistula, R = renal, radial, L = limb), Fanconi anemia, thrombocytopenia absent radius (TAR), chromosomal abnormalities (trisomy 13, 18), and craniofacial syndromes such as Nager acrofacial dysostosis. Some of these conditions are genetic. Fanconi anemia (1:350,000 live births, but genetic carriers may be 1:600) and TAR (1:240,000 live births) are autosomal recessive, and Holt-Oram (cardiac septal defects and radial deficiency) is autosomal dominant. Mutations in the TBX5 gene have been identified as the causal factor for Holt-Oram syndrome. Most are sporadic including all the VACTERRL-syndrome children.

Clinical Evaluation

Any infant with a radial longitudinal deficiency needs a thorough physical exam, laboratory screening, and radiologic evaluation. Subspecialty consultation with genetics, cardiology, orthopaedics, hematology, general surgery, and craniofacial surgery may be necessary. There are now times where the diagnosis is made during pregnancy[3] (Figure 13-2), and initial consultations occur prenatally rather than in the neonate. A thorough physical exam in the nursery is performed looking for a cardiac murmur, obvious scoliosis, lower limb deficiencies, and breathing or feeding issues indicative of a tracheoesophageal fistula. A complete blood count to assess for thrombocytopenia or pancytopenia is obtained. With TAR, the platelet count is at its lowest in the neonate, usually <100,000 (normal range 150,000 to 300,000) at birth, and improves over the first year of life. The risk for these children is hemorrhage. Fanconi anemia and pancytopenia usually do not present

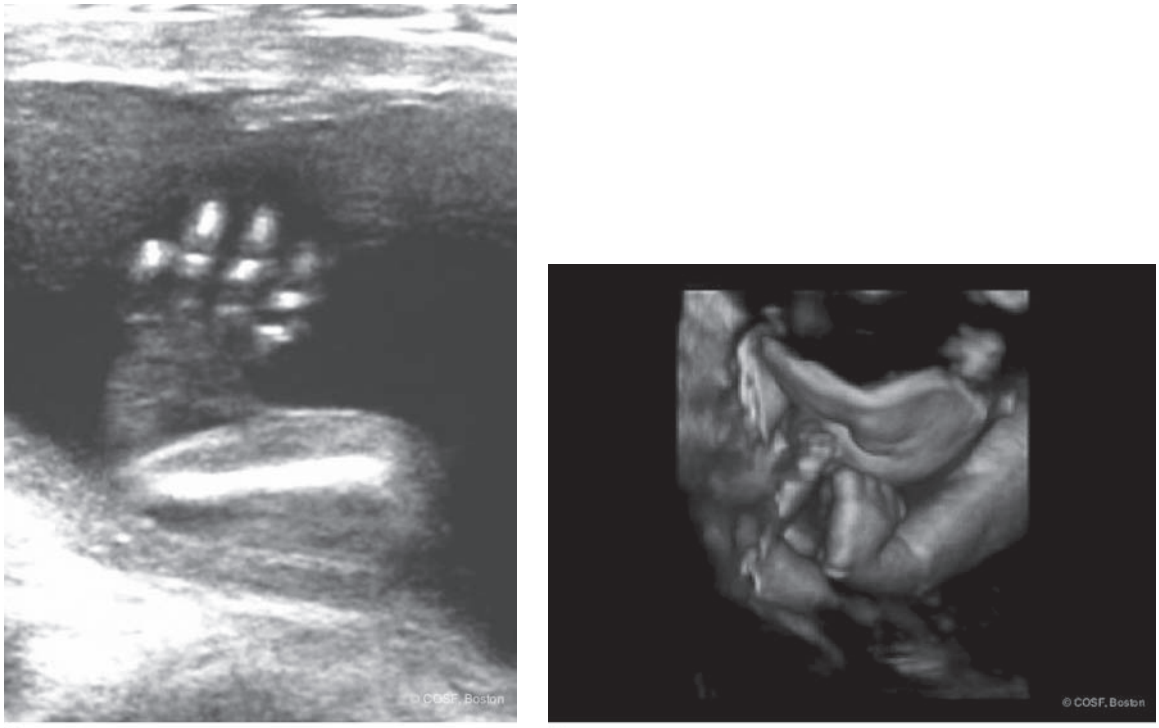
FIGURE 13-1 Clinical photograph of radial longitudinal deficiency with a rudimentary pouce flottant.

until preschool or school age. Therefore specific testing for chromosomal fragility and breakage needs to occur in infancy. The testing is done with either diepoxybutane or mitomycin C. These tests can also be performed prenatally with chorionic villi or amniotic fluid cells. Fanconi anemia is a potentially lethal disease if recognized late and may be curable with bone marrow transplantation if performed early before pancytopenia, myelodysplasia, or acute myelogenous leukemia develops. This is one of the few situations where a pediatric hand surgeon can save a life with proper referral and testing. Renal and cardiac ultrasounds are generally performed for identifying malformations. A chest x-ray as a part of cardiac workup will also provide a screening test for congenital scoliosis or other vertebral abnormalities.

Evaluation of the radial deficiency starts at the chest wall and shoulder. Entire upper limb involvement does occur with both obvious and subtle differences.

Phocomelia with preaxial deficiency is the most involved case. Elbow range of motion is critical to treatment decisions. In the presence of a stiff extended elbow, extreme wrist radial deviation functionally substitutes for elbow flexion. In the absence of at least 90 degrees of elbow flexion, definitive correction of the wrist deformity is contraindicated.

The obvious deficiencies are in the wrist and hand. This condition can have profound limitations of (1) forearm length, (2) wrist stability and motion, (3) thumb development and function, and (4) digital motion and strength. Anatomic variations abound, and the degree of soft tissue anatomic abnormalities tends to parallel the degree of osseous deficiency. Muscle deficiencies throughout the entire upper limb, but in particular in the forearm, wrist, and hand, include partial or complete absence, hypoplasia, abnormal origins and/or insertions, and/or fusion to adjacent muscles and accessory muscles. Brachial plexus, radial, ulnar, and median nerve anomalies have been well described.[4] The median nerve is usually present



A B

FIGURE 13-2 **A:** Prenatal ultrasound of severe radial longitudinal deficiency. **B:** A 3-D ultrasound of same patient. Clinical photograph of same patient shortly after birth is seen in Figure 13-1.

but with aberrant anatomic course through the forearm and wrist. Vascular anomalies also are frequently present, and, again, the more deficient the radius, the more likely an abnormal radial artery and palmar arch.[5] The spectrum of thumb deficiency ranges from mild hypoplasia to complete absence (Blauth classification). Digital involvement spreads from the radial side to the middle of the hand depending on the degree of preaxial osseous and muscle deficiency. Digital lack of motion is common and greatly affects function. The ulnar digits tend to have more developed joints, as well as intrinsic and extrinsic muscles, than the middle or radial side of the hand. Ulnar prehension is common. Very few of the more involved children can perform power grip and normal pinch activities. Spherical grip is most often used for functional grasp. The hand tends to be assistive rather than independent. Since 50% to 60% have bilateral involvement, this can be debilitating.

Osseous classification is by the amount of preaxial deficiency. Bayne and Klug classified this by types I through IV, from a minor deficiency in length to complete absence (I = short distal radius, II = hypoplastic radius, III = partial absence radius, IV = complete absence radius). James et al. added type O for radial carpal and thumb deficiency with a normal radius. We use a type V for elbow involvement and phocomelia. Unfortunately, type IV is the most common type, meaning those with this deformity have a lot of involvement. The osseous classification can be misleading because it focuses only on the radius and precludes thinking of the ulna, muscle, and soft tissue involvement. In types III and IV, the ulna is always foreshortened (at best 60% of normal length) and frequently bowed. The osseous classification can lead us to think simplistically. "If I only straighten the forearm, wrist, and hand, all will be well," forgetting the profound degree of muscle and soft tissue impairment.

Treatment

Experience is that marvelous thing that enables you to recognize a mistake when you make it again.
—Franklin P. Jones

In all of congenital hand surgery care, at the present time there may be no greater variation and polarity of opinion than care of the severe radial club hand. A generation back, it appeared to be quite straightforward. Stretch the soft tissues with splints and/or casts early in infancy, surgically place the hand on the end of the ulna, and reconstruct the thumb. All in sequence during the first 1 to 2 years of life. Done deal. Unfortunately, as our partner Dr. John Emans says, "There is nothing that shakes your confidence as much as surgical follow-up." Nowadays, there are the nihilists who almost believe in virtually no surgical intervention for type IV radial club hand and the optimists who believe that you use everything you have in your toolbox, including external fixation, lengthening, as well as microvascular bone and joint transfers. For the neophyte, even for the experienced surgeon, and especially for the parents, treatment selection can be confusing and daunting. The range of strong opinions makes for interesting debate but hard choices.

Nonsurgical

It is clear that the place to begin treatment is with stretching of the wrist from its malaligned position of radial deviation and flexion into extension and neutral to ulnar deviation. This can be by serial casting or by passive stretching many times a day and progressive forearm-based splinting of the wrist into a corrected position (Figure 13-3). With our skilled therapists, we tend to use progressive splinting and stretching followed by maintenance nighttime splinting in the first 6 to 12 months of life. For the mild type I or II radial deficiency, this is all the care that is needed for the wrist and forearm in infancy. They will correct and usually maintain their alignment throughout growth. If there is recurrent deformity, reinitiation of splinting and stretching is begun.

If the elbow is stiff in extension, a corrected wrist may impair hand-to-mouth, hand-to-head, and bimanual hand activities. Thus, most surgeons state that lack of elbow flexion is a contraindication to wrist surgery in radial longitudinal deficiency. We concur with that opinion.

Surgical Indications

Surgical intervention for radial club hand is for persistent wrist deformity that limits function. There is also the unspoken motivation to improve aesthetics. A well-designed and executed surgical plan will address the deficiencies in (1) wrist stability, (2) wrist alignment, and (3) forearm length. These often are not achievable in a single-stage procedure. Surgery does not come without a cost. For example, creating a straight, stable wrist may come at the cost of future growth of the ulna or wrist mobility and function. The more you strive to maintain or improve wrist motion, the more risk there is of recurrence. Ultimately, the functional outcome of any radial dysplasia patient, regardless of treatment, will be determined more by the quality of the fingers and thumb than the position and stability of the wrist.

Most of the time with more marked deformity, the stretching and splinting/casting precedes open or external fixation definitive surgical correction. The more difficult decision is what to do with a wrist, usually a Bayne type III or more commonly type IV deformity, that is uncorrectable by therapy, casting, and/or splinting. If it is extreme, most surgeons now progress to external fixation for soft tissue stretching and joint alignment.[6–8] If the residual deformity is mild to moderate, many surgeons proceed to single-stage correction by open surgery. But there are some who do either a minimal soft tissue realignment with a bilobed flap[9] or nothing, hence the controversy.

FIGURE 13-3 Static progressive splints, combined with therapist-assisted stretching, are used during the first 6 to 9 months of life to correct radial deviations of the wrist.

SURGICAL PROCEDURES

Well, boys, it's a round ball and a round bat and you got to hit the ball square.
—Joe Schultz

◆ Centralization and Radialization

Classic treatment for longitudinal radial deficiency has been to centralize the hand over the distal ulna and stabilize the wrist in a single-stage procedure.[10] A wealth of surgical experience for longitudinal radial deficiency came in the thalidomide crisis. All of the variations of procedures require extensive soft tissue rebalancing with releases, transfers, and capsular reefing. The amount of skeletal reconstruction differs. The extreme form of centralization (aligning the ulna and the third metacarpal) is the equivalent of a wrist arthrodesis by placing the distal ulna in a lunate-capitate carpal slot. This chondrodesis prioritizes wrist stability and alignment over motion and, ultimately, distal ulnar growth. A centralization procedure without a chondrodesis slot may involve a carpectomy or some distal ulna and carpal shaving to achieve alignment. This requires extensive soft releases and rebalancing to maintain correction. The goal of this modification is to maintain some wrist motion.[11–13] The recurrence of radial deviation deformity, however, increases. A radialization (aligning the distal ulna with the second metacarpal) was advocated by Buck-Gramcko in order to maintain motion while lessening recurrence rate.[14] This is done by increasing the ulnar deviation and extension static and dynamic forces.

There are also variations in skin incisions utilized. The most common are (1) radial Z-plasty and ulnar transverse ellipse,[15] (2) dorsal wrist and forearm longitudinal S, and (3) bilobed flaps[16] (Figure 13-4). We have used them all for different deformities and at various stages in our careers. Each allows for radial soft tissue release, rebalancing tendon transfers, and capsular reefing. The more severe the deformity, the bigger the incision we use to allow for the best repair with the least harm. Remember, the anatomy in these children is not normal and that in particular includes neurovascular structures. The more severe the radial dysplasia, the more likely the nerves and arteries will be anomalous or absent.

Case Scenario: Classic Centralization

The incision used in this particular case is a longitudinal dorsal S (Figure 13-5A). The skin and subcutaneous flaps are elevated extensively while preserving venous outflow. The extensor digiti quinti, extensor carpi ulnaris (ECU), and extensor digiti communis are isolated and protected (Figure 13-5B). These tendons can be very adherent to adjacent tissue and difficult to distinguish. The radial-sided anatomy is defined. The median nerve is usually displaced

A

B

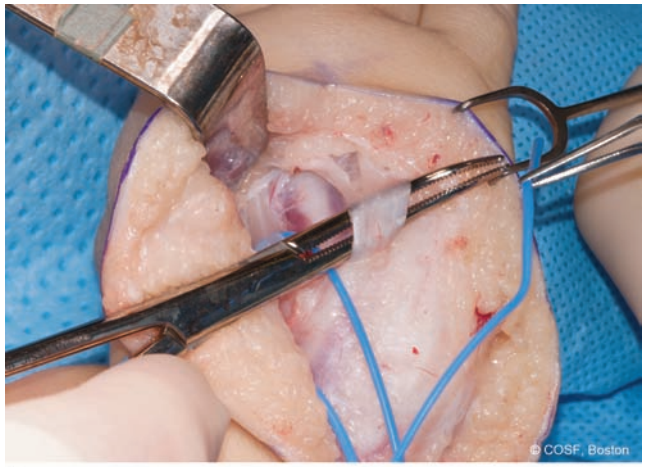
C

FIGURE 13-4 Clinical incisions used for centralization procedures. **A:** Ulnar ellipse to excise redundant ulnar soft tissues, used opposite Z-plasty incisions on the radial side of the wrist. **B:** Dorsal forearm and wrist "lazy S" incision with extension volarly and ulnarly. **C:** Dorsal bilobed flap incisions.

and taut. It needs to be protected. The radial artery may or may not be present. There may be an aberrant median artery. Release of fibrotic deforming forces is carefully performed. Tight musculotendinous units are released and tagged with sutures in case they can be transferred dorsoulnarly to improve dynamic stability. The volar-radial wrist capsule usually needs to be opened and released for joint reduction and alignment. The dorsal ulnar capsule is opened in a transverse incision to visualize and stabilize joint reduction. The ECU is isolated. Care is taken to truly identify and enter the joint rather than plunge through the distal ulna or carpal cartilage. The articular surface and the distal physis are often oriented volar radially. The flaps are elevated while protecting the adjacent extensor

A

B



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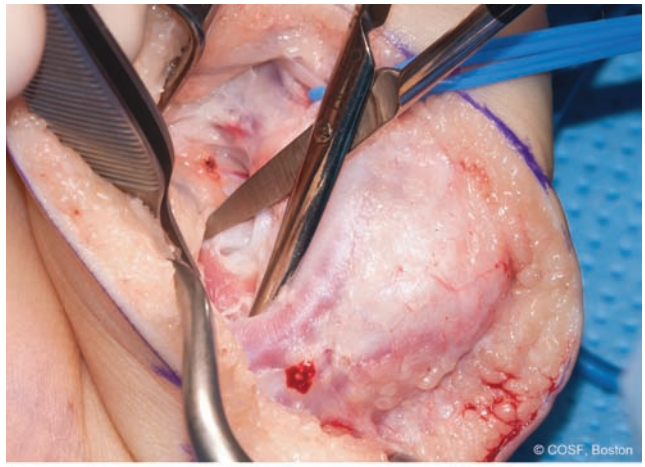

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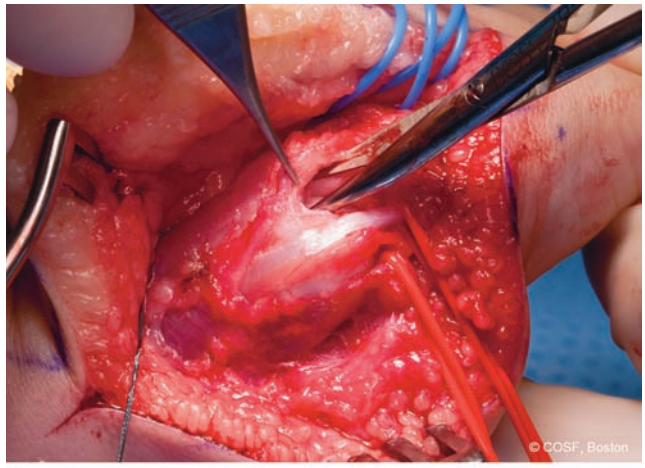

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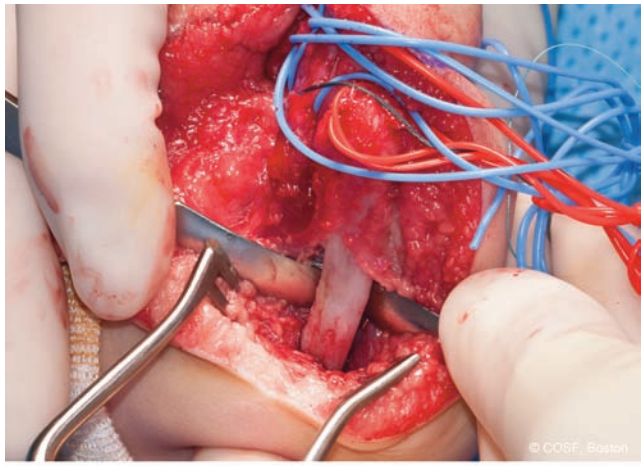
FIGURE 13-5 Operative centralization reconstruction. **A:** Clinical incisions using dorsal curved incision with extension volarly and ulnarly at the level of wrist flexion crease. **B:** Wide subcutaneous flaps are raised, allowing exposure of the volar-radial, dorsal, and ulnar structures. **C:** The dorsal extensor tendons are sequentially isolated with elastic loops. **D:** Tight radial structures are released, with protection of the displaced flexor tendons, median nerve, and radial artery, if present. **E:** After the ECU is identified and protected (isolated with red vessel loop here), the dorsal wrist capsule is entered.



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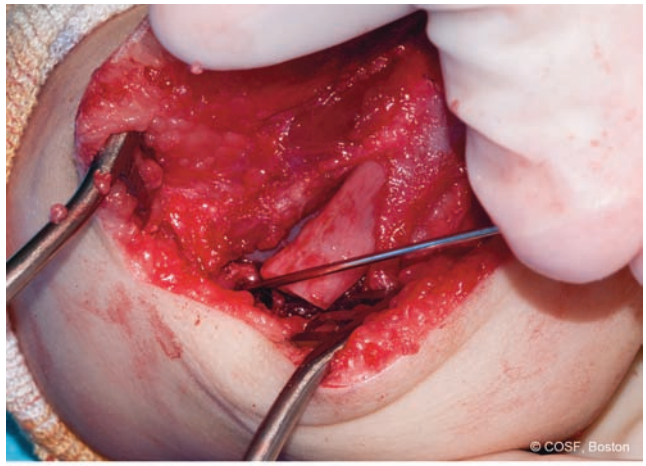

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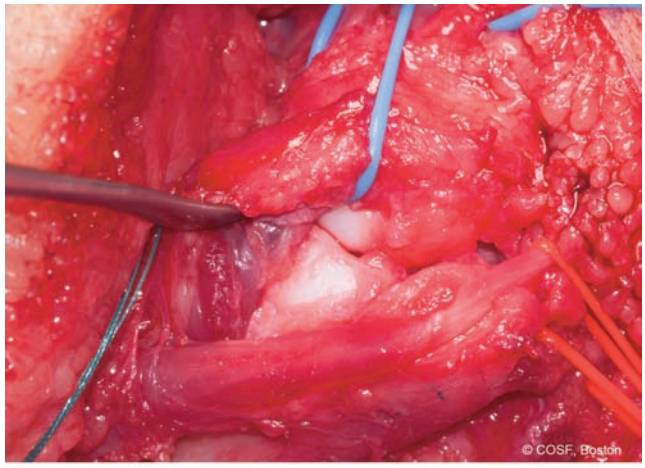

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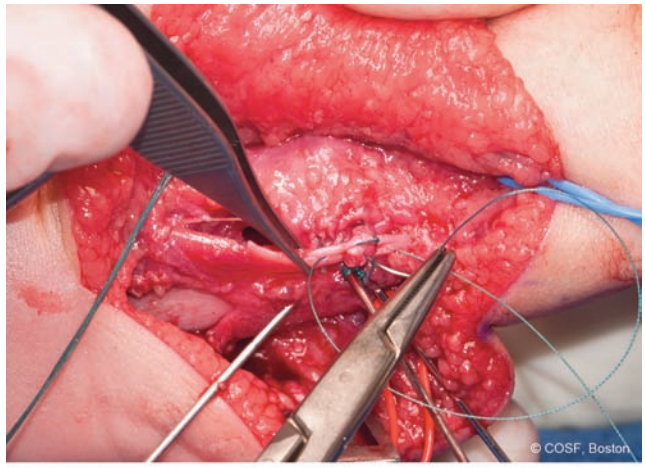

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K

FIGURE 13-5 *(continued)* **F:** If a corrective osteotomy is to be performed for a bowed ulna, it is subperiosteally exposed in the proximal wound. **G:** Following ulnar osteotomy, a smooth K-wire is inserted in the medullary canal. **H:** The carpus is then aligned onto the end of the distal ulna and stabilized with the previously placed K-wire. **I:** The wrist capsule is closed and the ECU advanced and transferred to provide dynamic stability. **J:** Final intraoperative appearance demonstrating corrected forearm and wrist longitudinal alignment. **K:** Sagittal profile demonstrating correction of the ulnar bow.

tendons. Subsequent reefing of the capsule and ulnocarpal ligaments will help stabilize the ulnocarpal joint reduction. The ECU tendon is detached distally in preparation for advancement to improve dynamic joint stability (Figure 13-5C).

There is now a bit of back and forth between volar-radial release and dorsal ulnocarpal reduction as joint reduction without tension is performed (Figure 13-5D). The volar flexor tendons, vascular structures (ulnar artery, aberrant median artery, or hypoplastic radial artery, if present), and nerves (ulnar and median) are protected as more and more release is performed to tease a tension-free reduction (Figure 13-5E). Our preoperative plan is to perform the joint reduction and stabilization without cartilage resection. However, there are times that proximal carpal resection or even distal ulna cartilage shaving, while protecting the distal ulna physis, needs to occur in order to achieve a stable reduction. These are the intraoperative compromises from the ideal that will test your judgment and preoperative planning.

Once the reduction is performed, it is pinned in place. We use a single smooth pin. If a centralization is performed, the pin extends from the third metacarpal across the joint into the ulna medullary canal. As it passes proximally, it may be appropriate to do a closing-wedge ulna osteotomy at the apex of the maximum deformity if it is >30 degrees. If a radialization is performed, the pin extends from the second metacarpal across the joint into the ulna. External fixation can also be used for stabilization.

The ulnocarpal capsule is reefed for static stability. This is a critical step and is performed with nonabsorbable suture in a "pants-over-vest" fashion.

The ECU tendon is advanced and repaired. If there is an extensor carpi radialis (longus and/or brevis), it too is transferred to the dorsal ulnar aspect of the wrist. Similarly, the flexor carpi ulnaris can be transferred dorsally. The digital extensors should now be centralized. If there are useful volar-radial donor muscles, they too are transferred to the dorsal hand. The skin flaps are now rotated and closed without tension.

Closure usually occurs after tourniquet deflation in order to assess digital viability, arterial inflow, venous outflow, bleeding, and flap vascularity. A subcutaneous drain is used for up to 24 hours. If pin fixation is used, then a bivalved, well-padded long-arm cast is applied. This is supplemented with a stockinette sling and swathe, as this foreshortened limb is at risk for cast loosening at home. If external fixation is used, then frame completion and tightening is performed. Care is taken to protect the child's face from the end of the pins.

External Fixation

Over the years external fixation techniques have been used for reconstruction of radial longitudinal deficiencies. Most commonly, external fixation has been used for (1) soft tissue distraction before open centralization,[8,17] (2) correction of severe or neglected deformities,[7,18] and (3) correction of recurrent deformity with concurrent ulnar lengthening of a foreshortened forearm[19,20] (Figure 13-6).

Techniques have included monoaxial, multiaxial, and hybrid frames. Specific devices have been developed for the infantile hand and forearm. The device used by different surgeons is based upon surgeon familiarity and preference, as well as age of patient and goal of surgery. Techniques focus on both (1) distraction of contracted radial and volar soft tissues for joint reduction without neurovascular compromise and (2) bony correction and lengthening.

Without industry or financial conflict of interest, we tend to use a multiaxial system in the infants when sufficient soft tissue correction is not possible with therapy and progressive static splinting (MiniRail, Orthofix, McKinney, TX). The pins are placed on the ulnar side of the hand and ulna as the fixator spans the wrist (Figure 13-6). Planning of the pin placement takes into account gradual distraction, extension, and ulnar deviation correction. The infant is kept in hospital until the parents are comfortable with all aspects of pin care, distraction technique, and infant safety with the frame. Correction is completed at home with visiting nurse and occupational therapy assistance to assess for pin track infections, loosening, or digital contractures. Once soft tissue distraction is completed and stable, the frame is removed and an open centralization as outlined above is performed.

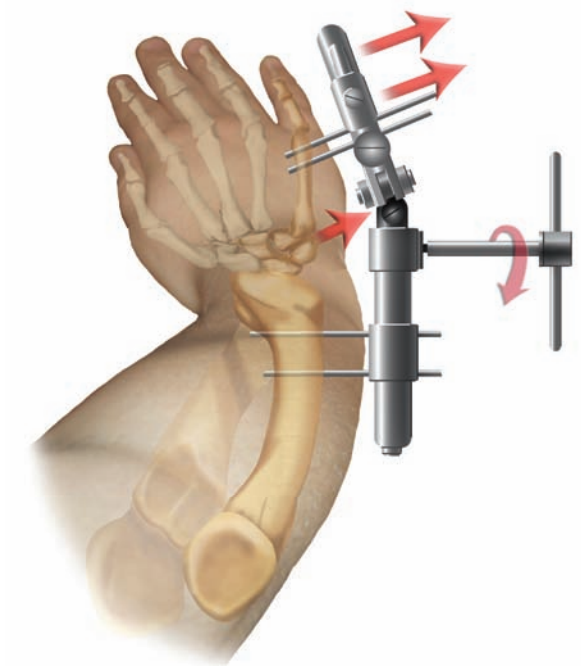
There are some markedly foreshortened forearms and deformed wrists that benefit from late correction and lengthening. The quality of the hand is an important consideration in this decision. With minimal digital motion and use, correction and lengthening is predominantly aesthetic. (Mind you, there are lots of aesthetic operations performed worldwide.) With an adequate hand, the concern is not to lose digital motion or function. Frame design and placement requires planning for wrist correction followed by diaphyseal ulnar lengthening. In older adolescents and young adults, a wrist fusion may be considered. However, this will eliminate any wrist tenodesis benefit for digital function.

Microvascular Transfer

Vilkki introduced distraction and microvascular epiphyseal transfer to provide radial buttress support for radial carpus and growth. This is an expansion of previous fibular nonvascularized, nonphyseal transfers. It is not a method we have experience with, but limited published results are positive.[21]

Do Nothing

It is far more difficult to be simple than to be complicated.
—John Ruskin



A

B

C

FIGURE 13-6 **A:** Monorail correction system for distraction and realignment of radial longitudinal deficiency. **B:** After fixator application with initial correction. **C:** With fixator correction before open centralization. (Case courtesy of Allan Peljovich MD.)

There are nihilists in the surgical community regarding surgical correction of severe radial club hands. There also are patients who are better off with nonoperative care (Figure 13-7). These are the difficult decisions. Without higher levels of evidence, these patients cause cognitive dissonance. Simply, keep your minds and eyes open. As our friend Jack Flynn likes to say about the limits of any one surgeon's knowledge and awareness: "I may not have seen it, but I am sure it has seen me."

ANTICIPATED RESULTS

You see, you spend a good piece of your life gripping a baseball, and in the end it turns out that it was the other way around all the time.
—Jim Bouton

The anticipated results are dependent on the type of radial dysplasia. The more severe the deformity, the less functional the hand. The more abnormal the original anatomy, the more likely there will be long-term issues with length, recurrence,[19] or limited use. Decisions need to be made with the original operative plan in prioritizing stability versus motion. This will affect long-term length. In the end, generally a stable wrist with mild deformity and a foreshortened forearm can be achieved.

COMPLICATIONS

Recurrence is the most common complication with growth. This can range from mild to severe. A severe deformity may require repeat correction, often with a concurrent lengthening.

FIGURE 13-7 **A:** Adolescent radial longitudinal deficiency patient with absent thumb demonstrating normal grasp of pen. **B:** At rest, the radial deviation of the wrist and absent thumb are noted.

Forearm shortening is expected but can be marked. This can become a real issue in adolescence and young adulthood in some patients. Again, lengthening may be appropriate and can be performed with repeat wrist correction and stabilization.

Limited digital motion can be worsened by distraction and correction. This should be addressed with intensive range-of-motion therapy preoperatively and postoperatively to lessen the risk of worsening hand function with correction.

The most worrisome complication is neurovascular compromise. Remember, the vascular and nerve anatomy is usually abnormal. Meticulous planning and techniques are required to prevent a disaster.

CASE OUTCOME

After sequential pollicizations between 6 and 12 months of life, the child was allowed to grow and attain functional use of her hand and thumbs before wrist correction. Due to the limits of her left elbow motion, this will be a prolonged delay if at all. In terms of her right wrist, the plan is for a bilobed flap reconstruction before school age.

SUMMARY

Care of these children is not over in infancy. The long-term follow-up can challenge your resolve on infantile surgical correction due to the difficulties of high recurrence rates, digital stiffness, and foreshortened limbs. Like many other pediatric hand conditions, the quality of the digits in terms of mobility and strength determines the quality of the functional outcome with radial dysplasia. In the presence of a good hand, aggressive surgical treatment is warranted. With a poor hand, wrist realignment, stabilization, and limb lengthening are predominately cosmetic.

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CHAPTER

14

Ulnar Longitudinal Deficiency

CASE PRESENTATION

A 12-month-old male child presents with ulnar longitudinal deficiency for second opinion and potential care. He has no associated medical conditions. There is no family history of any congenital differences. He has a three-digit hand. His thumb is in the same plane as the other two digits (Figure 14-1A). His index finger has limited passive and active motion. His long finger has near full active and passive motion. His small and ring finger rays are absent. He has an extreme internal rotation posture to his affected upper limb with no elbow motion (Figure 14-1B). He has moderate wrist motion with a nonprogressive ulnar deviation posture according to his parents and outside records. The issue is whether there is an operation that can improve his function.

CLINICAL QUESTIONS

- What are the characteristic anatomic features of ulnar longitudinal deficiency?
- What are the associated conditions with ulnar longitudinal deficiency?
- How is ulnar longitudinal deficiency classified?
- What are the common operative interventions for ulnar club hand?
- What are the expected long-term outcomes by natural history and surgery?
- What are the present limitations to surgical care for these children?

THE FUNDAMENTALS

From the functional viewpoint, the deformed limb is much more useful than its anatomic condition would have led one to expect.
—A.R. Southwood on ulnar longitudinal deficiency, cited by Adrian Flatt

In the presence of a normal brain and contralateral arm and hand, the functional deficits from a unilateral ulnar longitudinal deficiency are less than those the parents initially expect. The quality of the thumb and remaining digits is critical for functional use. Since the ulna predominately determines anatomic elbow motion and function, children with more involved ulnar deficiencies will be dependent on compensatory motion for placement of the hand in space. The arm is usually foreshortened, which helps hand-to-face activities when elbow motion is absent or limited. The internally rotated arm with ulnar-deviated wrist and bowed forearm can put the hand in a disadvantaged position. Scapulothoracic, glenohumeral, head, and neck motions compensate for these difficult anatomic variations. In the end, the goal of treatment is to improve function because, as of yet, we cannot normalize the situation. In the nearly 100 years since Southwood's statement, and 30 years since Flatt's citation, too little unfortunately has changed.

Etiology and Epidemiology

Longitudinal deficiency of the ulna is a very rare upper limb congenital difference, seen in about 1:100,000 live births.[1] It is much less common than radial longitudinal deficiency. Ogino's experimental animal model revealed that lethal cardiac anomalies can occur with embryonic ulnar dysplasia.[2] Unlike radial dysplasia, ulnar dysplasia that comes to term in human pregnancies is usually not associated with nonmusculoskeletal organ system anomalies. These children can have proximal femoral focal deficiency, fibular deficiency, phocomelia, and/or scoliosis. They do not require screening for cardiac, renal, gastrointestinal, or hematopoietic malformations the way radial club hand infants do. Some ulnar longitudinal deficiencies can be genetic, such as fibula-ulna or femur-fibula-ulna syndromes. These children are a mesomelic dwarfism variation and require combined upper and lower extremity orthopaedic care. Cornelia de Lange syndrome children can also have ulnar longitudinal deficiency.

Unilateral involvement is much more common. The vast majority of ulnar club hands are missing digits on the ulnar side, but most also have thumb malformations. Thus the malformation often extends beyond a strict ulnar longitudinal deficiency. Syndactyly is seen in about one-third

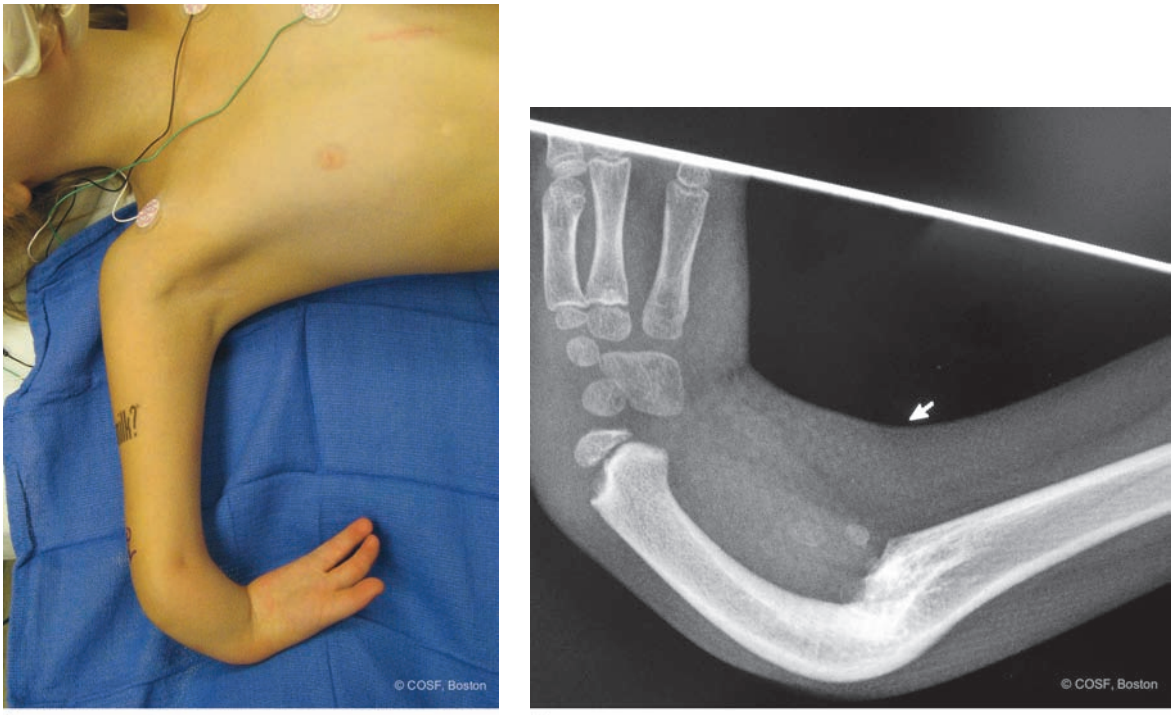


FIGURE 14-1 **A:** Ulnar longitudinal deficiency with elbow synostosis, foreshortened forearm, and three-digit hand. The thumb is in the same plane as the other two digits, which limits pinch. **B:** Radiograph of same patient. Note carpal coalition.

of the cases.[3–6] Carpal anomalies and fusions are very common with the pisiform almost always absent and the hamate commonly absent. The radius is present but usually foreshortened with a concavity ulnarly.

There have been many classification systems since Kummel in 1895. The classification systems have variably focused on the forearm, hand, thumb, or some combination thereof.[2,3,6–10] Bayne's classification parallels the radial longitudinal classification and makes it easy for most to remember. Type I is a hypoplastic ulna, type II is an absent distal ulna, type III is complete absence of the ulna, and type IV is complete absence of the ulna with radial-humeral fusion. Manske emphasized the status of the thumb in surgical decision making, similar to his classification for cleft hands.

Clinical Evaluation

As with any congenital difference, there is parental and primary care concern about malformations of other organ systems. However, these cases occur almost always in isolation or less commonly, with associated musculoskeletal malformations. Evaluation of the upper limb deficiency is by serial clinical exams and plain radiographs. Deformity is monitored over time to see if there is progressive wrist ulnar deviation, forearm instability, limb foreshortening, or functional deficits. The presence or absence of pain is recorded in older children. Their emotional well-being and social status is followed. Anyone who cares for children with congenital differences needs to be a high-ranking amateur psychologist; but, we also need to know the boundaries of our skills and knowledge.

The spectrum of ulnar longitudinal deficiency is broad. The simplest is absence of ulnar digital ray(s). These children are normal functionally. Since most people do not count fingers, cosmetically their deficiency is often not noted socially. Reassurance and time for the parents to be convinced that all is well is the major form of care for these children.

When the deficiency extends into the forearm, there is more extensive involvement of the hand, wrist, and elbow. Besides absent rays, hand and carpal involvement can include: digital hypoplasia, limited joint development, extrinsic and/or intrinsic weakness or absence, carpal absence or coalitions,[11] and thumb out of anatomic plane. Syndactyly can be present. The extreme form of hand malformation with ulnar longitudinal deficiency is monodactyly (Figure 14-2). Care for the more involved hand is geared to improving alignment and maximizing motion and strength. Passive stretching and progressive nighttime splinting programs are commonplace. Surgery to improve independent digital and combined hand function is indicated.

Wrist involvement can extend from a mild negative ulnar variance all the way to an unstable forearm. The wrist ulnar deviation can be static or progressive. Historically the ulnar anlage, a fibrocartilaginous connection between the residual ulna and the wrist, was thought

FIGURE 14-2 Ulnar deficiency with single floating digit.

to be responsible for progressive ulnar deviation deformity. Surgical excision in infancy was recommended for nearly every infant with ulnar longitudinal deficiency.[9,12] Now, ulnar anlage excision is rarely performed in our institution.[8,13,14] If the deformity is extreme, limits function, and/or is progressive, then a radial osteotomy and/or ulnar soft tissue release is considered.

The unstable forearm and elbow are also less clear in terms of treatment[12,13] (Figure 14-3). In the absence of pain, many of these children can be more functional with an unstable, mobile forearm and elbow than a surgical single bone forearm. It can be alarming to the parents that we endorse no treatment. In some respects, they need to be conditioned to the same limits of care available that we have over time. The best treatment here is often to get out of the way of the child and let them maximize their native intelligence, whole body capabilities, and adaptive abilities. Occupational and physical therapy can help with specific tasks.

The fused elbow is even more of an enigma to the parents (Figure 14-4). They cannot understand why in this age of artificial joints and biologic wonders, we cannot provide their children with a mobile, stable elbow that grows. Our job is to (1) provide them with reality-based evaluations and (2) continue research that hopefully one day achieves its goal.

Surgical Indications

Above all, keep it simple.
—Auguste Escoffier

FIGURE 14-3 Complete absence of ulna with proximal radius dislocation (type III) and complete, complex syndactylized digits.

Children with ulnar longitudinal deficiency can have a combination of problems with limb shortening and malalignment; unstable, malaligned, and/or fused joints; missing digital rays; limitations in grasp and pinch; and syndactyly. We have established operations for all these conditions. However, multiple extensive surgeries have not necessarily made these children have more function. Surgery for the hand has a clear benefit. Syndactyly reconstruction gives more independent digital use. Realignment

FIGURE 14-4 Complete absence of ulna with radiohumeral synostosis. Forearm is markedly bowed and foreshortened with a two-digit hand.

of the thumb and deepening of the first web space provide better pinch and grasp. The indications for derotational and/or angular corrective osteotomy, ulnar anlage resection, forearm and elbow stabilization, and limb lengthening are progressively less clear. We usually let the functional status of the child and our knowledge of surgical outcomes, rather than parental pressure to normalize the situation, be the main drivers in surgical decision making. Aside from thumb and digital surgery, changing one element of the limb in these children can affect functional use in another part. This makes surgical intervention complex in the forearm, elbow, and humerus. At present, collectively we are not as smart and talented as patients and families want us to be.

SURGICAL PROCEDURES

Nonoperative Management

These children are usually most unstable and malaligned in Bayne type II and III conditions at birth. As with radial longitudinal deficiency, patients benefit from a progressive stretching and splinting program. Some centers use serial casting, but we tend to use our therapists to guide this program. They also are quite skilled at educating parents on home developmental programs, answering their inquiries and providing additional resources. If you care for children with congenital differences, having skilled physical and occupational therapists in your program is essential. Obviously the more experience everyone has, the more sound and accurate the advice and care you all can give.

Syndactyly Reconstruction

Syndactyly release and reconstruction is almost always indicated in these children. The principles and surgical treatment follow the techniques outlined in Chapter 2. Since up to one-third of these children will have syndactyly of their remaining digits, reconstruction with flaps and skin grafts will improve hand function. Some of these digits though will be hypoplastic with limited motion and strength. This should be assessed preoperatively to be certain they will function better independent of the syndactylized digits.

Ulnar Anlage Excision

It is so simple to be wise. Just think of something stupid to say, and then don't say it.
—Sam Levenson

The pressure to do something is high. Ulnar anlage excision is one of those things that can be done. Unfortunately, it has not been shown to alter natural history dramatically in most situations. It is most helpful with severe (at least >30 degrees) wrist deformity that is unresponsive to splinting and stretching.[8]

A straight ulnar incision is utilized from the distal end of the hypoplastic ulna or humerus depending on the type of deficiency to the carpus. The normal anatomy will often be absent, with the flexor carpi ulnaris, extensor carpi ulnaris, and ulnar digital flexors replaced by a broad band of fibrous tissue extending from the distal humerus/proximal ulna to the carpus/radial epiphysis. If present, the ulnar neurovascular bundle will be adjacent to the band and needs to be protected and preserved. Proximal and distal release, or usually complete excision, is performed. This untethers the carpus and hand. The hand is reduced on the distal radius. Pinning of the realigned joint with a smooth, radial-sided small pin is performed for 4 weeks. Long-arm cast immobilization for 1 month is followed by splinting and therapy.

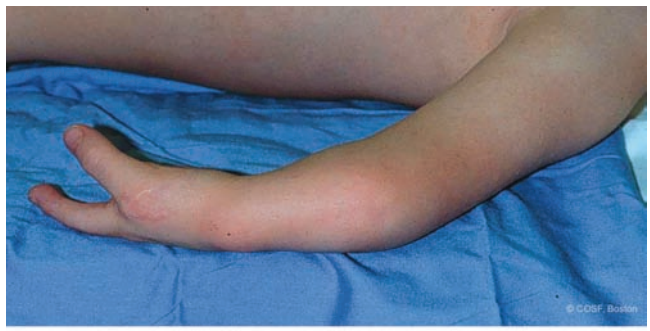
Osteotomies

Ulnar anlage excision alone may not realign and/or stabilize the wrist joint. In these situations, a simultaneous or second-stage radial osteotomy may be indicated to realign the hand. The complicating factors are rotational or angular deformity and/or a fused or unstable elbow. For example, straightening the wrist with a fused elbow may make the child less functional because it places the straightened hand farther from the face. Or, realigning the wrist with an unstable forearm may require a single bone fusion to have functional benefit. Or, functional improvement may require both rotational and angular correction, either through the forearm alone or rotational correction through the humerus and angular correction through the radius. The technical aspects of each of these operations are detailed elsewhere in the book and are not individually complicated (see "For Distal Radial Osteotomy" in see Chapters 15 and 24; "Humeral Osteotomy" in Chapter 21; "Single Bone Forearm" in Chapter 47). The real problem is deciding what is best and then performing simultaneous or staged surgery with the fewest complications and best results. This situation can quickly jump to the double black diamond level due to the rarity of the condition, lack of evidence for care, and degree of difficulty in decision making and getting each piece to fit with the other to properly position the hand. The goal of moving the hand from the flank to a more frontal position may take several steps to get cosmetic and functional benefit. Distraction hinged techniques may be useful. Be careful here, as you can quickly get in over your head and not provide the benefit to the patient that everyone desired.

Modified Pollicization

The goal is to realign the thumb for better pinch. Since up to 75% of ulnar longitudinal deficiencies can have thumb malformations, a thumb metacarpal osteotomy and first web-space deepening surgery is common and useful. Through Z-plasty incisions for rotation flaps, a transverse osteotomy of the metacarpal is made away from the

A



B

FIGURE 14-5 **A:** Modified pollicization to position thumb for better pinch. **B:** Follow-up photograph.

proximal physis while protecting the neighboring neurovascular pedicles and tendons. The thumb is rotated into the plane for opposition with simultaneous flap rotation. The thumb is pinned in palmar abduction and opposition for proper pinch. The flaps are closed without tension with absorbable (Chromic, Ethicon, Inc., Somerville, NJ) suture. Skin grafts are rarely necessary. Long-arm cast and pin immobilization is discontinued at 4 weeks. Splinting and therapy are then initiated (Figure 14-5).

ANTICIPATED RESULTS

Surgery has to do better than natural history to be worthwhile. That is clear for thumb repositioning and syndactyly reconstructions. The anticipated result is better assistive and independent hand function with these procedures (Figures 14-5 and 14-6).

The complexity of placing the hand better in space surgically than the patient can with compensatory motion

A

B

FIGURE 14-6 **A:** Ulnar deficiency with hypoplastic, floating middle digit in three-digit hand. **B:** Intraoperative photograph after middle digit excision and repositioning of thumb for improved opposition.

is less clear. To move the hand away from the flank or backside can be complicated and often requires staged, multiple surgeries.[8] When performed in the extreme situation, especially in the child with limitations or instability at the shoulder, there can be functional and cosmetic benefit to the child and, ultimately, independent adult.

COMPLICATIONS

The more common complication is the failure to improve the situation sufficiently to warrant the surgical intervention. Then the risks of anesthesia, infection, neurovascular compromise, and even the impact of scarring are magnified.

CASE OUTCOME

Recommendation was made for a modified pollicization[15] procedure to provide better active pinch and grasp function. The parents agreed. Immediate intraoperative views are seen (Figure 14-5). Indeed, the patient developed tip pinch and better three-fingered grasp postoperatively.

SUMMARY

Ulnar longitudinal deficiency is a very rare congenital malformation. Between one-third to one-half of these children can have other musculoskeletal congenital differences. Unlike radial longitudinal deficiencies, other organ system differences are not expected. Thumb realignment and syndactyly reconstruction are indicated, and the results are the most reliable for these children. Wrist, forearm, elbow, and upper arm surgical indications are less clear and, therefore, individualized.

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CHAPTER

15

Madelung Deformity

CASE PRESENTATION

A 13-year-old female presents for evaluation of wrist pain and deformity. Patient reports noting "ugly bony bumps" on the ulnar aspects of the bilateral wrists, associated with diminished range of motion (ROM) and right wrist pain with activities of daily living and sports (Figure 15-1). Initial attempts at splinting and activity modification have not resulted in symptomatic improvement.

CLINICAL QUESTIONS

- What is Madelung deformity?
- Who was Madelung?
- What causes the deformity? Is it hereditary? Are there associated conditions?
- What is Vicker ligament?
- What are the indications for surgical treatment?
- What are the surgical procedures that are performed for Madelung's?
- What are the expected outcomes and possible complications from surgery?

THE FUNDAMENTALS

There are two theories on hitting the knuckleball. Unfortunately, neither of them work.
—Charlie Lau

Etiology and Epidemiology

While previously described by Dupuytren, Malgaigne, and others, Otto W. Madelung was the first to provide a comprehensive description—including discussion regarding causality and treatment—on the condition that now bears his name.[1–4]

Madelung's is a relatively uncommon condition. In Flatt series of 1,476 patients with congenital hand and upper limb differences, only 1.7% of cases had Madelung's.[5] Females are more commonly affected than males, and there is often bilateral wrist involvement. Madelung's is thought to be transmitted in an autosomal dominant fashion with variable expressivity and incomplete penetrance. This is clearly true in cases of dyschondrosteosis, or mesomelic dwarfism, with associated lower limb involvement.

The etiology of Madelung's is unknown. Historically, identification of a thickened, fibrous volar ligament between the lunate and volar distal radius (the so-called Vicker ligament) raised the question of whether the deformity may be secondary to a soft tissue tether between the carpus and forearm.[6] More recent study has elucidated that Vicker ligament is indeed an abnormally thick, short radiolunate ligament.[7] We believe, as do most others, that Vicker ligament is secondary to, not the cause of, Madelung deformity. This is supported by the observation that if the tethering soft tissue structure was present at birth, greater deformity would be seen early in life, due to the hand doubling that occurs by the age of 3 years.[8]

More recent investigation has revealed that the classic Madelung deformity seen in females is likely due to a mutation in the SHOX homeobox gene on the X chromosome.[9–12]

A number of associated syndromes or genetic conditions have been identified. Most notable is Leri-Weill mesomelic dwarfism, also known as dyschondrosteosis.[13–15] This genetic association is often undiagnosed, as the short-statured patient has many relatives of similar height, and the only other obvious manifestation is the Madelung deformity (see Coach's Corner). Other reports have cited an association with Turner syndrome.[10,16] It is apparent, however, that the clinical presentation may be quite varied, and many cases may not have an obvious genetic or hereditary association.[17–19]

In addition to the classic Madelung deformity discussed here, any number of other conditions may result in similar changes in the distal radius and wrist, mimicking a Madelung-like deformity. These include post-traumatic distal radial physeal arrest, sickle cell disease, post-infectious wrist deformity, and a host of skeletal dysplasias, such as multiple hereditary exostoses, Ollier disease, and post-infectious mucopolysaccharidosis.[20]

FIGURE 15-1 **A, B:** Clinical photographs of a patient with Madelung deformity. Note the seemingly prominent ulnar head and apparent volar subluxation of the wrist on the forearm.

Clinical Evaluation

Madelung deformity is characterized by shortening and accentuated articular volar-ulnar tilt of the distal radius, due to abnormalities of the volar-ulnar distal radial physis. As the ulna is unaffected, it grows normally and adopts a seemingly elongated and dorsally prominent position (even though it is the radius that relatively shortens and grows abnormally volarly). In advanced or severe cases, the distal radioulnar joint (DRUJ) may be incongruent and widened, and the carpus will migrate proximally and volarly. Ultimately, this results in pain, decreased ROM (most notably supination and extension), and aesthetic differences of the wrist.

Patients will typically present between the ages of 8 and 14 years. While the typical complaint is of pain and difficulty with activities of daily living and/or sports, it is the visible aesthetic deformity that troubles many patients the most. Without a tinge of gender bias, this is what drives many adolescent females in to see us.

Physical examination will demonstrate the prominent distal ulna and relative volar subluxation of the carpus compared with the forearm. When observed closely, the hand sits out of plane of the forearm. Forearm supination and wrist extension may be limited according to the severity of the structural changes. The DRUJ may be lax or unstable. Distal hand function and elbow motion are preserved. In rare situations, patients may present with spontaneous ruptures of the extensor tendons, which may lead to the diagnosis.[21,22]

Radiographs will confirm the diagnosis (Figure 15-2). A number of radiographic measures have been proposed to quantify and categorize Madelung deformity.[23,24] One of the challenges in radiographic evaluation is that traditional parameters or landmarks used in other traumatic or acquired wrist conditions cannot be utilized owing to the abnormal skeletal anatomy. McCarroll et al. have proposed radiographic measures based upon the ulnar axis, given that the ulna may be the only unaffected structure of the wrist. Ulnar tilt, lunate subsidence, lunate fossa angle, palmar tilt, and palmar carpal displacement have been described, but only ulnar tilt and lunate subsidence were found to be reliable and reproducible, with unknown correlation to wrist function or patient-rated outcomes.

Surgical Indications

Surgical treatment is recommended for persistent pain and functional limitations or progressive bony deformity in the skeletally immature patient. Patients without symptoms or with mild deformity may be observed. While aesthetics are not a primary indication for surgery, many adolescent female patients find the visible deformity troubling and may wish to proceed with surgical

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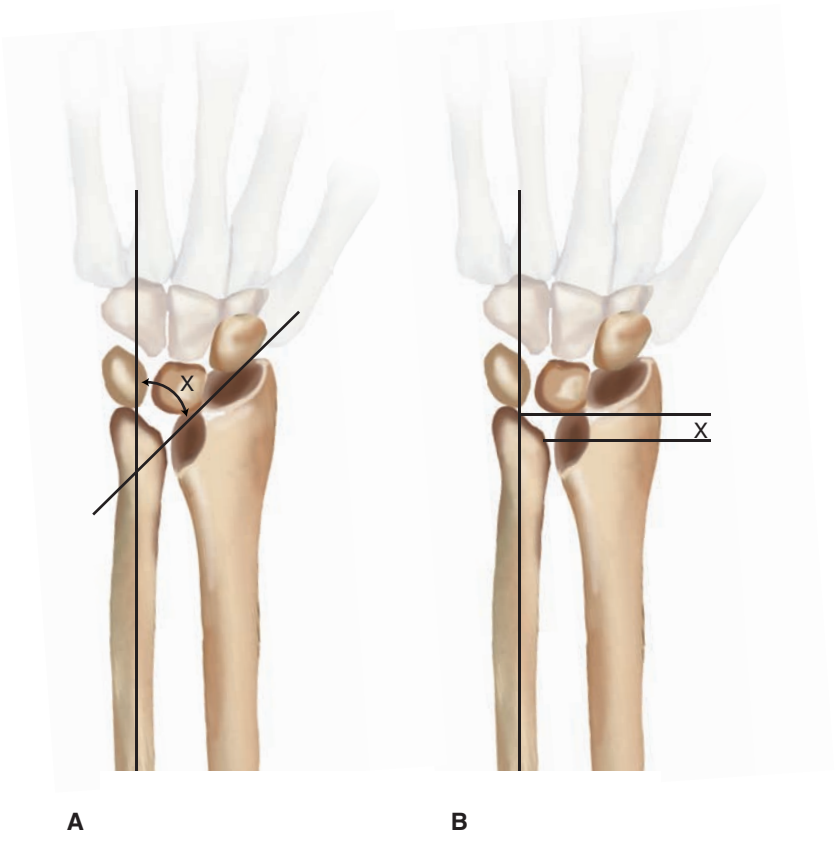

FIGURE 15-2 **A, B:** Schematic representations of measurements of ulnar tilt and lunate subsidence.

correction, though they do not yet have pain or functional issues. Many of these patients have sufficient enough deformity and joint incongruity that they are at risk for ulnocarpal impaction syndrome. A thorough preoperative discussion is needed regarding the relative risks and benefits of any surgical intervention, particularly if a strong motivation is the desire for a more normal-appearing wrist. If it is subtle and pain free, most will not trade the scar and surgical grief to be rid of a small bump. If it is severe, they may be better off having surgery before carpal cartilage or triangular fibrocartilage complex injuries occur.

A number of surgical treatment strategies have been employed. In very young children with growth remaining, Vicker ligament release and physiolysis have been advocated to "untether" the distal radius and allow for spontaneous correction with growth.[6] In older adolescents with established deformities and symptoms, corrective osteotomies are typically performed to (1) correct the alignment of the distal radial articular surface, (2) release any restrictive soft tissue structures, and (3) shorten the ulna to rebalance the wrist.[25–33] We perform corrective dome osteotomies of the distal radius, as it is technically easy, allows for intraoperative adjustment of deformity correction, avoids the use of bulky implants, and leads to reliable bony healing. While gradual distraction lengthening of the radius or elaborate three-dimensional correction of the deformity using Ilizarov techniques have been advocated, these have not been shown to provide superior results, are more complex in their application and maintenance, and are not currently utilized at our institution.[34,35] In some patients, dome osteotomy alone is not enough. Either an ulnar epiphysiodesis or ulnar shortening osteotomy is necessary depending on the age of the patient and degree of deformity.

SURGICAL PROCEDURES

Golf is deceptively simple and endlessly complicated.
—Arnold Palmer

Physiolysis, Vicker Ligament Release

This is an isolated operation for the very young Madelung patient with the goal of realigning the carpus and restoring radial growth. A longitudinal incision is created overlying the flexor carpi radialis (FCR) tendon in the fashion of a classic Henry approach to the volar distal radius. The FCR tendon sheath is incised and the FCR tendon retracted ulnarly. The floor of the FCR is incised, and blunt dissection will allow for safe visualization of the pronator quadratus (PQ). The PQ

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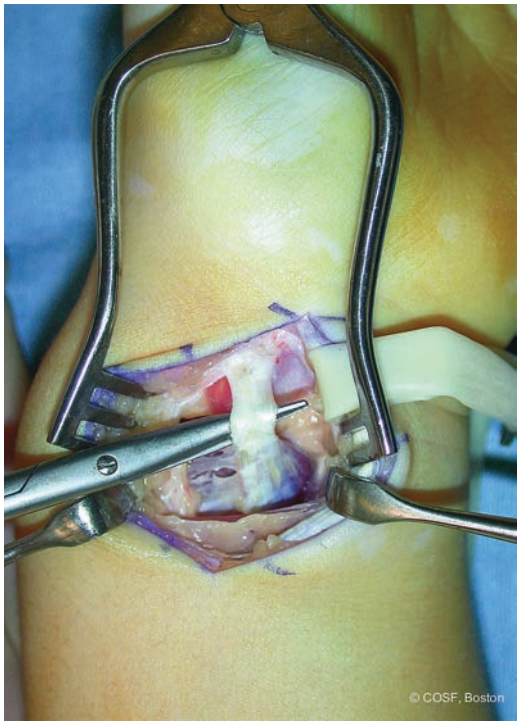

FIGURE 15-3 Intraoperative photograph depicting Vicker ligament.

is incised along its radial border, leaving a cuff of soft tissue for subsequent repair, and the pronator is swept ulnarly with careful subperiosteal elevation. Distal ulnar dissection along the volar aspect of the distal radius will allow for identification of any bipedicled PQ insertion and/or the stout Vicker ligament (in essence, usually a short radiolunate ligament), which can measure 5 to 7 mm in thickness (Figure 15-3).[36] Vicker ligament is then transected, releasing the soft tissue tether. Any change in lunate position is noted on fluoroscopy. Following this, based on preoperative imaging and planning, intraoperative fluoroscopy, and direct visualization, the bony bridge in the volar-ulnar aspect of the distal radial physis is curetted, with care taken to avoid injury to the adjacent healthy physeal cartilage. Pronator muscle or fat interposition is then performed to lessen the risk of physeal bar recurrence. The pronator is repaired, and soft tissues are closed in layers. The wrist is immobilized in a short-arm cast for 2 weeks. The patient's growth is followed closely every 6 months with radiographs. If ulnar overgrowth is recurring, early consideration for an ulnar epiphysiodesis versus later repeat radial reconstruction should occur.

Dome Osteotomy

In older patients with established deformity, limited remaining skeletal growth, and pain or functional limitations, a radial dome osteotomy is performed.[28,29] Standard volar approach to the distal radius is performed with release of the Vicker ligament as described above. When an osteotomy is planned, circumferential periosteal elevation is required with judicious placement of small Homan or Bennett retractors. Following this, the level of the planned osteotomy is identified by direct visualization and fluoroscopic assistance, with great care being made to avoid violation of the DRUJ and radial physis, if still open (Figure 15-4). It is imperative that the dome be created concave distal; if the osteotomy is made convex distal, the prominent metaphyseal spike on the distal fragment will block radial deviation and extension of the osteotomy. (If you make the osteotomy look like a smile, not a frown, you will end up happy.) The path of the planned osteotomy is created using 0.045" K-wires to perforate the volar and/or dorsal cortex. Prior to completion of the osteotomy, a small stab incision is made overlying the radial styloid, and careful subcutaneous spreading is performed; the radial sensory nerve is almost ubiquitously beneath this incision and must be retracted and protected as do the extensor tendons and radial artery. Two parallel or divergent smooth 0.0625" K-wires are then placed into the radial styloid and driven to the level of the planned osteotomy. As the distal fragment will be rotated, these K-wires must be oriented in nearly a vertical or longitudinal fashion. If placed too transversely, they will miss the proximal fragment after the osteotomy is mobilized. Following this, curved osteotomes are used to connect the cortical perforations in the distal radius and complete the osteotomy. The curve of the osteotome blade is utilized to create an osteotomy plane that is curved concave distal in both the frontal and sagittal planes; this will facilitate correction of the flexion deformity as well. After the osteotomy is mobilized and the desired amount of correction is achieved, the previously placed K-wires are driven across the osteotomy, engaging the proximal ulnar cortex of the radius. Often a small spike of bone is removed to maximize correction and is used as local bone graft. Radiographs are obtained to confirm desired correction (Figure 15-5). Pins are bent and cut outside the skin. Volar skin flaps are raised, and, under direct visualization, a limited prophylactic volar forearm fasciotomy is performed. The PQ is reapproximated.

Dome Osteotomy with Ulnar Epiphysiodesis

If the patient is young enough to have recurrent deformity with continued ulnar growth, a distal ulnar epiphysiodesis is simultaneously performed. The physis is located by palpation and fluoroscopy. A longitudinal incision is made over the physis. Care is taken to identify and protect the ulnar sensory nerve. A 25-gauge needle is placed in the physis and the location confirmed by fluoroscopy. Either mini-incision drilling or open epiphysiodesis can be performed. It is easy to get off the mark and mainly drill or curette the metaphysis (the metaphysis actually offers less

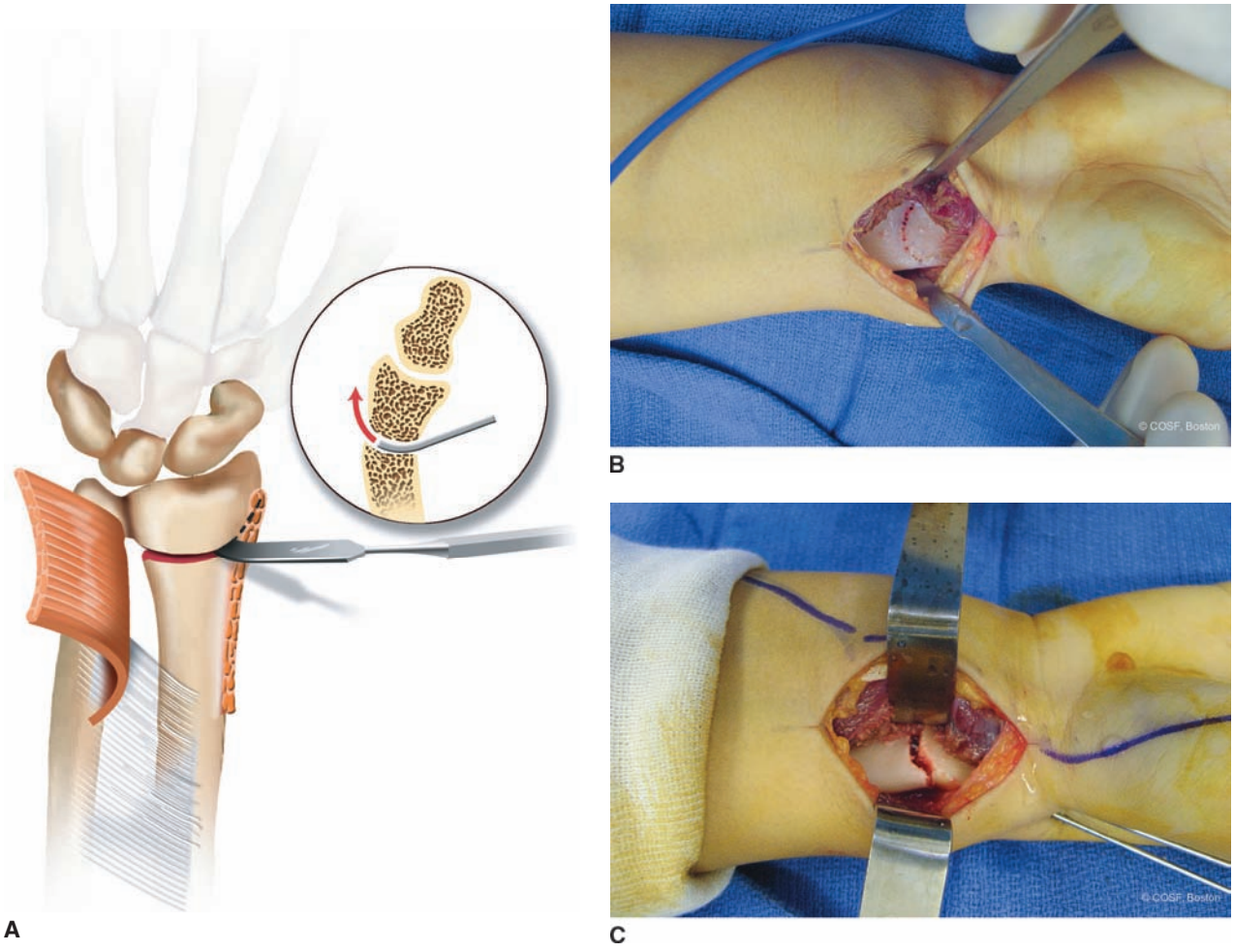

FIGURE 15-4 **A:** Schematic diagram of the dome osteotomy. **B:** After the pronator has been elevated and Vicker ligament released, the cortex is perforated with K-wires in preparation of a concave-distal osteotomy. **C:** Intraoperative appearance after completion of the osteotomy and pin fixation. Note that the distal articular fragment has been corrected in two planes, providing both radial inclination as well as extension.

resistance than the physis). At times, the ulnar growth plate can be difficult to "kill," and so we tend to be aggressive. Subperiosteal dissection is performed. Direct visualization of the physis while drilling and curetting is performed. A reversed block of cortical cancellous bone is inserted and confirmed by fluoroscopy. Soft tissues are then closed in the standard fashion. The limb is immobilized in a bulky, well-padded long-arm cast, which is bivalved to allow for postoperative swelling.

◆ Dome Osteotomy and Ulnar Shortening Osteotomy

In patients with advanced deformity and late presentation, Vicker ligament release and radial dome osteotomy may be insufficient. Despite correction of radial inclination and volar tilt, the wrist remains imbalanced due to positive ulnar variance. In these situations, a concomitant ulnar shortening osteotomy is performed.

Following dome osteotomy as described above, a second longitudinal incision is made on the ulnar border of the distal forearm. The extensor carpi ulnaris–flexor carpi ulnaris interval is identified and incised. The dorsal ulnar sensory nerve is protected. The ulna is exposed subperiosteally. Two stacked 5-hole one-third tubular stainless steel plates are applied to the ulna (Synthes, Paoli, PA). These implants are chosen for the following reasons: (1) they are narrower and lower profile than traditional 3.5-mm plates, thus better fitting on the younger child or adolescent; (2) by stacking the plates, the bending rigidity is increased eightfold; and (3) four cortices are sufficient fixation in younger patients, and, if only two holes are needed distally, the osteotomy site is placed in more metaphyseal rather than diaphyseal bone, thereby reducing the risk of nonunion/delayed union. After the plates are applied, the distal two screw holes are drilled and partially filled. Markings are made along the edge of the plate in the area of the planned osteotomy to guide rotation. The plate and screws are removed. Following this,

FIGURE 15-5 **A, B:** Preoperative anteroposterior and lateral radiographs. **C, D:** Postoperative anteroposterior and lateral radiographs following dome osteotomy.

two parallel cuts are made obliquely using a microsagittal saw. The ring of intercalated bone is then removed corresponding to the amount of desired shortening. The double-stacked one-third tubular plates are reapplied, and fixation into the distal ulnar fragment is obtained utilizing the previously placed drill holes. (This technique illustrates a cardinal principle of all pediatric osteotomies: gain and maintain control of the smaller, articular osteotomy fragment.) The osteotomy is reduced under direct visualization, taking care to restore the original rotation as indicated by the bony markings. Proximal fixation is achieved with the screws applied in compression. Fluoroscopic images are obtained to confirm alignment and implant placement. Subcutaneous flaps are raised, and dorsal and volar forearm fasciotomies performed. Periosteum is reapproximated around the ulna and implant. Soft tissues are closed in the standard fashion. The forearm is placed in a bulky soft dressing and immobilized in a long-arm bivalved cast.

POSTOPERATIVE

Following dome osteotomy, pins are removed at 4 weeks and the wrist is transitioned into a short-arm cast. At 6 weeks, immobilization is discontinued and gentle ROM is begun. We do not routinely remove plate and screw implants in the upper limb unless symptomatic.

ANTICIPATED RESULTS

Vicker ligament release with or without physiolysis may halt the progression of deformity and, in some cases, offer mild deformity correction.[6] In Vicker's original report on this technique, deformity progression was stopped in 15 wrists in 11 patients at early clinical and radiographic follow-up.

Following osteotomies, bony healing and deformity correction can be achieved in most cases. Despite the use of temporary smooth pin fixation, delayed union or nonunion is quite rare, given that the osteotomy is performed through the vascularized distal radial metaphysis leaving a broad surface area for healing. Carter and Ezaki[36] have previously reported complete pain relief with excellent deformity correction in their series of 23 wrists in 18 patients. In a similar series of 26 wrists in 18 patients, dome osteotomy reduced pain, increased motion, and provided aesthetic improvements at almost 2 years follow-up.[29] Three wrists went on to ulnar shortening osteotomy or even Darrach distal ulnar resection due to persistent ulnar-sided issues.

COMPLICATIONS

The superficial branches of the radial sensory nerve are at risk during pin placement with dome osteotomy. Direct pin placement through the nerve can be avoided by using a small incision, carefully spreading the subcutaneous soft tissues, and placing retractors during pin placement. Given the very longitudinal orientation with which these pins are preset, a sharp "axilla" is created between the pin and the radial styloid, in which the nerve may be pinched or compressed. Placing the pins with oscillating—rather than spinning—motion will further decrease the risk of iatrogenic injury. In cases where superficial radial nerve irritation is seen, patients/families should be counseled that the vast majority will resolve after pin removal.

Incomplete sagittal plane correction is a common problem. Judicious circumferential subperiosteal elevation will assist in freeing up the distal fragment during osteotomy. Furthermore, the use of curved osteotomes, as described above, will help to correct volar tilt. Careful intraoperative fluoroscopy is used to monitor and confirm appropriate sagittal alignment correction.

Recurrence is common after Madelung deformity correction, particularly in the younger child. Patients and families should be counseled at length about this during the preoperative discussion. Several strategies may help to minimize the risk of recurrence. First, Vicker ligament should be released in all cases to avoid leaving a soft tissue tether and potential cause for recurrence. Second, in younger patients with growth remaining, consideration should be made for distal ulnar epiphysiodesis with or without concomitant completion epiphysiodesis of the distal radial physis. This will allow for preservation of the alignment achieved at surgery, though it may result in a shortened forearm segment. Usually patients with mesomelic dwarfism do not "miss" the growth lost from epiphysiodesis; indeed, there is gain in apparent length from the realignment of the distal radius. Finally, in advanced cases, ulnar shortening osteotomy performed at the initial procedure or in a staged fashion may provide the best opportunity for deformity correction, restoration of motion, and resolution of pain.

CASE OUTCOME

Based upon clinical examination and radiographic findings, the diagnosis of bilateral Madelung deformity was made. Due to pain and functional limitations, a dome osteotomy of the distal radius and ulnar shortening osteotomy of each wrist were performed (Figure 15-6). Pain improved, and the patient was pleased with the aesthetic result.

FIGURE 15-6 Postoperative anteroposterior radiograph following radial dome and ulnar shortening osteotomies.

SUMMARY

While the etiology of Madelung's remains unknown, patients with pain, deformity, and aesthetic differences may be successfully and safely treated with corrective soft tissue and bony procedures. Vicker ligament release, physiolysis, radial dome osteotomy, and/or ulnar shortening procedures will effectively correct radiographical alignment and usually provide improvement in aesthetics and pain. Risk of recurrent deformity remains, particularly in the younger patient.

COACH'S CORNER

Is Formal Genetics Consultation Needed in Patients with Madelung Deformity?

I don't play small. You have to go out and play with what you have. I admit I used to want to be tall. But I made it in high school, college, and now the pros. So it doesn't matter.
—Spud Webb

Often patients are seen with newly diagnosed Madelung deformity, and the diagnosis of Leri-Weill mesomelic dwarfism, or dyschondrosteosis, is raised. Clinically, Felman and Kirkpatrick have developed criteria for distinguishing isolated Madelung's from that associated with dyschondrosteosis.[37] Patients with isolated Madelung disease are greater than 25th percentile for height and have no family history of wrist troubles. Patients with Madelung deformity, in the setting of dyschondrosteosis, are typically <5 ft in height at skeletal maturity, have short tibias and fibulas, and often exhibit subtle proximal radius abnormalities.

At present, we do not believe that genetic evaluation or counseling confers substantial benefits for patients with Madelung deformity. Aside from short stature and the wrist issues for which these patients are presenting, no associated systemic complications are expected. Therefore, genetic testing offers little new information and does not prevent unsuspecting or potentially harmful consequences. In addition, as many of these patients have affected relatives with short stature, the diagnosis of "dwarfism" is not beneficial. These patients do not feel they are different; they are simply similar to their parents/relatives, just as they are in eye color, hair color, or personality. Rather than proceed with genetics consultation, the concept that their wrist deformity and short stature are related and hereditary is shared with the patients/families at the time of diagnosis.

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CHAPTER

16

Congenital Radial Head Dislocation

CASE PRESENTATION

A 13-year-old male presents with an isolated unilateral congenital dislocation of the radial head on the left side. He is right-hand dominant. Diagnosis was made at age 8 when he and his family noted a prominence on the lateral aspect of his elbow, and he began experiencing pain. Then he lacked only 5 degrees of elbow extension with pronation to 70 degrees and supination to 30 degrees and minimal pain with sports. Over the past 5 years, he developed increasing pain, mild loss of motion, and, most recently, in the past 3 months, intermittent locking of his elbow. He is now limited in both athletics and activities of daily living. On exam, his radial head is prominent posterolaterally. He has flexion to 130 degrees and extension to –40 degrees. His forearm rotation is 60 degrees pronation and 5 degrees supination. His radiographs and MRI scan are outlined in Figure 16-1.

CLINICAL QUESTIONS

- How do you distinguish a congenital from a traumatic radial head dislocation?
- Is there a predominant direction of dislocation for a congenital radial head?
- What are the associated upper limb conditions and systemic syndromes with a congenital radial head dislocation?
- Are there functional limitations with a congenital dislocation of the radial head?
- What are the indications for open reduction of a congenital radial head dislocation?
- Is it appropriate to excise a dislocated radial head in a skeletally immature child?
- What are the expected outcomes from operative intervention?

THE FUNDAMENTALS

Congenital dislocation of the radial head needs to be distinguished from a traumatic dislocation. It has been written that a unilateral dislocation indicates traumatic etiology.[1] That is not true, though bilateral dislocations are clearly more commonly congenital.[2,3] It has been stated that direction of displacement distinguished congenital from traumatic dislocations. That also is not true, though anterior dislocations tend to be more traumatic and posterolateral dislocations more congenital in origin (Figure 16-2). The local changes in the capitellum, radial head, and forearm alignment are very helpful in this distinction. In general, congenital dislocations will exhibit a convex, aspherical radial head; a hypoplastic, flattened capitellum; an elongated, bowed radial neck; an ulna greater than radial length; and mild proximal ulnar bowing. However, local and regional deformity does occur with traumatic dislocations. And just to add to the confusion, a congenital dislocation can suffer a fracture, and a traumatic dislocation has been described at birth.[4,5]

The reason all this matters is decision making regarding operative intervention.[6] It is not unusual to be referred a patient from the emergency room for surgical intervention who has undergone multiple failed attempts at closed reduction of a misdiagnosed traumatic Monteggia lesion when he or she actually has an undiagnosed congenital dislocation of the radial head. Reconstruction of a chronic Monteggia may be successfully performed by a surgeon at the double black diamond level (see Chapter 30), if the radial head is not convex. Late reconstruction of a congenital dislocation will be fraught with failure except in very unusual circumstances.[7,8]

Etiology and Epidemiology

Congenital dislocation of the radial head can be seen in isolation, in conjunction with other congenital differences about the elbow and upper limb, or as part of a syndromic condition. Approximately 66% occur in isolation, while

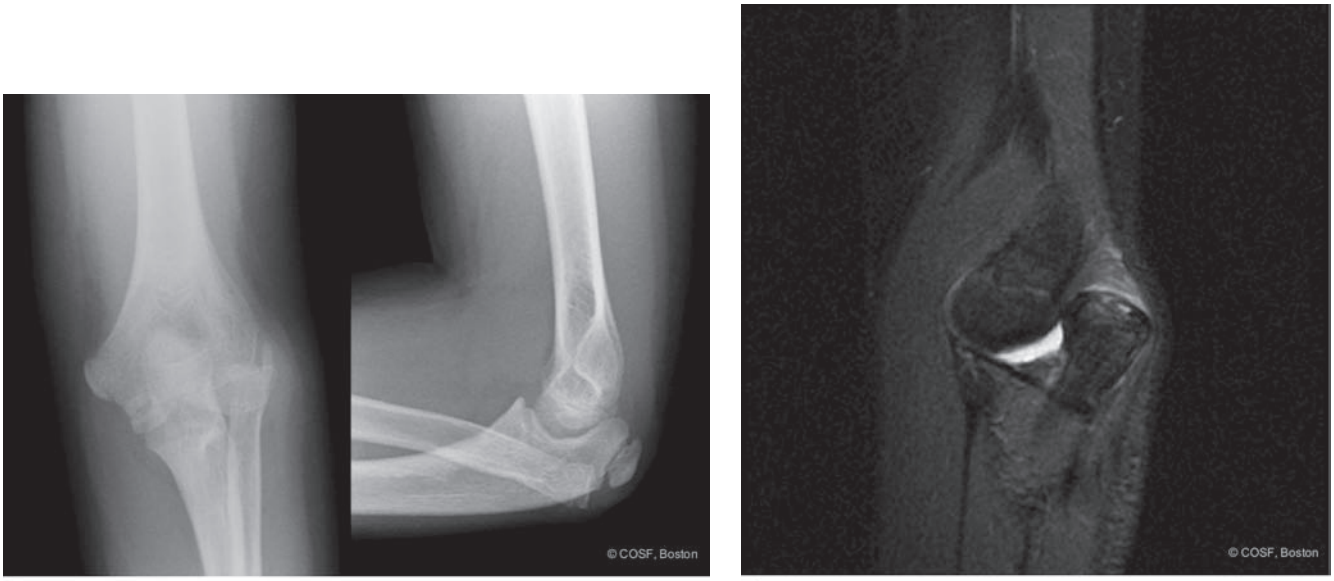


FIGURE 16-1 **A:** Anteroposterior and lateral radiographs of congenital posterolateral radial head dislocation. The patient is now developing pain with activities of daily living and recreation. **B:** Sagittal MRI scan reveals impingement and effusion.

33% are associated with regional or syndromic anomalies. The exact incidence in the general population of the isolated congenital dislocation is unknown. Congenital dislocations associated with ulnar dysplasia, radioulnar synostosis, below-elbow amputations, congenital pseudarthrosis of the ulna, osteogenesis imperfecta, nail patella syndrome, trisomy 8 and 12, omodysplasia, and familial inheritance, among others, are well described.[9–12]

Clinical Evaluation

The degree and direction of dislocation, along with associated conditions, affect the timing of presentation. Most isolated congenital dislocations do not present for evaluation and care until later in life, often around school age. The child's lack of full elbow extension or forearm rotation may only be noted when specific arm and hand motion tasks are attempted under direct supervision or observation. The child's compensatory shoulder and wrist motion usually prevents functional limitations and parental awareness until direct observation and inspection occurs. This is similar to the presentation of radioulnar synostosis (see Chapter 17).

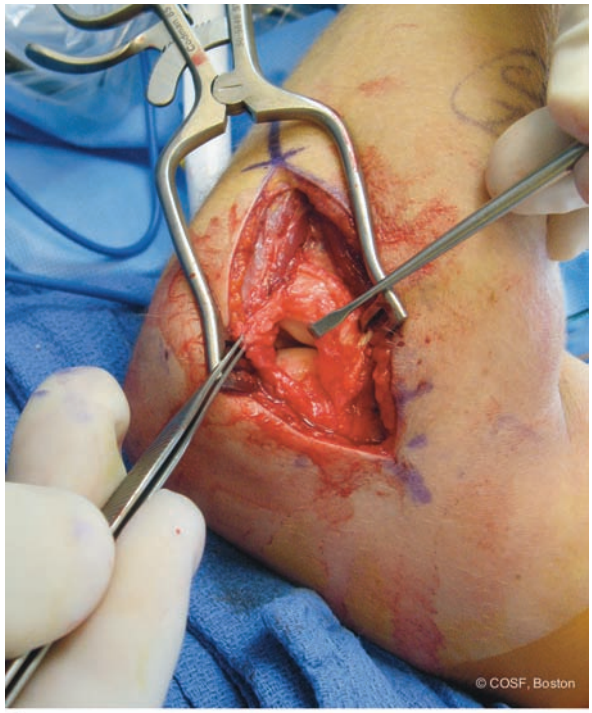
FIGURE 16-2 Sagittal MRI scan of rare anterior congenital radial head dislocation with impingement against a hypoplastic capitellum.

Early on, pain is rare, if present at all. Occasionally, the children will complain of instability with forearm rotation, or the parents will hear a snapping sound with rotatory motion in the subluxed or minimally dislocated situation[13] (Figure 16-3). Later, osteochondral deterioration of the radial head and capitellum can create activity-related pain, produce loose bodies, and cause locking and crepitus. Some of these children present acutely to the emergency room with a locked joint or, more commonly, pain with activities such as sports.[14]

Finally, some adolescents only present when they are disturbed by the aesthetic appearance of a prominent posterolateral dislocation. Their desire for excision is more psychosocial than functional.

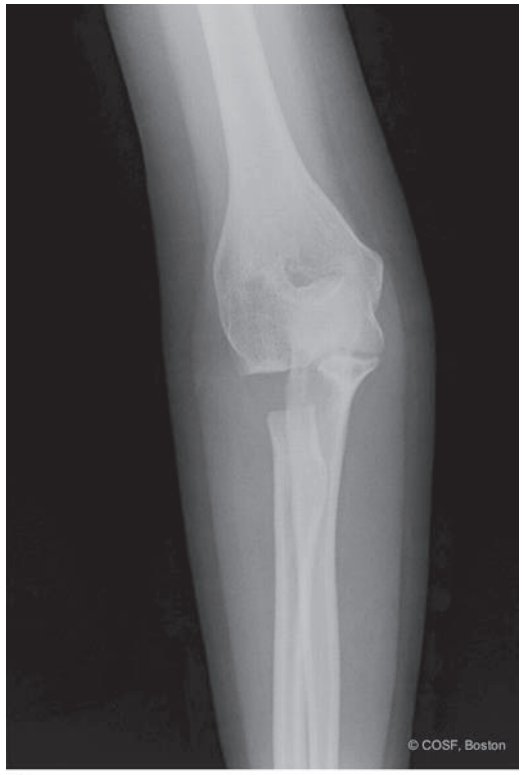
Examination of an isolated posterolateral dislocation usually reveals a 5- to 40-degree lack of elbow extension and <50% full forearm rotation. There is often compensatory wrist and shoulder rotation that prevents functional impairment. Bilateral involvement can be more disabling. With local dysplasia or syndromic conditions, the limitations on exam become more regional or systemic. If there is hand and/or brain involvement, the functional limitations become more marked.

A



B

C1



C2

FIGURE 16-3 **A:** Mild posterolateral lateral radial head subluxation with marked pain and snapping. **B:** Modified Kocher posterolateral exposure of the congenital dislocation. **C1,2:** Postoperative anteroposterior and lateral elbow x-rays demonstrating radial head excision at the desired level.

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D

FIGURE 16-3 (*continued*) **D:** Forearm x-ray revealing radial head resection and neutral ulnar variance.

Radiographs will reveal the direction of dislocation. The contour of the radial head; bowing of the radial neck and shaft; radiocapitellar, proximal, and distal radioulnar articulations; distal ulnar variance; and shape and contour of the ulna are all evaluated on plain radiographs of the forearm, wrist, and elbow. Other regional anatomic abnormalities, such as radioulnar synostosis, are recorded. Osteochondral deterioration is noted. On rare occasions in which the diagnosis is made perinatally or in infancy, ultrasound or MRI scan is used to determine the feasibility of an open reduction.

Surgical Indications

One of the lessons of history is that nothing is often a good thing to do and always a clever thing to say.
—Will Durant

The ideal surgical solution for a congenital dislocation of the radial head includes (1) early recognition by prenatal or infantile ultrasound and (2) successful operative reduction of the radial head that leads to proximal radioulnar and radiocapitellar joint remodeling, normal alignment, and motion. The first is often difficult, and there is debate if the second is achievable. Too often these children are not diagnosed until later in life due to minimally noticeable disability. It is not a common or severe enough problem to warrant neonatal screening, such as with developmental dysplasia of the hip. Usually at the time of diagnosis, there is too much radial head and capitellar deformity to warrant open reduction.[7,15–17] Remodeling will not occur with reduction at this stage. The only surgical option is radial head excision when and if pain and progressive limitation of motion and function develop.[1,18,19]

The evidence for successful open reduction and reconstruction of a congenital dislocation is limited to small retrospective case series or case reports.[13,20,21] There are plenty of reports of failed reconstruction. Natural history is asymptomatic in some patients through to adulthood. Thus, the presence of a congenital radial head dislocation alone is not an indication for surgery.

SURGICAL PROCEDURES

Radial Head Excision

The technical aspects of radial head excision are not hard. It is deciding "if and when" to operate that is key. The presence of a radial head dislocation alone is not an indication for excision. Unremitting and unresolved pain with other treatment modalities can be a proper indication. Limitations in elbow extension and forearm rotation without pain are *not* an indication for surgery. Athletes desiring more motion for sports such as tennis or gymnastics could be very disappointed by their lack of improvement or the development of wrist pain with radial head excision. Conversely, skeletal immaturity is not always a contraindication to radial head excision. In some young patients, there are progressive osteochondral injury, deformity, loose bodies, and marked pain that responds to radial head excision.[18] Finally, there are adolescents with marked posterolateral dislocations who have radial head excision for predominately aesthetic benefit.[19] The degree of ulnar variance at the wrist should be radiographically measured before consideration for radial head excision. If there is a positive variance, radial head excision can lead to or worsen wrist pain.

The patient is placed supine with a fluoroscopic arm table for the affected limb. A standard posterolateral approach is utilized through the anconeus-extensor carpi ulnaris interval. The lateral collateral ligament is preserved anteriorly. The capsule is opened and radiocapitellar joint is inspected (Figure 16-3B). The capitellum is generally deformed with marked osteochondral injury (Figure 16-4). The radial head usually has similar arthritic-like deterioration (Figure 16-5A). Dissection is carried down the radial neck while preserving the annular ligament and protecting the posterior interosseous nerve. Excision of the radial head is carried out extraperiosteally to lessen the risk of reformation of bone that could lead to recurrent impingement. The bone cut is made perpendicular to the diaphyseal forearm rather than the radial neck, as the neck is bowed posteriorly in the usual posterolateral dislocation. The cut

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FIGURE 16-4 Operative exposure revealing capitellar deformity and degenerative change with chondral thinning from a congenital radial head dislocation and now pain in adolescence.

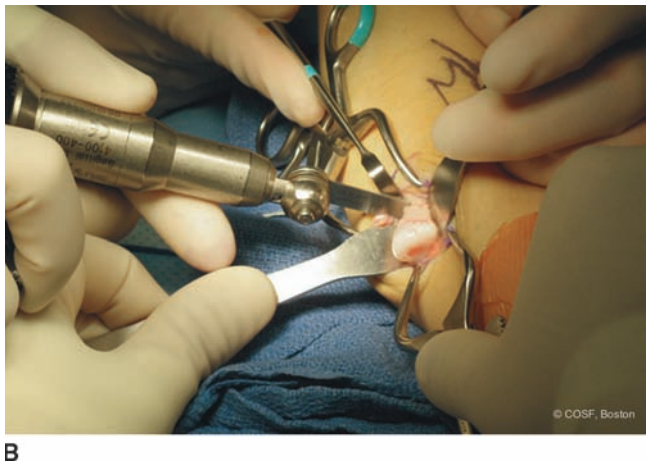
can be started with the saw (Figure 16-5B) but is usually finished with an osteotome for better control and less risk of chondral or nerve injury in the tight space. Fluoroscopy is used to determine the level of excision and proper angle of cut to prevent impingement (Figure 16-3C). Biceps tendon insertion is preserved. Full forearm rotation should be possible with improved flexion-extension arc.

After excision, the joint is inspected for loose bodies and debrided of synovitis and fibrosis overgrowth. Final fluoroscopic views are obtained to be certain that the level and angle of excision are as desired and that there are no remaining loose bodies in the joint. Bone wax is placed over the proximal radial neck. If appropriate due to the age of the patient and degree of chondral damage, an anconeus muscle flap is placed in the joint.[19] Since the anconeus has dual proximal and distal blood supply, it can be mobilized and inserted while still viable. Generally, the distal aspect is left intact, and the proximal aspect is used for the interpositional arthroplasty. Capsular and fascial closure is performed over a drain. Before skin closure, full forearm rotation is confirmed once again. A loose-fitting splint is applied that allows for forearm rotation to begin immediately. A regional block is helpful to allow for pain-free rotation. This enables the parents and child to immediately see and feel the full motion that the patient never had previously. After 10 to 14 days of wound healing, the splint is removed, and more aggressive therapy is begun. Ultimately the goal is for the patient to be pain free with improved forearm rotation.

◆ Wrist Pain after Radial Head Resection

A disappointing and major concern is the development of wrist pain after excision of a congenital radial head dislocation. This indicates longitudinal instability of the forearm. Is the pain sufficient to warrant operative intervention? Wrist pain with neutral variance may be

A



B

FIGURE 16-5 **A:** Resected specimen with arthrosis and deformity of the radial head. **B:** Radial head resection with oscillating saw perpendicular to the radial neck while protecting posterior interosseous nerve.

FIGURE 16-6 Congenital radial head dislocation long-term lateral radiograph with marked arthrosis.

tolerable, but with positive variance, it is often disabling (Figure 16-6). The choice of operative intervention to rebalance the forearm and provide longitudinal stability can be difficult. Of note, radial head implants are rarely used in children and in their present form have long-term radiocapitellar problems. Reconstructions of the interosseous ligament have had marginal results in adults. The most common operative interventions for this rare situation are (1) an ulnar shortening osteotomy to rebalance the forearm or (2) the creation of a single-bone forearm. In a longitudinally unstable forearm, you can "whittle away" at either end trying to keep motion and resolve impingement. The definitive treatment is the creation of a single-bone forearm, but this comes at the cost of loss of forearm rotation. The details of these procedures are in Chapters 34 and 47.

In the young, and especially those who need functional forearm rotation, we begin with an ulnar shortening osteotomy. Hopefully, this resolves their pain and stabilizes their radioulnar relationships. If this fails, or if the patient (1) needs definitive treatment and (2) can tolerate loss of forearm rotation, then a single bone forearm is the current treatment of choice.

◆◆ Open Reduction Congenital Dislocation

The best advice I can give for playing a ball out of water is—don't.
—Tony Lema

For us, open reduction for a congenital radial head dislocation is an operation rarely performed. The circumstances have to be just right: diagnosis in infancy; limited deformity of the radial head and capitellum; no other regional or systemic abnormalities that would negatively affect the outcome; patient's family educated about natural history versus potential benefit of operative reconstruction. For example, the most ideal candidate for us is an infant, with an isolated congenital dislocation, diagnosed around birth, with a parent who had a painful congenital radial head dislocation. How often does that scenario come along? Fortunately, open reduction, radial osteotomy, and annular ligament reconstruction were successful.

Surgery follows principles and techniques described in chronic Monteggia reconstruction[21] (see Chapter 30). The difference is that a radial osteotomy may be required to achieve stable joint reduction.[13] This is rare enough, and there is enough pathoanatomic variation that, beyond following the principles outlined, the surgeon has to have a high level of skill and knowledge to be able to adapt and figure it out in the operating room.

POSTOPERATIVE

After radial head resection, early motion is imperative to improve forearm rotation. This is begun in the recovery room in a bulky splint and continues throughout the first 6 to 12 weeks after surgery. The elbow flexion-extension arc is protected either in a hinged brace or bulky splint for 2 weeks with wound healing, and then rehabilitation is begun to maintain or improve elbow extension.

With open reduction, long-arm cast protection in the young is maintained for 4 weeks to assure joint stability. Therapy is initiated after discontinuation of the cast.

ANTICIPATED RESULTS

Natural history can result in minor pain, minimal functional problems, minor limitations of elbow extension, and more restriction of forearm rotation, especially supination.[22,23] Operative intervention should not do worse than that. With infantile open reduction, the goal is restoration of anatomic, stable radiocapitellar and radioulnar joints with full forearm rotation. The published results vary to the extremes from complete failure to complete success.[13,17,21,24]

Arthrosis can occur by natural history (Figure 16-6). In the presence of progressive pain, radial head excision can provide pain relief and improved forearm rotation without significant change in elbow arc of motion. This is most often performed at skeletal maturity but can be performed earlier if symptoms warrant.[17,18,25,26] By the adult traumatic literature, the results tend to be long-standing. There also will be an aesthetic improvement if the radial head dislocation was very prominent.

COMPLICATIONS

Radial Head Excision

Minor wrist pain can occur. Fortunately, the wrist pain is usually much less severe than the preoperative elbow pain.[18] "Regrowth" of the proximal radius does occur in 10% to 30% of patients, especially in the skeletally immature.[18,25] If this causes recurrent impingement, then repeat excision is warranted. Longitudinal forearm instability is much less common in congenital radial head excisions than post-traumatic. However, progressive positive ulnar variance at the wrist with painful ulnocarpal impaction does occur (Figure 16-7). Finally, the posterior interosseous nerve needs to be protected to prevent nerve injury and palsy.

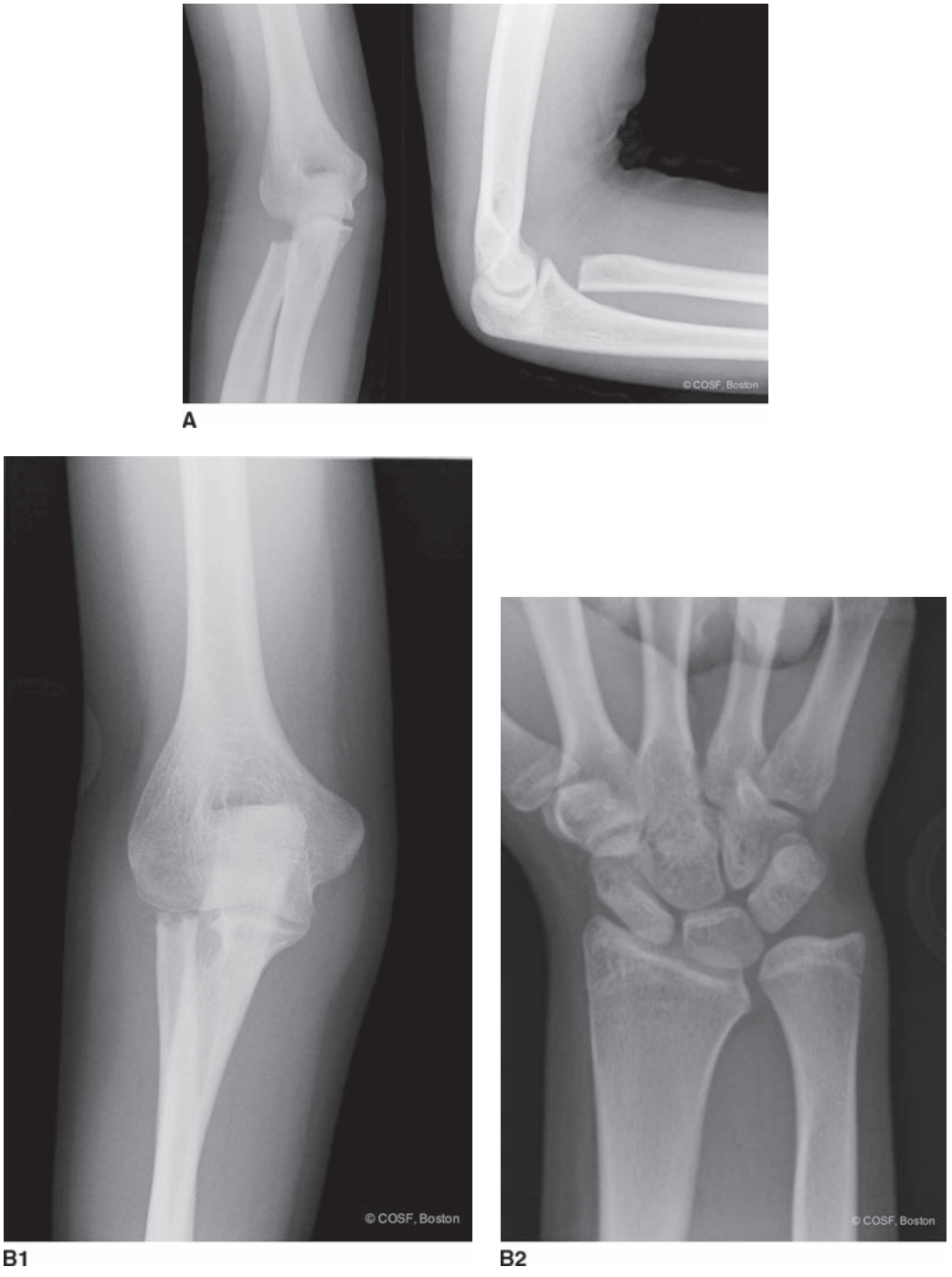


FIGURE 16-7 **A:** Postoperative AP and lateral radiographs of congenital radial head resection. **B:** Longer term postoperative AP radiographs of the elbow (B1) and wrist (B2) revealing proximal migration of the radial neck with recurrent radiocapitellar impingement and now positive variance at wrist.

Open Reduction Congenital Dislocation

The major complications here are loss of reduction, limitations of motion, and failure of remodeling. Surgical intervention then is for naught.

CASE OUTCOME

This symptomatic patient underwent radial head excision. On the operative table, his forearm rotation was restored to full pronation and supination to 70 degrees passively, and elbow extension was improved to –10 degrees. He started physical therapy in the recovery room under regional anesthesia. He continued protected therapy for 6 weeks. At 3 months, he was pain free and back to sports with improved appearance, arc of forearm rotation from 60 degrees supination to 80 degrees pronation, and elbow motion for 10 to 135 degrees of flexion. Fortunately, he did not develop wrist pain, and his elbow pain and locking resolved (Figure 16-3C and D).

SUMMARY

Congenital dislocation of the radial head is an isolated problem about two-thirds of the time, with associated regional anomalies or syndromic conditions in about one-third of patients. There are often minor restrictions in elbow extension and more marked limitations in forearm rotation in the isolated posterolateral dislocation. Function is generally not significantly impaired due to adaptive mechanisms. Surgical excision of the radial head is indicated only when progressive pain markedly limits function. This is most often in adolescence or early adulthood. Wrist pain and reformation of proximal radius bone are the most common complications. There is limited experience with open reduction of the radial head with case series reporting both success and failure. There are some very prominent radial head dislocations for which cosmetic excision is warranted in adolescence or early adulthood.

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CHAPTER

17

Radioulnar and Metacarpal Synostosis

I. RADIOULNAR SYNOSTOSIS

CASE PRESENTATION

A 12-year-old male presents for evaluation of an elbow deformity. The patient was in a usual state of health until he sustained a fall onto his elbow while playing baseball. At that time, there was minimal swelling or deformity, though he was noted to have limited forearm rotation. Radiographs of the forearm were obtained to rule out a fracture, and the patient was diagnosed with a "birth defect" (Figure 17-1). He presents now for orthopaedic consultation. Of note, with further questioning, his parents report he's always had difficulty with certain activities, including fielding a ground ball at second base and swinging a bat.

CLINICAL QUESTIONS

- What is the cause of a congenital radioulnar synostosis (RUS)?
- Is it hereditary? Are there any associated syndromes?
- How is congenital RUS classified?
- What are the indications for surgical treatment?
- What are the surgical treatment options?
- Is there an optimal position for fixed forearm rotation?
- What are the complications of surgery for RUS?
- What are the expected outcomes?

THE FUNDAMENTALS

Etiology and Epidemiology

Congenital RUS refers to an abnormal connection between the radius and the ulna due to an embryological failure of formation.[1] During the fourth to sixth week of gestation, the upper limb bud develops into the fully formed upper extremity. Between roughly the 37th and 57th day of gestation, a distinct humerus, radius, and ulna are formed. During this period, the forearm arises from a single cartilaginous anlage, which separates longitudinally to form a radius and ulna. Failure of separation results in a congenital RUS. As the separation occurs sequentially from distal to proximal, the RUS characteristically involves the proximal third of the forearm. Furthermore, as the forearm is positioned in pronation in utero, the resulting fusion between the radius and ulna results in varying degrees of fixed forearm pronation.[2–5] It has been hypothesized that both congenital RUS and radial head dislocation are developmentally related, distinguished only by subtle differences in the timing of the developmental insult.[6]

Given that up to 20% of patients will have a positive family history, it is thought that congenital RUS may be inherited in an autosomal dominant fashion with variable penetrance and expressivity.[7]

Approximately one-third of patients with RUS will have associated syndromes or anomalies, including Apert syndrome, Carpenter syndrome, arthrogryposis, Williams syndrome, and Klinefelter syndrome.[3] Other conditions, including polydactyly, syndactyly, carpal coalition, and radial longitudinal dysplasia, have also been associated with RUS. Sex chromosomal anomalies have also been associated with RUS.[8]

Clinical Evaluation

Given the infrequency with which the condition occurs, diagnosis is often not made until patients are of school age.[7] As elbow flexion and wrist flexion-extension are typically unaffected, and young children demonstrate great compensatory rotation through the radiocarpal and midcarpal joints, patients with RUS have little initial functional limitations. The lack of true forearm rotation and usually mild elbow flexion contracture (~20 degrees) are not usually noted early on in life. Later, relatives, teachers, or coaches will identify limitations of forearm rotation with specific activities (e.g., hand washing at school, toilet training due to inability to place the supinated hand to the perineum, catching a ball, swinging a racquet or baseball bat). It is not uncommon for the diagnosis to be made incidentally on radiographs obtained after traumatic events.

Patients will present with fixed forearm pronation (Figure 17-2). In severe cases, "backhanding" may be seen with hand-to-mouth activities or in placing objects in the

FIGURE 17-1 Elbow radiographs of a congenital RUS.

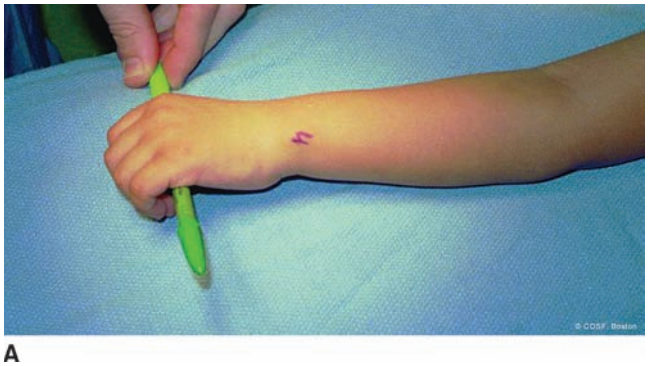

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FIGURE 17-2 **A:** Clinical photographs demonstrating fixed left forearm pronation. **B:** Compensatory motion is seen through the wrist, simulating forearm supination to neutral.

affected palm. Careful physical examination should be performed, as compensatory rotation through the wrist may mask fixed forearm position. Forearm position can be reliably assessed by determining the axis between the radial and ulnar styloids when the arm is adducted and elbow flexed 90 degrees. Elbow flexion and wrist flexion and extension are preserved, and the distal radioulnar joint is typically stable. In severe cases, forearm segment shortening and abnormal elbow carrying angle may be seen. The majority of patients, however, will have minimal impairment of hand function.[9]

Radiographs of the entire forearm will demonstrate a bony connection between the proximal radius and ulna; less commonly, there is a more extensive synostosis. At times, the lack of forearm rotation is due to a cartilaginous or fibrous connection between the two bones. The ulnohumeral is typically normal in appearance. The distal radioulnar joint may be distorted in cases of extreme forearm pronation. Depending upon the severity of involvement, there may or may not be a congenital radial head dislocation or absence of the radial head as it is a part of the synostosis. Often a subtle bow to the proximal ulna is seen. This ulnar bow may be a part of the mild elbow flexion contracture commonly noted on physical examination.

Several classification systems have been proposed. Mital classified RUS into two types.[2] Type 1 refers to a synostosis between the radial epiphysis and the metaphysis. Type 2 refers to a synostosis distal to the radial physis, associated with a radial head dislocation. Cleary and Omer based their classification upon the morphology and position of the radial head.[7] Type 1 patients have a normal-appearing radial head and radiocapitellar alignment with a fibrous synostosis. Type 2 denotes a bony synostosis with a normal-appearing, reducted radial head. Type 3 refers to bony synostosis with a hypoplastic and posteriorly dislocated radial head. In Type 4 RUS, the radial head is dislocated anteriorly.

Surgical Indications

Keep it simple, when you get too complex you forget the obvious.
—Al McGuire

Surgery is recommended for functionally limiting loss of forearm rotation; this is dependent upon both the severity of the pronation deformity and whether there is unilateral or bilateral involvement.[10] Bilateral involvement with hyperpronation of the forearms results in greater difficulties with daily activities, whereas unilateral involvement with mild pronation position leads to little functional compromise. In their series of 23 patients with RUS observed over 22 years, Cleary and Omer reported that over 95% of patients report little or no limitations with activities of daily living or work.[7] Simmons et al.[3] and Ogino et al.[11,12] both reported that patients with >60 degrees of pronation had difficulties with daily living.

The optimal position of forearm rotation remains controversial. Historically, in cases of bilateral involvement, 30 to 45 degrees of pronation of the dominant limb and 20 to 30 degrees of supination of the nondominant limb were considered ideal.[12] Simmons et al.[3] advocated that the dominant limb should be positioned in 10 to 20 degrees of pronation with the nondominant limb in neutral rotation. Given the tabletop and keyboarding demands of the modern-day world, mild pronation of both limbs is currently considered ideal.[13]

SURGICAL PROCEDURES

Not even God can hit a one-iron.
—Lee Trevino

While theoretically reconstructing a proximal radioulnar joint would restore forearm rotation and improve function, attempts at synostosis resection and joint reconstruction have been met with near-universal failure. Attempts at simple bony resection have not succeeded.[5,14–16] Interpositional arthroplasties with soft tissue and metallic implants have been similarly tried.[17] More recently, attempts at synostosis resection and free vascularized tissue interposition have been reported, with gains in short-term forearm rotation.[18–21] Given the complexity and morbidity associated with these techniques, in addition to the reliability of simpler surgical strategies, microvascular free tissue procedures have not yet become the standard of care for RUS.

Rather than attempting to create a proximal radioulnar joint where none had ever developed, most current surgical treatment strategies have focused on derotating the forearm-hand unit to a more functional position. A number of techniques have been advocated, all of which involve osteotomies of the radius and/or ulna and derotation from an extreme pronated position to a more functional one. Green and Mital[12] advocated osteotomy through the synostosis and K-wire fixation (Figure 17-3). Lin et al.[22] described their technique of radioulnar osteoclasis, in which percutaneous osteotomies were performed of the radial and ulnar diaphyses at different levels. After initial osteotomies, no attempt is made at derotation, and a long-arm cast is applied. Approximately 1 week later, the cast is removed and the forearm is derotated under general anesthesia to the desired position. No internal fixation was utilized in their technique, and cast immobilization for an additional 6 to 8 weeks was used until bony healing. A delayed union rate of up to 16% has been reported with this technique.[23] Others have advocated variations of this technique using internal fixation with osteotomies of one or both forearm bones.[24–28]

Radioulnar Synostosis Osteotomy

Under general anesthesia and tourniquet control, fluoroscopic guidance is used to identify the level of the RUS. A longitudinal incision is made over the subcutaneous border of the ulna at the level of the RUS. Careful subperiosteal elevation is performed circumferentially around

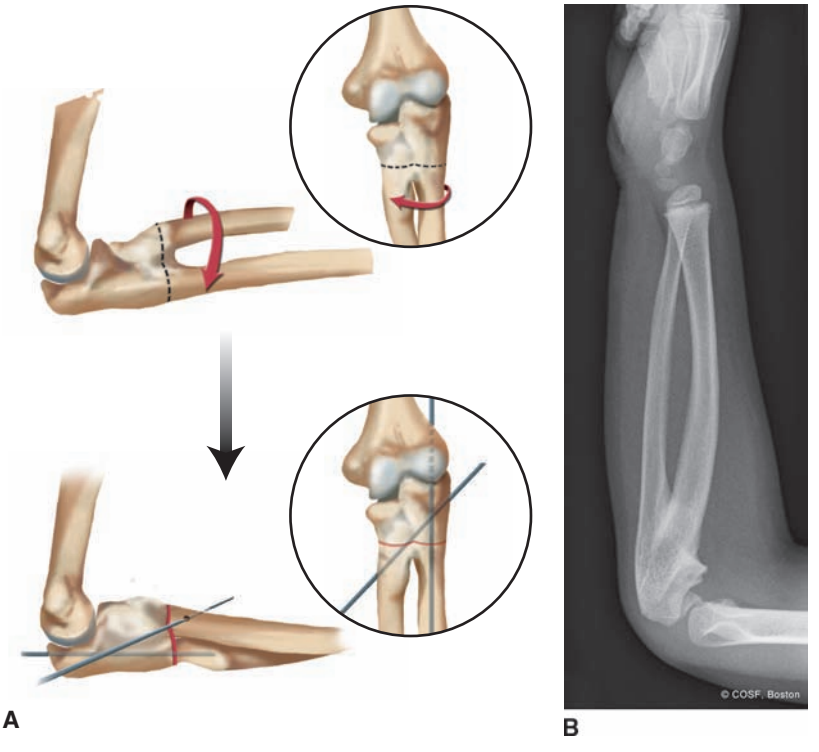
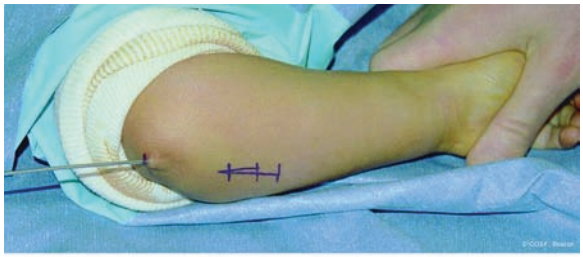


FIGURE 17-3 Derotational osteotomy for congenital RUS. **A:** Schematic representation of the surgical technique. **B:** Preoperative radiograph of a 6-year-old boy with a left RUS and hyperpronation deformity.



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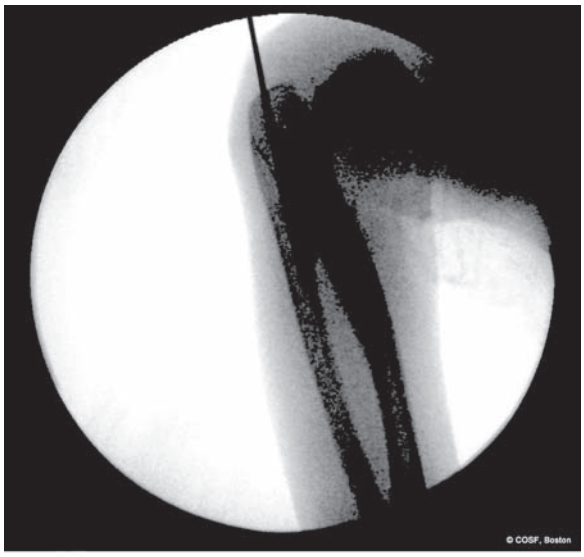

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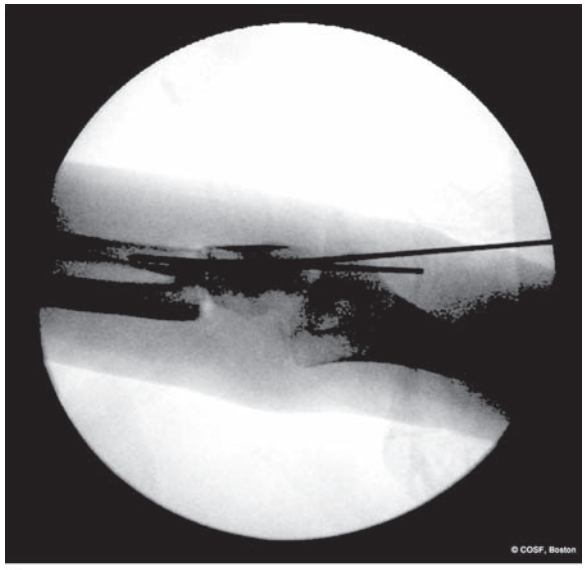

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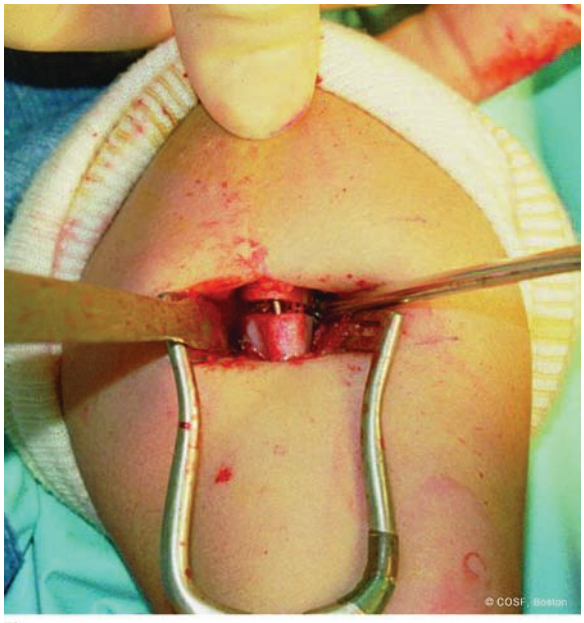

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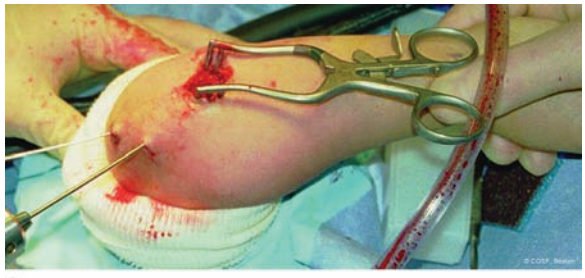

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FIGURE 17-3 *(continued)* **C:** Intraoperative photograph depicting the osteotomy incision and trajectory of the IM ulnar K-wire. **D:** Intraoperative fluoroscopic image after IM ulnar pin has been placed. **E:** Intraoperative photograph demonstrating the osteotomy cut with IM K-wire evident. **F:** Radiograph after the second oblique pin has been placed following derotation correction. **G:** Intraoperative photograph after the second oblique K-wire has been placed. **H:** Intraoperative photograph depicting the prophylactic forearm fasciotomy.

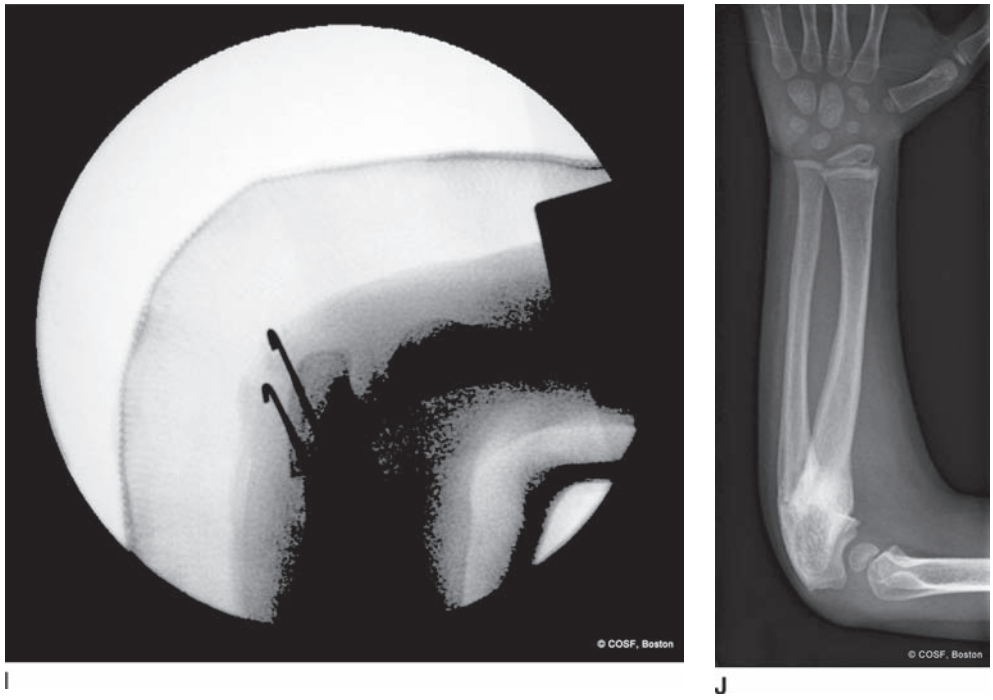


FIGURE 17-3 *(continued)* **I:** Radiographs obtained after final position has been achieved. Note the bulky postoperative dressing and the large girth of the cast to allow for postoperative swelling. **J:** Follow-up radiographs after 3 months. Note complete bony healing in a position of neutral rotation to slight pronation.

the synostosis, with particular attention to avoid buttonholing through the soft tissue envelope anteriorly. Care is made to avoid violation of the elbow joint. After the synostosis is exposed, an appropriately sized stainless steel K-wire is introduced into the olecranon apophysis percutaneously and passed down the intramedullary (IM) canal of the ulna, well beyond the synostosis (Figure 17-3). Care is taken to only make the cortical entry with power and then tap the remainder of the way with a mallet. This prevents false passage of the wire out the opposite cortex, a mishap that can truly prolong your operative time. The IM wire allows for derotation after the osteotomy is made while preventing angulation or translation of the osteotomy fragments.

After the IM K-wire is placed, a transverse osteotomy is performed with the use of a narrow sagittal saw at the level of the synostosis distal to the joint. Copious irrigation is used to avoid thermal necrosis. Judicious placement of small Homan or Bennett retractors will provide adequate soft tissue protection including the posterior interosseous nerve. Care is made to avoid notching or hitting the previously placed K-wire during the osteotomy cut. After the osteotomy is created, the forearm may be gradually derotated into its new position, typically 10 to 20 degrees of pronation. Rotational control and additional stability are then achieved by placing percutaneous oblique K- or C-wires across the osteotomy.

Following confirmation that the appropriate forearm position has been achieved, the wires are bent and cut outside the skin. Under direct visualization and subcutaneous skin flap elevation, limited prophylactic dorsal and forearm fasciotomies are performed to lessen the risk of postoperative compartment syndrome. Periosteum is reapproximated with heavy absorbable sutures, and the wound is closed. A well-padded long-arm cast is then applied, which is then bivalved to allow for postoperative swelling.

POSTOPERATIVE

Following derotational osteotomy, patients are admitted for observation, with serial clinical examinations to rule out compartment syndrome. Patients are kept in a long-arm cast for 4 weeks, after which pins are removed. Depending on the age of the patient and degree of radiographic healing, additional cast immobilization for 2 weeks may be needed before discontinuing the cast and initiating range of motion (ROM) exercises.

ANTICIPATED RESULTS

With appropriate patient selection and surgical technique, excellent outcomes can be expected with respect to bony

healing and improvement in forearm position. Patients will report high levels of satisfaction with their abilities to perform activities of daily living and other recreational activities. Furthermore, as these patients never had forearm rotation, the persistent lack of motion is not troubling.

COMPLICATIONS

Early reports of surgical treatment for RUS cite complication rates as high as 36% from surgical treatment.[3] Potential complications include infection, loss of position, implant failure, neurovascular compromise, and compartment syndrome.[29] Careful soft tissue dissection and retraction, use of prophylactic fasciotomies, and judicious bony resection (see Coach's Corner) will aid in reducing the risk of these postoperative complications.

Given the tension on the neurovascular structures and the risk for compartment syndrome, percutaneous K-wire fixation confers additional advantages. Postoperatively, if a patient is demonstrating neurological deficits or signs of impending compartment syndrome, the pins may be removed at the bedside, and the forearm allowed to rotate around the IM K-wire back into a position of comfort and safety. This avoids the need for a second anesthetic and allows for immediate intervention, if necessary. This can also be achieved with an external fixation. Plate and screw fixation should clearly be avoided.

CASE OUTCOME

Radiographs demonstrate a congenital RUS. Clinically, the forearm was fixed in 90 degrees of pronation with mild compensatory radiocarpal supination. Given the radiographic findings and functional limitations, the patient underwent derotational osteotomy through the synostosis site, positioning the forearm in 10-degree pronation. Postoperatively there was no neurovascular compromise, and pins were removed at 4 weeks (Figure 17-3). He went on to successful bony union and functional improvement, particularly with personal hygiene, carrying objects, and baseball activities.

SUMMARY

Congenital RUS represents a failure of differentiation in which the proximal radius and ulna are fused, typically in a position of forearm pronation. Clinical presentation and diagnosis are often delayed due to the compensatory supination through the young, flexible wrist. In cases of extreme pronation with accompanying functional limitations, surgical treatment is indicated. Derotational osteotomy through the synostosis site is safe, reliable, and results in improved forearm position.

COACH'S CORNER

Removing the "Napkin Ring" of Bone

Simplify the game as much as possible. When you add, you must subtract.
—Don Meyer

In cases of hyperpronation, a great deal of derotation is required to position the forearm and hand in the most functional position. While this can be achieved in a single-stage procedure as described above, excessive derotation can put tension on the adjacent soft tissues and, in particular, neurovascular bundles, especially the interosseous vessels. Given the additional soft tissue swelling that can be expected following any osteotomy and the change in cross-sectional dimensions of the forearm, compartment syndrome is clearly a postoperative risk. From the green circle to the black diamond level of surgery, we perform limited prophylactic dorsal and volar forearm fasciotomies to minimize these risks. With elevation and retraction of the skin flaps, long tenotomy scissors may be used to release the fascia in the region of the osteotomy under direct visualization. This maneuver also facilitates periosteal closure at the osteotomy site and, therefore, bony healing.

II. METACARPAL SYNOSTOSIS

CASE PRESENTATION

A 1-year-old female presents for evaluation of a deformed finger (Figure 17-4). The family reports that the left small finger has stuck out to the side since birth. The child has difficulty with fist formation and catching the finger on objects. The family also reports that the "knuckle" is missing, and the finger appears short.

FIGURE 17-4 Clinical photograph of a child with a small-ring metacarpal synostosis. Note the abducted position of the small finger.

CLINICAL QUESTIONS

- What is metacarpal synostosis?
- Why does it occur?
- What are the characteristic clinical features?
- What are the surgical treatment options?

THE FUNDAMENTALS

Etiology and Epidemiology

Metacarpal synostosis refers to abnormal congenital bony connections between adjacent rays, due to a failure of differentiation during the embryological formation of the hand. Most commonly affecting the small and ring finger metacarpals, the condition may be bilateral in up to 60% to 80% of cases[30] (Table 17.1). Although the proximal ends of the metacarpals are fused, often the metacarpophalangeal (MCP) joint is splayed and/or rotated on the ulnar aspect of the hand. This results in an abducted small finger that is frequently hypoplastic.

In an animal model, Ogino and Ohshio were able to produce metacarpal synostosis with polydactyly using the teratogen busulfan. They and others have postulated a failure of differentiation due to an abnormality in ectoderm-mesoderm interaction in the developing limb bud.[11]

There may be a familial component to this condition, and both X-linked and autosomal dominant inheritance patterns have been described.[31–33]

Clinical Evaluation

Clinical presentation is variable. While some infants are evaluated due to obvious abnormalities in appearance and limitations in small finger function, occasionally patients will not present until adolescence if the angular and rotational deformity is subtle. In the latter situations, patients may only note a shorter digit or aesthetic difference in the appearance of the MCP joint in flexion, exacerbated during the adolescent growth spurt.

In the typical cases of small-ring finger involvement, physical examination of the hand will demonstrate an abducted and hypoplastic small finger. Digital overlap or underlap ("scissoring") may be seen with attempted fist formation. Abnormal or absent digital flexion and extension creases will reflect the degree of skeletal involvement and affected digital motion.[31] Patients will complain of difficulty with fist formation, power grip, or placing their hands in pockets or sleeves. Adduction of the small finger is difficult due to both bony alignment and absence or hypoplasia of the third volar interosseous muscle.

A number of associated conditions and syndromes have been described, including Apert syndrome, central polydactyly, symbrachydactyly, thumb hypoplasia, and radial and ulnar longitudinal dysplasia.[30,34]

Plain radiographs will confirm the diagnosis. Buck-Gramcko and Wood[30] have previously characterized three types of deformity. In type I cases, the proximal aspects of the metacarpals are fused, resulting in normal growth potential and minimal deformity. Type II synostosis extended half the length of the metacarpal. In these situations, the small finger was small, short, and ulnarly deviated. In type III patients, synostosis extended more than half the length of the metacarpals, often involving the entire bone. Type III was divided into two subtypes, according to the degree of MCP joint involvement. Type IIIA had distinct MCP joints for the small and ring fingers, whereas type IIIB patients had a conjoined MCP (the so-called super digit, where two fingers appear to arise from a single metacarpal).[35]

Foucher et al.[36] have proposed another classification system, based not on the degree of synostosis but rather on the pattern of deformity. This radiographic classification is helpful in guiding surgical treatment. I-shaped synostoses, either distinct or fused, require no treatment. U-shaped synostoses denote parallel epiphyses and therefore are only operated on if there are length differences. Y-shaped deformities are treated with a trapezoidal osteotomy with subsequent interposition to restore appropriate alignment.

Table 17.1

Patterns of metacarpal synostosis, as described by Buck-Gramcko and Wood in a series of 109 patients

Metacarpals Involved	Number (Out of 109)
Fourth-fifth	99
Third-fourth	13
First-second	9
Second-third	1
Fifth-sixth	6
Third-fourth-fifth	3
First-second-third-fourth	2
Second-third-fourth	1

Adapted from Buck-Gramcko D, Wood VE. The treatment of metacarpal synostosis. *J Hand Surg Am.* 1993;18:565–581.

Surgical Indications

Surgical reconstruction is indicated in patients with functional limitations or progressive deformity. Patients and families are dissuaded from pursuing surgical intervention for aesthetic reasons only. In cases of the so-called super digit, great caution is taken before undertaking reconstruction, as often two mobile functioning digits may be transformed into straighter, stiffer, less functional fingers despite improved radiographic appearance. In these situations, surgical treatment is best addressed in the phalanges rather than through the shared conjoined metacarpal.[37]

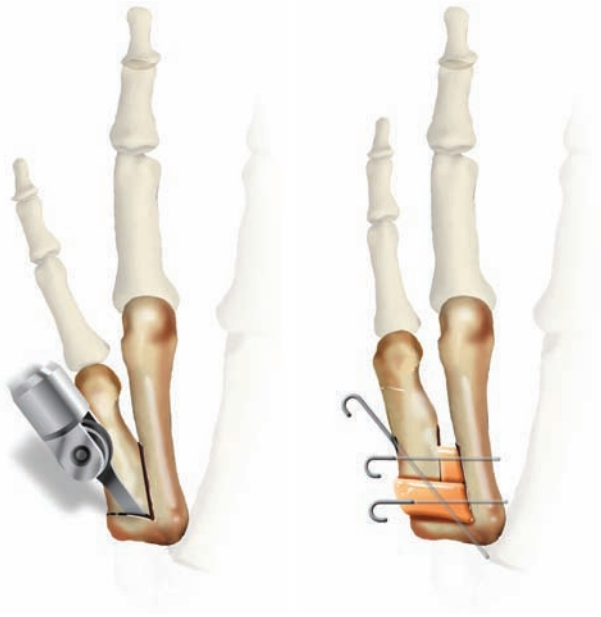


FIGURE 17-5 Schematic diagram of surgical reconstruction of the small-ring metacarpal synostosis with bone graft lengthening of small finger.

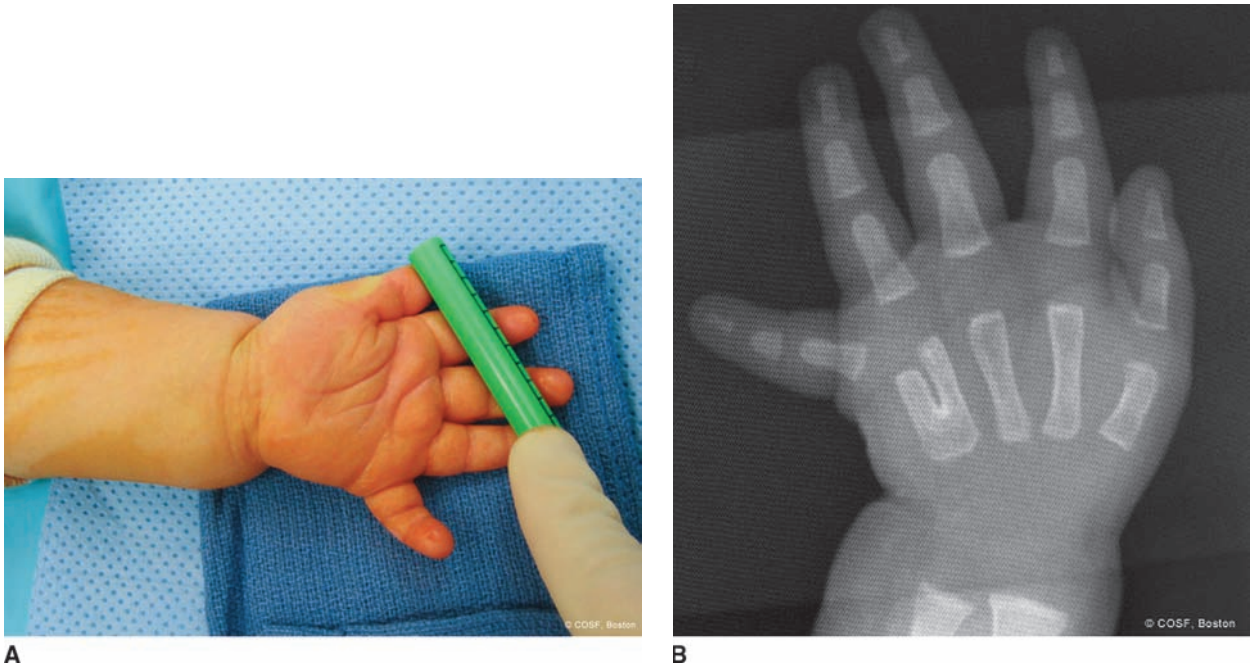
Surgical principles involve separation of the conjoined metacarpals and restoration of angular and rotational alignment. This usually involves osteotomies and bone grafting to reconstitute the intermetacarpal distance[30,38–40] (Figure 17-5). External fixation with gradual distraction lengthening and realignment has also been advocated.[41,42] In the past, silicone or costal cartilage interpositions have been attempted, with often imperfect and unreliable outcomes.[41,43–46] Metacarpal lengthenings have also been described.[47] Although rare, amputation of a stiff, hypoplastic, nonfunctioning digit may offer the best functional gain, particularly in cases of central polysyndactyly. Soft tissue realignment, particularly release of the abductor digiti quinti and/or transfer to the extensors of the ring finger, may be necessary.[35] For us, the most reliable surgery has been longitudinal separation of the ring and small finger metacarpals with broad allograft interposition as advocated by Light. Some of the other techniques brought disappointment or mild satisfaction; this technique has brought long-term outcomes.

Ideal timing of surgery is controversial and remains individualized. While early surgery (before the age of 2 years) has brought long-term positive outcomes, the small size of the skeletal structures and risks of physeal disturbance provide technical challenges. Surgery in older children and adolescents is more facile, but fixed contractures can occur, and fine motor function can be more difficult to relearn.

SURGICAL PROCEDURES

Metacarpal Synostosis Osteotomy with Bone Grafting

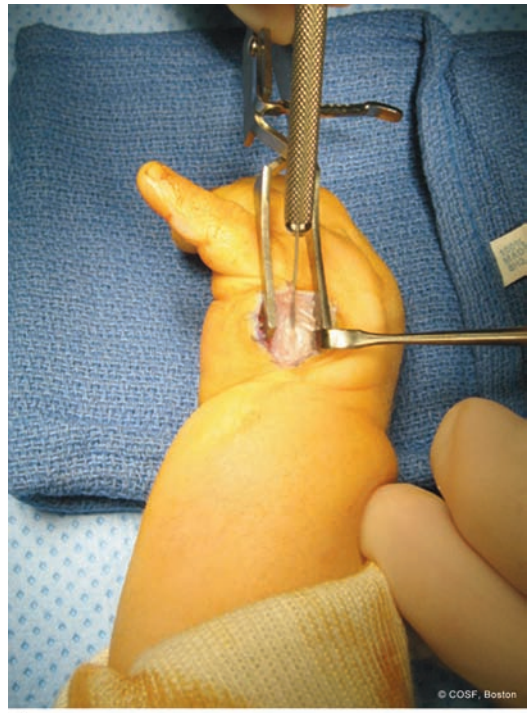
Under general anesthesia and tourniquet control, a dorsal longitudinal incision is created overlying the synostosis between the small and ring fingers (Figure 17-6).



A B

FIGURE 17-6 Osteotomy and bone grafting for small-ring metacarpal synostosis. **A:** Preoperative volar view of the abducted, shortened small finger. **B:** Radiograph depicting the synostosis (Buck-Gramcko and Wood type I, Foucher U-type).

C



D

E

F

FIGURE 17-6 *(continued)* **C:** Dorsal incision. **D:** Periosteum is incised directly at the level of the synostosis, protecting the distal physes. **E:** An osteotome is used to perform a longitudinal osteotomy. **F:** After bone graft placement and deformity correction, radiographs depict improved alignment and transverse intermetacarpal pin fixation.

After identification and protective retraction of the extensor tendons, the periosteum overlying the synostosis site is incised. Intraoperative fluoroscopy is utilized to prevent inadvertent violation of the physes. Careful subperiosteal elevation is performed, exposing the synostosis site. Under direct visualization and with fluoroscopic guidance, a longitudinal or oblique osteotomy is created, dorsal to volar, between the metacarpals. This may be extended through the base of the metacarpals into the carpometacarpal (CMC) joint or obliquely passed ulnarly just distal to the fifth CMC joint. The two metacarpals need to be completely separated. Once the synostosis has been osteotomized, a small laminar spreader is placed into the intermetacarpal space. As the laminar spreader is opened, gradual improvement in the longitudinal and rotational alignment of the small finger spontaneously occurs. Once the appropriate alignment has been achieved, structural autogenous bone graft or allograft is placed in the gap. If the fifth ray is considerably shorter, bone graft may be positioned to lengthen the metacarpal as well as increase the distance between the adjacent metacarpal bases. Inspection of the alignment is made both with the digits extended and with tenodesis maneuver to confirm adequate correction of the malrotation. Percutaneous transmetacarpal pins (typically 0.035" in younger patients) are then passed transversely from ulnar to radial, engaging the small finger ray, bone graft, and ring finger metacarpal. Fluoroscopy is utilized to confirm graft position and pin placement. Pins are bent and cut outside the skin to facilitate subsequent removal. Soft tissues are reapproximated and skin closed. A well-padded hand-based cast is then applied.

POSTOPERATIVE

Patients remain casted until 4 to 6 weeks postoperatively. At that time, pins are removed in the office, and cast immobilization continued until evidence of bony healing, particularly in the young, noncompliant, or nonverbal child. Once healing has been achieved, ROM and strengthening are begun, typically under the supervision of a certified hand therapist with splint protection.

ANTICIPATED RESULTS AND COMPLICATIONS

Using the techniques described here, excellent bony healing and functional hand improvement will result. Complications are not common with the single-stage correction described here. Despite improvements in alignment, often MCP joint motion improves incompletely, and persistent differences in metacarpal length remain. (Usually the affected fifth ray is ~60% to 70% of normal.) Families must be counseled in advance regarding the potential of persistent stiffness and length discrepancies.

CASE OUTCOME

Based upon clinical presentation and radiographic findings, the diagnosis of metacarpal synostosis was made. Given the ulnar deviation of the small finger and its effect on hand function, this patient underwent surgery at 18 months of age (Figure 17-6). The synostosis was osteotomized while preserving the cartilaginous CMC joint, and bone graft was placed at the synostosis site to increase the intermetacarpal distance. This resulted in correction of both malrotation and angulation of the small finger. The patient went on to successful bony healing and hand use.

SUMMARY

Metacarpal synostosis represents a congenital failure of differentiation. Most commonly affecting the small and ring metacarpals, bilateral involvement is common. Osteotomy and bone grafting of the synostosis site will often improve longitudinal and rotational alignment. Care should be made to evaluate the small finger, which is often hypoplastic and may require additional surgical reconstruction.

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CHAPTER

18

Congenital Pseudarthrosis of the Clavicle

CASE PRESENTATION

A 16-year-old male presents again with a right clavicular prominence noted since childhood. Diagnosis in childhood was congenital pseudarthrosis of the clavicle based on exam and radiographs. He has noted increasing prominence over the years and is now having pain and numbness with overhead activities. Clinical photograph, radiograph, and computed tomography (CT) scan are seen in Figure 18-1.

CLINICAL QUESTIONS

- What causes congenital pseudarthrosis of the clavicle?
- What are the conditions associated with congenital pseudarthrosis of the clavicle?
- What is the natural history?
- What are the surgical indications for repair?
- Is the type of surgery time dependent?
- What are the complications of both natural history and surgery?

THE FUNDAMENTALS

The obscure we see eventually. The completely obvious, it seems, takes longer.
—Edward R. Murrow

The clavicle is an S-shaped bone overlying the subclavian vessels and brachial plexus. This bone articulates medially with the sternoclavicular joint and laterally with the acromioclavicular joint. The two membranous primary centers of ossification appear at about 6 weeks postconception and fuse about 1 week later. The medial cartilaginous mass contributes more to clavicular growth than the lateral mass does. The junction of the two centers of ossification is between the medial two-thirds and lateral third of the clavicle.

Congenital pseudarthrosis of the clavicle is a failure of coalescence of these two centers. The congenital nonunion is hypertrophic and can be progressive in size with growth. This nonunion can lead to local neurovascular compression.[1,2] Definitive treatment involves open repair with bone grafting.[3]

Etiology and Epidemiology

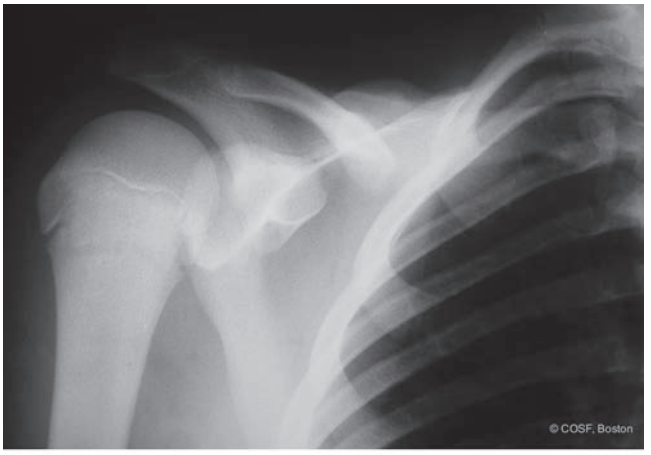
Congenital pseudarthrosis of the clavicle is a rare condition, most often presenting as an isolated anatomic variation.[4–7] Unilateral cases almost universally affect the right clavicle. There can be an associated high first rib and/or cervical rib. Left-sided presentation does occur[8] and is generally associated with dextrocardia and situs inversus.

The theory is that the failure of consolidation of the ossification centers is related to the high subclavian artery on the right side (or left side in dextrocardia).[5] Bilateral cases do occur. There is a familial incidence.[9] Associated conditions include cleidocranial dysostosis, neurofibromatosis, trisomy 21, and other rarer syndromes (Goltz, Floating Harbor, Prader Willi, chromosome 10p deletion). Histologic evaluation of the pseudarthroses indicates enchondral ossification on both sides of the resected specimens, indicative of failure of coalescence of the two primary centers of ossification.[10,11]

Clinical Evaluation

These children generally present with a right-sided prominence of their diaphyseal clavicle. There may be a foreshortened shoulder girth. Initially, this foreshortening is usually asymptomatic. The children may present at birth (Figure 18-2). In some respects, early presentation is most fortunate because surgery is less invasive in infancy.[12] The prominence often increases in size with growth. Range of motion, strength, and sensibility testing are generally normal at presentation. Later, patients may develop signs and symptoms of thoracic outlet syndrome due to the compressive effect of the pseudarthrosis on the underlying neurovascular structures in certain positions. This effect includes numbness in C8–T1-ulnar nerve distribution; loss of radial pulse in abduction and external rotation of the shoulder; and, at times, weakness of the hand and arm, especially with overhead activities.[13,14] Radiographs at any

A



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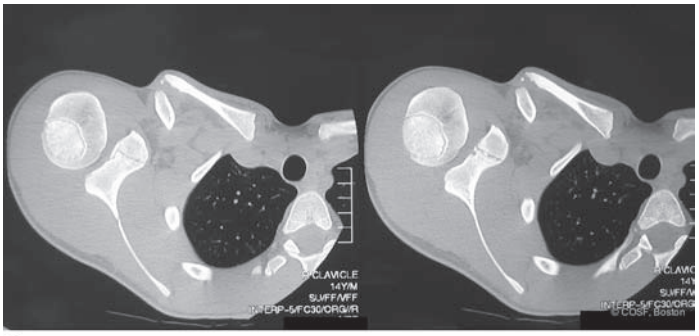


C

FIGURE 18-1 **A:** Obvious deformity of right clavicle due to a congenital clavicular pseudarthrosis. **B:** AP x-ray of same patient. **C:** CT scan revealing wide diastasis of the narrow, sclerotic bony fragments.

age will reveal the obvious pseudarthrosis.[15,16] Magnetic resonance imaging or CT scan may help better define neurovascular compromise or bony anatomy.

Associated conditions such as cleidocranial dysostosis are evaluated. Generally, pseudarthrosis of the clavicle is an isolated anatomic variant. It can be post-traumatic or associated with neurofibromatosis. Either way, the treatment is the same: observation[17] or surgical intervention. Attempts can be made to lessen the thoracic outlet symptoms with postural and scapular stabilization exercises, but this condition usually comes to surgery. There are reports of vascular lesions including aneurysm of the subclavian artery or vein, acute ischemia, and subclavian vein thrombosis in adulthood in association with congenital pseudarthrosis of the clavicle.[18–20] These worrisome reports make surgical repair in childhood seem more urgent. Vascular studies should be undertaken in symptomatic patients with pseudarthrosis of the clavicle whose radial pulse disappears during postural tests. Duplex Doppler of the subclavian artery is an excellent screening exam, but selective arteriography is the gold standard.

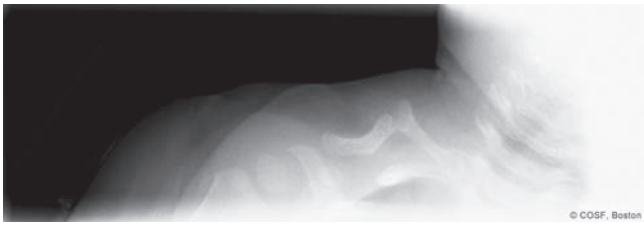


FIGURE 18-2 Radiograph of an infant with pseudarthrosis. This should not be mistaken for traumatic birth fracture.

Surgical Indications

There is debate if the mere presence of a congenital pseudarthrosis of the clavicle is an indication for operative intervention. There are reports of asymptomatic individuals into adulthood. However, there are also worrisome reports of late vascular insufficiency and/or thoracic outlet syndrome in adulthood in untreated patients. Most patients either become symptomatic or are bothered enough by the aesthetics of their prominent pseudarthrosis that they come to surgical reconstruction before adulthood.[21,22]

SURGICAL PROCEDURES

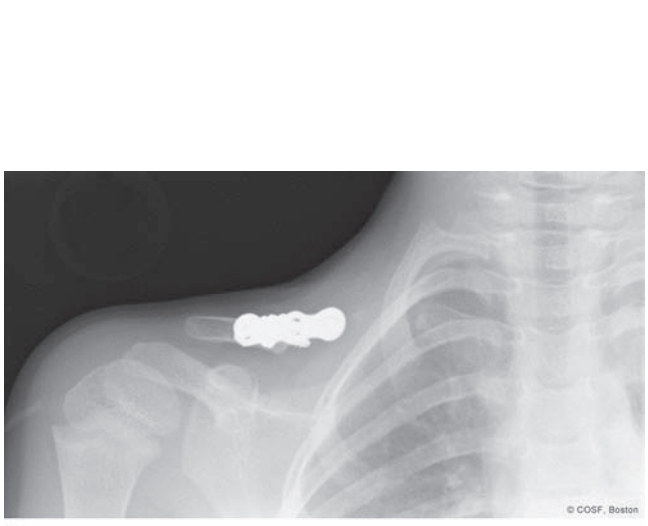
◆ Resection of Pseudarthrosis, Bone Grafting, and Internal Fixation

In the noninfant, surgical reconstruction for congenital pseudarthrosis follows the same principles as

FIGURE 18-3 Operative exposure of pseudarthrosis site with protected cutaneous nerves (*arrows*).

reconstruction for post-traumatic clavicular nonunion[23] (see Chapter 25). An incision in the skin lines is placed just below the clavicle to lessen the prominence postoperatively. The cutaneous nerves are identified and protected. Subperiosteal exposure of the clavicle is performed initially medial and lateral to the pseudarthrosis; then careful dissection is performed at the nonunion site (Figure 18-3). While tedious, careful subperiosteal elevation protects the underlying neurovascular structures and keeps the periosteum in continuity for later repair.

Debridement of the cartilaginous portions of the nonunion is performed, and the specimen is sent to pathology. The hypertrophic bone is resected and can be used for later bone grafting. The medial and lateral ends are placed in apposition to one another. If there is sufficient bone overlap to allow for primary reconstruction, then a superior plate is appropriately contoured for definitive fixation. The local bone graft can be added after compression plating. Often, iliac crest bone is necessary for anatomic reconstruction and healing, particularly in cases where resection of abnormal bone yields a large, intercalary defect.[24] There should be no gaps in the bone-to-bone contact. The plate and screws used should be age and size appropriate. Adult clavicle plates are often too large for the young (figure complication of nonunion and bone resorption) (Figure 18-4), but can be appropriate in the adult-size adolescent. Care is taken to protect the underlying neurovascular structures with drilling and screw placement. K-wires have been used in some case series with success,[25] but we worry about complications of hardware migration, breakage, prolonged immobilization, and persistent nonunion with this technique. After completion of the plating and bone grafting, the periosteum is reapproximated. This is critical to provide vascularity to the nonunion site. The platysma and fascia are also closed in layers while again protecting the cutaneous nerves. The closure should be meticulous for aesthetic reasons. Postoperative immobilization is by sling and swathe in the older patient and potentially shoulder spica cast in the hyperactive, younger patient.



A

B

FIGURE 18-4 **A:** Congenital pseudarthrosis treated with open reduction internal fixation at another facility with persistent nonunion and symptoms. **B:** CT scan reveals wide diastasis at the persistent nonunion site and bone resorption.

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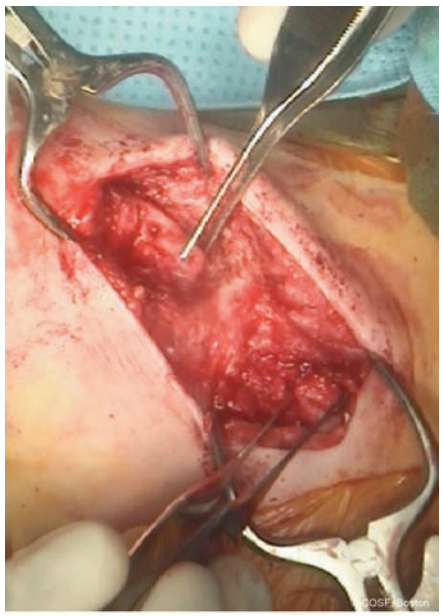
C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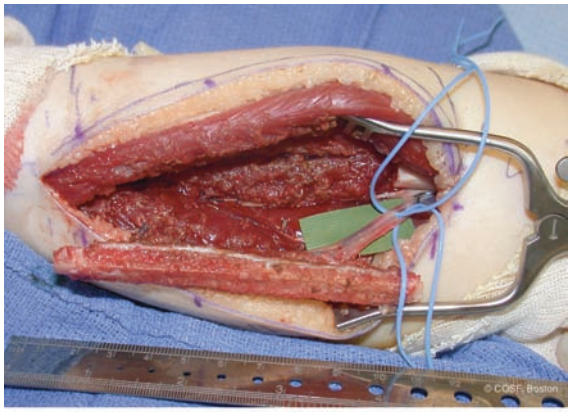
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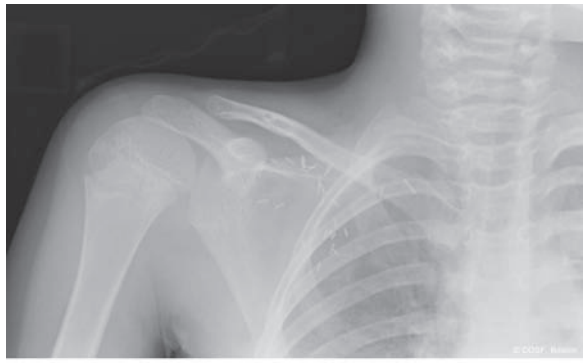
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FIGURE 18-4 *(continued)* **C:** Loose hardware noted at surgery. **D:** Unstable wide bony gap after hardware removal with unprotected neurovascular pedicles underneath. **E:** Vascularized fibular graft harvest noted with pedicle evident. **F:** Late follow-up radiograph revealing healed clavicle-fibula with remarkable remodeling.

◆◆ Open Reconstruction of Infantile Pseudarthrosis

Never take the advice of someone who has not had your kind of trouble.
—Sydney J. Harris

If the surgeon is fortunate enough to be referred a congenital pseudarthrosis patient in infancy, we would recommend surgical intervention between 6 and 12 months of life[12] (Figure 18-5). Reconstruction in infancy can be performed without internal fixation. Incision is again below the clavicle for cosmetic reasons. Exposure of the clavicle is through the same tissue planes as in an older child but obviously is more delicate due to the small space and proximity of complicated anatomy. Subperiosteal exposure has to be meticulous and gentle, as subsequent periosteal repair is the key to the healing of the pseudarthrosis. The risk of getting out of plane here is much higher. It helps to have experience exposing the brachial plexus in infants for microsurgical reconstruction. The periosteum is incised sharply with a knife and kept intact with elevation off the bone. When done, the periosteum should comprise a continuous soft tissue envelope from medial to lateral on both the superior and inferior sides of the clavicle.

The pseudarthrosis site is gently debrided back to bleeding bone with a small rongeur. The hypertrophic component of the bone is saved for bone graft. Medullary drilling or curettage to open the canals of the lateral and medial segments can be beneficial to healing. The pseudarthrosis is usually oblique, and the superolateral

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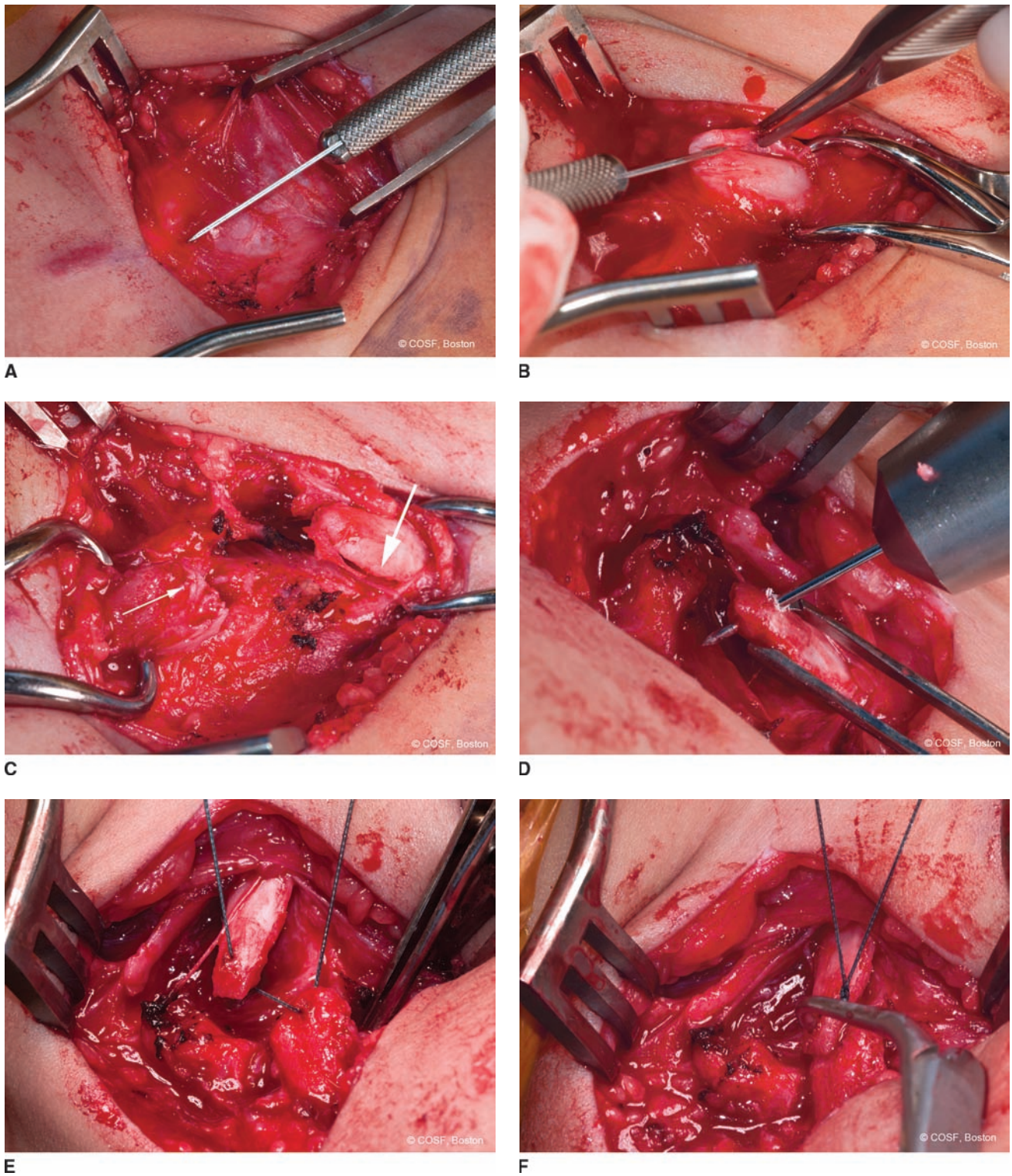

FIGURE 18-5 Repair of infantile congenital pseudarthrosis of the clavicle. **A:** After skin incision and dissection through the deltotrapezial fascia, sharp dissection is performed directly on the palpable pseudarthrosis site. **B:** Sharp subperiosteal dissection is performed on each of the bony ends, preserving the thick periosteal soft tissue sleeve. **C:** Both medial and lateral segments are mobilized by grasping with towel clips. Note is made of the tapered, sclerotic bony end on the medial side (*thick arrow*) without normal intramedullary canal. The lateral side (*thin arrow*) has been debrided of overlying cartilage down to bleeding bone. **D:** After debridement to normal bleeding bone, drill holes are made in each segment for suture passage. **E:** Nonabsorbable sutures are passed through the drill holes. **F:** Sutures are tied, reapproximating the bony ends. The preserved periosteal sleeve is then closed over the top.

segment can be apposed to the inferomedial clavicle. Drill holes are made on either side of the bony overlap with a small (0.028") smooth C-wire. Suture repair leads to bone-on-bone contact and moderate stability in these infants. The bone graft is then placed. Tight periosteal repair is performed. During completion of closure and application of immobilization, the repair is protected. Immobilization can be by adaptive sling and swathe similar to brachial plexus patients or spica cast depending on the patient's age and the surgeon's preference.

POSTOPERATIVE

The immobilization is continued until bony healing. This is usually by 6 weeks but can take up to 3 months. Therapy is a supervised home program to regain full motion and strength. Unlimited activities for the infants and sports for the older children are when the bone is healed and they have full motion and strength, usually by 3 months.

ANTICIPATED RESULTS

Fortunately, these children generally heal their pseudarthrosis with operative reconstruction and regain full motion and strength.[26] The symptoms of thoracic outlet usually resolve with repair and therapy. In the young, the clavicle can remodel. In the older child, there may still be some shoulder girdle asymmetry. There may be hardware irritation prompting hardware removal. Patients and families should be counseled regarding refracture risk after implant removal.

COMPLICATIONS

There is a risk of continued nonunion. This is probably more of a risk with infantile surgery. Fortunately, repeat surgery later with internal fixation and bone grafting will often resolve the persistent nonunion. Vascularized grafting has been used in extreme situations. If necessary, a vascularized fibula can be used to replace a clavicle with end-to-side arterial and end-to-end venous anastomoses.

Local neurovascular compromise while placing hardware or by prominent hardware can occur.[27] This risk is higher in patients who fail to obtain union and develop loose or migrating implants. Meticulous care in placement and successful union will hopefully prevent this. K-wires have been reported to migrate from the clavicular region to very dangerous places. It is why we do not use them. If used, they need to be removed promptly after healing.

The scar can be unsightly. The trading of a displeasing bump for a worrisome scar can be a problem. That possibly should be discussed preoperatively in the asymptomatic patient.

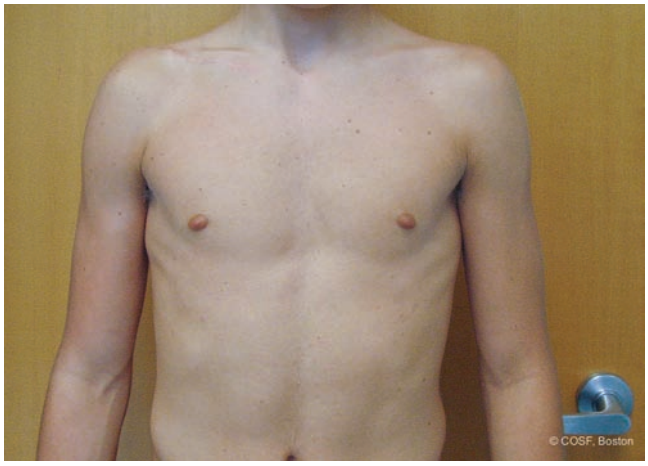

FIGURE 18-6 Late clinical photograph of healed repair with complete resolution of symptoms.

CASE OUTCOME

The adolescent patient with the symptomatic congenital pseudarthrosis of the clavicle was diagnosed with thoracic outlet syndrome due to his hypertrophic nonunion. He was treated with resection of the nonunion, an open reduction internal fixation of the clavicle with iliac crest bone graft. He healed, regained full motion and strength, and was pain free with all activities (Figure 18-6). His numbness resolved.

SUMMARY

Congenital pseudarthrosis of the clavicle usually presents with a diagnostic mass. Many are asymptomatic. Thoracic outlet symptoms can develop. Definitive treatment is resection of the nonunion, open reduction, and bone grafting. In the infant, this can be by bone suture and periosteal repair. In the older child, internal fixation is necessary. Plates and screws are currently recommended.

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CHAPTER

19

Sprengel Deformity

CASE PRESENTATION

An 8-year-old child presents for evaluation of an asymmetric shoulder deformity. The family reports no antecedent trauma or associated anomalies. In addition to the shoulder deformity, they report that the child has had progressive difficulty with overhead activities, including swimming. Radiographs were obtained by the pediatrician and demonstrated a "birth defect" of the right shoulder blade (Figure 19-1).

CLINICAL QUESTIONS

- What is Sprengel deformity?
- What are the associated conditions?
- How is Sprengel deformity classified?
- What are the surgical indications?
- What procedures may be performed for Sprengel's?
- What complications may occur from surgical reconstruction?

THE FUNDAMENTALS

Etiology and Epidemiology

When all is said and done, as a rule, more is said than done.
—Lou Holtz

While described by several surgeons prior to 1891, Sprengel is attributed with describing the congenital abnormality of the scapula that now bears his name.[1,2] While Sprengel deformity is often referred to as congenital elevation of the scapula, in fact, it represents a failure of the normal descent or caudal migration of the scapula, which occurs during the 9th to 12th week of embryonic development. As the scapula typically migrates from a sagittal to coronal position, patients with Sprengel deformity will have the scapula protracted, with the inferomedial angle medial and the glenoid tilting inferiorly. In addition to the failure of descent, the affected scapula is often smaller, hypoplastic, and dysmorphic.

The etiology of Sprengel deformity remains unknown. Similarly, few definitive statements can be made regarding the epidemiology for Sprengel deformity, owing to its relative rarity and paucity of published information. In general, males and females are equally affected, and bilateral involvement may occur. While most cases are sporadic, an autosomal dominant inheritance pattern has been proposed.[3] A number of associated conditions have been described, most notably Klippel-Feil syndrome (congenital cervical spine fusions), congenital scoliosis, and shoulder girdle deficiencies.

Clinical Evaluation

While the scapula is undescended at birth, often the aesthetic differences are subtle. With continued growth, the deformity becomes more apparent, and thus the diagnosis is often delayed in children without more extensive spinal and shoulder girdle congenital differences.

Patients will present with aesthetic differences in scapular position and shoulder height, of varying severity. Shoulder abduction and scapulothoracic motion are limited, often resulting in functional limitations with overhead and away from body activities. Inspection will reveal a small, high-riding scapula, often with malrotation and inferior tilt. Careful palpation will allow for identification of an omovertebral bone, an abnormal bony, cartilaginous, or fibrous connection between the cervical spine and the superomedial scapula thought to be present in approximately one-third of patients. Children with associated Klippel-Feil syndrome or congenital rib anomalies may present with torticollis, scoliosis, thoracic insufficiency, and other manifestations of their spinal/thoracic condition.

A number of classification systems have been proposed to characterize the severity of deformity. Traditionally, the Cavendish classification has been used to characterize the clinical deformity with the patient clothed[4] (Table 19.1). Grade 1 deformities present without any visible deformity. Grade 2 deformity results in a mild prominence of the superomedial angle of the scapula. Grade 3 deformity signifies shoulder asymmetry of 2 to 5 cm. Grade 4 deformity results in >5 cm of shoulder height asymmetry.

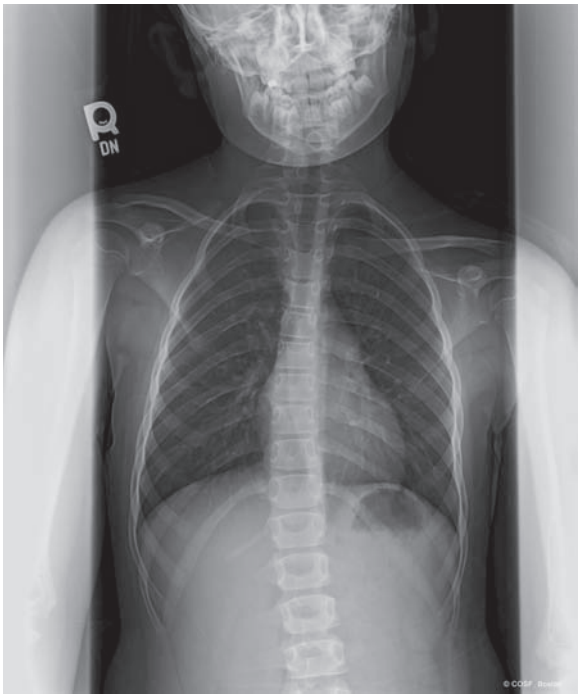

FIGURE 19-1 Frontal plain radiograph demonstrating a right Sprengel deformity.

Rigault et al.[5] proposed a radiographic classification based on the position of the superomedial angle of the scapula (Table 19.2).

Surgical Indications

I don't believe the old statement, "If it ain't broke, don't fix it." If that were the case, then Cadillacs and Jaguars and Mercedes would never make a change. I've always looked for ways to make things better.
—Vic Bubas

While the surgical indications for Sprengel deformity continue to evolve, in general, surgical reconstruction may be considered for patients at 3 to 4 years of age with severe deformity and functional limitations. While some authors have proposed surgical treatment based upon Cavendish or Rigault classification, every patient is different, and it is difficult to correlate aesthetic differences and shoulder impairment with clinical or radiographic appearance.[6–9] Surgical treatment is not recommended for mild aesthetic differences in the absence of pain or functional limitations.

A fundamental tenet of pediatric orthopaedic surgery is that surgical treatment should only be recommended when the natural history can be favorably altered. Unfortunately, the natural history of Sprengel deformity is not well characterized. The best insight into the natural history of this condition comes from Farsetti et al.,[6] who reported on 14 patients with Cavendish grade 1 to 3 Sprengel deformity observed until the ages of 18 to 67 years. One-half had mild-to-moderate pain with activity, and shoulder abduction was restricted in all. While there were no improvements in deformity over time, there were no cases of progressive deformity. When compared with a similar cohort of patients who underwent operative reconstruction, surgical patients had improved shoulder abduction of about 40 degrees, improved aesthetics, and no cases of recurrent deformity.

While a host of procedures have been proposed, most reconstructive strategies are variations of either the Woodward or Green procedures.[10,11] The Woodward procedure is preferred by most due to its relative technical ease and potential biomechanical advantage of displacing the muscle origins inferiorly, thereby rotating and lowering the scapula.[12,15]

SURGICAL PROCEDURES

Resection of Superomedial Angle of Scapula

Some have advocated simple resection of the prominent superomedial angle of the scapula, in essence excising the major cause of the aesthetic difference.[4,13,14] While this may take away some of the visible bony bump, it

Table 19.1
Cavendish classification of Sprengel deformity

Grade	Appearance of Deformity with Patient Clothed
1	No visible deformity
2	Prominence of superomedial angle near neck; no shoulder asymmetry
3	Shoulder asymmetry of 2–5 cm; deformity easily visible
4	Asymmetric shoulder elevation >5 cm; with or without neck webbing

Table 19.2
Rigault Radiographic classification of Sprengel deformity

Grade	Radiographic Position of the Superomedial Angle of the Scapula
1	Lower than T2 but above the T4 transverse process
2	Between C5 and T2 transverse process
3	Above C5 transverse process

does not address the abnormal elevation or the functionally limiting inferior tilt of the glenoid. For this reason, we rarely perform this procedure alone. However, it will favorably change the appearance of the neck line.

◆ Modified Woodward Procedure

The patient is placed in the prone position, with care made to provide adequate padding of all bony prominences and sites of potential nerve compression (Figure 19-2). Adequate elevation of the thorax off the operating room table will facilitate ventilation and anesthesia, and the upper limbs should not be positioned in excessive abduction or extension to avoid positional brachial plexus traction injuries. A wide surgical field is sterilely prepped and draped, allowing access to the neck, thorax, upper lumbar spine, bilateral scapulae, and ipsilateral upper extremity.

A midline incision is created from the cervical spine to the lower thoracic level. Soft tissues are elevated until the medial border of the scapula is identified and exposed. The lateral border of the trapezius is identified in the lower (caudal) aspect of the wound, and the trapezius is separated from the underlying latissimus dorsi muscle and thoracodorsal fascia. (The lateral border of the trapezius is often more lateral than expected, owing to the Sprengel deformity.) Blunt finger dissection around the inferolateral trapezius is helpful in identifying the place between trapezius superficially and latissimus dorsi deep. Once the trapezius is isolated, it may be freed from its origin from the spinous processes in an extraperiosteal fashion, moving inferior to superior. At roughly the C4 level, the trapezius is detached and retracted laterally. The origins of the rhomboids are similarly identified and freed from the spinous processes. (The rhomboid minor arises from T1 to T2, and the rhomboid major originates from T2 to T5.) Care is made not to violate the deeper longitudinal muscle fibers of the paraspinals or violate the periosteum of the spinous processes. After the "sheet" of muscles is liberated and retracted laterally, direction is turned to the omovertebral bone and superomedial scapula.

When present, the omovertebral bone may be palpated in the superior aspect of the wound. The omovertebral

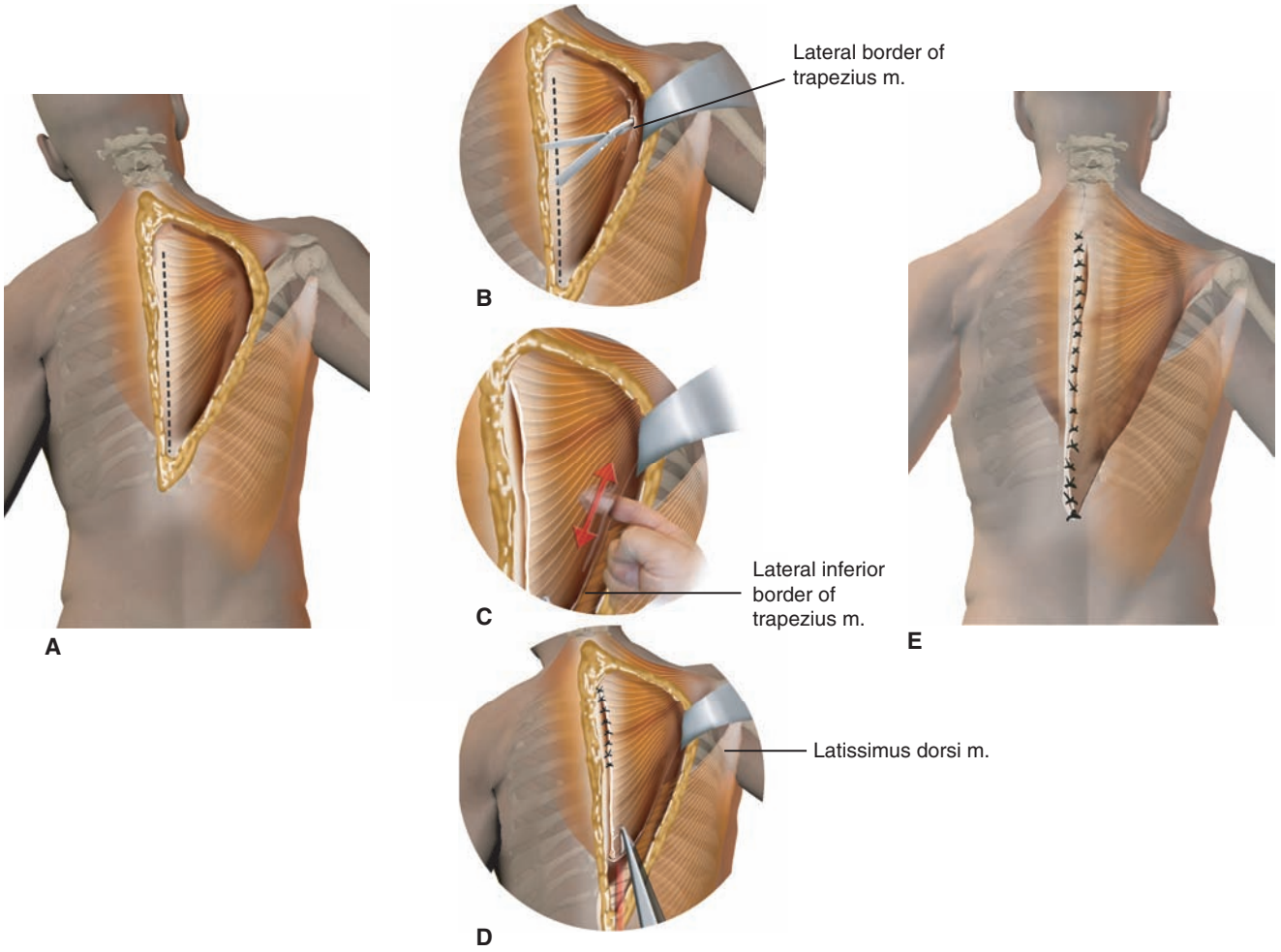

FIGURE 19-2 The modified Woodward technique. (**A**) A midline incision is created. (**B**, **C**) The lateral border of the trapezius is identified and trapezius separated from the underlying latissimus dorsi. (**D**) The trapezius origin is elevated. (**E**) After the omovertebral connections are removed and scapula mobilized, the trapezius is advanced and repaired.

connection is then circumferentially dissected, with care made to protect the deep structures of the vertebral column and remain superficial to the periosteum. Once isolated, small curved osteotomes or rongeurs may be utilized to resect the omovertebral bone. Sometimes the omovertebral connection can extend to the laminae of the involved vertebrae. It is not uncommon to find that the connection of the omovertebral "bone" to the cervical spine or scapula is cartilaginous or fibrous.

Often the superomedial angle of the scapula is abnormal, curving anteriorly, and it needs to be excised extraperiosteally using bone cutters, rongeurs, or osteotomes. This often requires elevation of the levator scapulae insertion and elevation of the supraspinatus muscle from the superomedial portion of the scapula. Resection of the superomedial scapula above the spine of the scapula gives a marked aesthetic improvement and lessens the risk of brachial plexus compression with surgical repositioning of the scapula. The transverse cervical artery runs deep to the levator scapulae and should be protected during division of the levator off the scapula. Similarly, care is made to avoid iatrogenic injury to the suprascapular artery or nerve laterally as they pass near the scapular notch during supraspinatus elevation.

Once the scapula is untethered, mobility may be checked with abduction of the ipsilateral extremity. Often blunt finger dissection is needed to release the adhesions in the subfascial plane between scapular body and chest wall. To aid in anatomic placement of the scapula, a "pocket" deep to the latissimus dorsi can be created to receive the newly positioned scapula. Adequate mobilization is achieved when the scapular spine lies at the same level as the unaffected, contralateral scapular spine. At this point, the supraspinatus is repaired to the newly contoured superomedial angle of the scapula. The rhomboid and trapezius origins are then advanced inferiorly and repaired to the spinous processes using multiple interrupted nonabsorbable sutures (Ethibond, Ethicon, Inc., Somerville, NJ). Doing so will result in redundant trapezial tissue inferiorly, which can be excised or imbricated. The wound is closed in layers over a drain. The affected limb is immobilized in sling and swathe postoperatively.

◆ Scapular Osteotomy

First described by Konig in 1914, vertical osteotomy of the scapula has also been advocated for Sprengel deformity.[16–18] In the prone position as described above, a vertical incision 3 cm lateral to the midline is created. Deep dissection is made in line with the surgical incision, through the infraspinatus fascia. The scapula is identified and periosteum incised. Offset holes are drilled on either side of the planned osteotomy line, with the distance between holes corresponding to the amount of vertical translation desired. The vertical osteotomy is then made through the scapular body with an osteotomy or microsagittal saw. If an omovertebral bone is present, it is excised in an extraperiosteal fashion. A towel clip is then applied to the inferior aspect of the lateral fragment and used to displace the lateral scapula inferiorly. Fixation is achieved by passing nonabsorbable sutures through the previously placed drill holes. The wound is closed in layers.

While this technique appears straightforward and appealing to orthopaedic surgeons, by definition it results in a partial, one-dimensional correction. While prior reports have shown improvements in shoulder abduction, correction of the often abnormal orientation of the glenoid is not readily achieved with this technique. Finally, as the scapula is often hypoplastic and abnormally shaped, concerns persist regarding suture fixation and healing potential. For these reasons, we do not currently utilize this technique.

◆◆ Modified Woodward Procedure with Clavicular Osteotomy

One potential complication of the modified Woodward procedure is brachial plexus injury (particularly affecting the radial nerve), caused by compression between the clavicle and first rib during surgical advancement of the scapula to a more anatomic, inferior position.[6,7,19,20] The risk of plexus injury is particularly high in older patients with long-standing deformities and less pliable tissues. To avoid this risk, clavicular morselization has been recommended for any reconstruction performed in children >7 years of age or in younger children with severe deformity.

After induction of general anesthesia and PRIOR to the scapular portion of the reconstruction, the patient is placed in the supine position. The clavicle and ipsilateral upper limb are prepped and draped in the typical fashion. A transverse incision is created in Langer skin lines, centered over the clavicular diaphysis. Skin and subcutaneous flaps are elevated. The platysma is divided in line with the incision, and care is made to identify and preserve the supraclavicular nerves. The periosteum over the clavicle is incised sharply, and careful subperiosteal elevation is performed, preserving the sleeve of periosteum for later repair. An osteotome, bone cutter, or microsagittal saw is then used to cut a 1 cm segment of clavicular diaphysis. This bone is then morselized and replaced into the osteotomy site, kept in place by the surrounding periosteal tube. The periosteum is then reapproximated using multiple absorbable sutures (Vicryl, Ethicon, Inc., Somerville, NJ). The wound is closed in layers, and a sterile dressing is applied. Upon completion of the clavicular morselization, the patient is turned prone and the modified Woodward procedure carried out.

POSTOPERATIVE

Sling and swathe immobilization is utilized for 4 weeks postoperatively. After this time, immobilization is discontinued and physical therapy initiated for gentle

range-of-motion exercises, with advancement to strengthening as tolerated.

ANTICIPATED RESULTS

With proper patient selection and meticulous surgical technique, improvements in scapular position, shoulder function, and aesthetics can be achieved. On average, surgical treatment results in approximately 40 degrees of improvement in shoulder abduction and one- or two-grade improvement in the Cavendish classification.[4,6,8,9,12,21–23] These improvements in both aesthetic appearance and shoulder function appear to be durable, and the risk of recurrent deformity is low.[6]

Of note, other reports cite similar improvements with the modified Green procedure, in which the muscular insertions are detached from and advanced onto the scapula to effect positional improvement. Andrault et al.[24] reported results in eight patients at a mean 4.5-year follow-up. All patients/families were pleased with the aesthetic improvements, and patients achieved one or two grades of improvement in the Rigault classification. Aydinli et al.[25] similarly demonstrated modest improvements in shoulder motion (flexion 95 to 105 degrees, abduction 81 to 97 degrees) and aesthetic improvements in 12 patients operated on at mean age 5 years. Others have reported similar experiences with modifications of Green technique.[7,21]

COMPLICATIONS

A number of complications have been described. First and foremost, brachial plexus injury has been described from overzealous correction in severe deformities or in older patients. For this reason, clavicular morselization is advised to prevent brachial plexus compression between the first rib and clavicle. Resection of the superomedial aspect of the scapula, when it projects anteriorly, lessens the risk of nerve compression with scapular repositioning. Some surgeons use spinal cord monitoring techniques with Sprengel correction to avoid severe or permanent injuries. In cases where a modified Woodward procedure is performed in isolation and a brachial plexus injury is discovered postoperatively, clavicular osteotomy and/or morselization may be performed in the immediate postoperative period.

Wound infection may similarly complicate reconstructive efforts, in part due to the wide surgical exposure and extensive soft tissue dissection required. Meticulous technique and utilization of a temporary postoperative drain may lessen the risk of infection.

Finally, inherent with the modified Woodward procedure is a long, at times, unsightly surgical scar. Patients should be counseled about this preoperatively, and emphasis again should be placed on the potential for functional improvement, not aesthetic appearance alone.

CASE OUTCOME

The diagnosis of Sprengel deformity was made. Due to both aesthetic concerns and functional limitations in shoulder abduction, the patient underwent a modified Woodward procedure. Postoperative course was unremarkable. The patient demonstrated improvements in shoulder symmetry, as well as 35 degrees of improved shoulder abduction without pain.

SUMMARY

Sprengel deformity results from the failure of embryologic descent, resulting in a hypoplastic, elevated, and rotated scapula. Patients will exhibit varying degrees of shoulder asymmetry and limitations in shoulder motion. In cases of severe deformity, pain, or functionally limited shoulder motion, surgical reconstruction with the modified Woodward procedure will result in both aesthetic improvement and functional gains. Morselization of the clavicle should be strongly considered in older patients or those with severe deformities.

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CHAPTER 20

Brachial Plexus Birth Palsy: Microsurgery

CASE PRESENTATION

A 5-month-old infant returns for follow-up evaluation. The child was a 10 lb 2 oz product of a full-term gestation. Delivery was vaginal and complicated by shoulder dystocia. Initially at birth, the left arm was flail except for intact digital flexion. No fractures, respiratory distress, or Horner syndrome were present by clinical and radiographic evaluation. During the first few weeks of life, the arm became internally rotated and adducted at the shoulder. Physical therapy was initiated to prevent contracture. There has been no return of biceps or deltoid function but improving wrist, finger, and thumb extension by this 5-month appointment.

CLINICAL QUESTIONS

- How common is brachial plexus birth palsy (BPBP)?
- Can we define the cause?
- How do you distinguish an avulsion injury from an extraforaminal rupture?
- What is the expected outcome by natural history?
- What are the indications for nerve surgery?
- What techniques are most commonly used for nerve reconstruction?
- What are the expected outcomes and differences from both avulsion and extraforaminal reconstructions?

THE FUNDAMENTALS

In order to care for infants and children with BPBP, it is critical that you have a thorough understanding of the neural anatomy (Figure 20-1). The brachial plexus consists of ventral nerve root contributions from C5 through T1. There are prefixed cords with contributions from C4 (22%) much more commonly than postfixed cords with contributions from T2 (1%). Routinely, C5 and C6 ventral nerve roots combine to form the upper trunk, the C7 nerve root becomes the middle trunk, and the C8 and T1 nerve roots join to form the lower trunk. Each trunk divides into anterior and posterior divisions. The divisions combine to become the medial, lateral, and posterior cords. Ultimately the cords separate into the individual, terminal nerves of the arm and hand.

Specifically, the typical patterns are that the (1) anterior divisions of the upper and middle trunks become the lateral cord; (2) the anterior division of the lower trunk becomes the medial cord; and (3) the posterior divisions of all three trunks become the posterior cord. The ulnar nerve is the terminal branch of the medial cord, the musculocutaneous (MCN) nerve of the lateral cord, the axillary and radial nerves of the posterior cord, and the median nerve from contributions of the medial and lateral cords. Along the way from nerve roots to terminal major nerves, the remaining muscles of the upper limb receive their neural supply from specific branches of the plexus. These branches are well outlined in Figure 20-1.

Any surgeon exploring and reconstructing the brachial plexus needs to be comfortable with the normal three-dimensional anatomy, facile in identifying anatomic variations, and able to do so in a distorted pathoanatomic situation. The brachial plexus lies between the anterior and the middle scalene muscles in the neck. The phrenic nerve arises from C3 to C5 ("3-4-5 keeps the diaphragm alive") and courses on the anterior scalene muscle; the phrenic nerve is a key anatomic landmark and, once identified, may be traced proximally to the C5 nerve root and thus the brachial plexus.

A key surgical principle is to identify the neuroma and then healthy nerve roots proximal (if present) and nerves distal to the neuroma. Each nerve root is isolated as it exits the foramina. In the presence of avulsion injuries, the

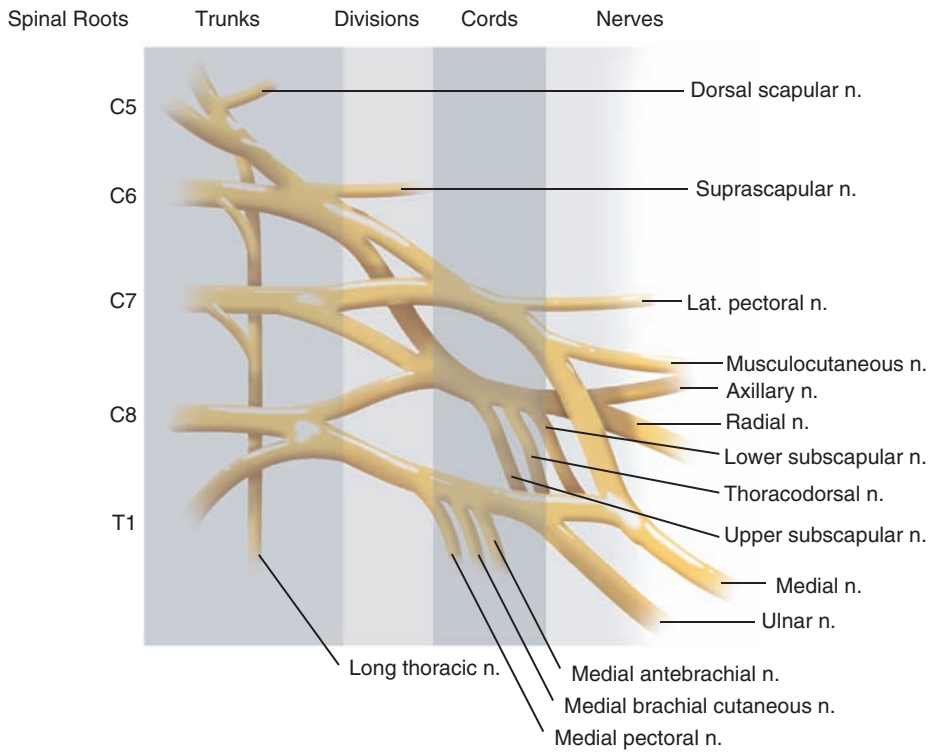


FIGURE 20-1 Normal anatomy of brachial plexus outlining nerve roots > trunks > cords > individual nerves. Obviously there are anatomic variations to this two-dimensional illustration, but this is the foundation of brachial plexus work.

foramina will be empty. Distal to the neuroma, depending on the size of the neuroma and extent of injury, more normal individual divisions, cords, and/or nerves are isolated. Each situation is different and, accordingly, recognized, dissected, and recorded. The simple goal is to provide healthy neural input to affected muscles. The method by which this is achieved varies from case to case.

Etiology and Epidemiology

The incidence of BPBPs has been reported in 0.4 to almost 2:1,000 live births. The difference may relate to the type of prenatal and obstetrical care as well as average infantile birth weight and maternal pelvic size in different geographic regions. Identified perinatal risk factors include large gestational age infants (macrosomia, infants of diabetic mothers), multiparous pregnancies, previous pregnancies complicated by a birth palsy, prolonged labor, and difficult (shoulder dystocia) and assisted (vacuum, forceps) deliveries.[1–6]

The mechanism for injury as far as the nerve(s) is concerned is mechanical: a stretch or traction injury. This does not define who or what is responsible.[7] The degree of force the nerve feels and the position of the arm and neck at the time of injury determine the extent of injury. The anatomic location of the injury is defined in each case. Usually, the neck and shoulder are distracted, and the upper plexus is injured. Thus the most common anatomic patterns for infantile paralysis are upper trunk (C5–C6) followed by C5–C6–C7 palsies. Complete plexus palsies are less common, and isolated lower trunk palsies are almost reportable. The degree and type of neural injury is defined by the classic Seddon and/or Sunderland classification systems. The postganglionic injuries occur most often and are defined as neurapraxia, axonotmesis, or neurotmesis as opposed to preganglionic nerve root avulsions (Figure 20-2). The main issue is predicting the extent of spontaneous recovery: what will naturally recover and over what time frame. Neurapraxias fortunately are common and have full spontaneous recovery in the first weeks to months of life. The degree of axonotmesis defines the extent of natural history recovery, and this is more prolonged. Nerve recovery does not always follow classic anatomic pathways.[8] The extent of natural recovery may not be known until 1 to 3 years of life.[9] Some of these children may have better outcomes with surgery. Neurotmesis requires postganglionic reconstruction. Avulsion injuries have a poor prognosis by natural history and also tend to have a limited surgical outcome.[10,11]

Clinical Evaluation

At birth, pseudoparalysis from a clavicle or humerus fracture can be confused with true BPBP. Both conditions also can coexist. With a fracture, the initial and subsequent radiographs are diagnostic. Fractures in infants heal readily with palpable callus present almost always by 10 days to at most 3 weeks. The persistence of weakness beyond this time is concerning for a concomitant birth palsy. Other possibilities in the differential diagnosis besides fracture

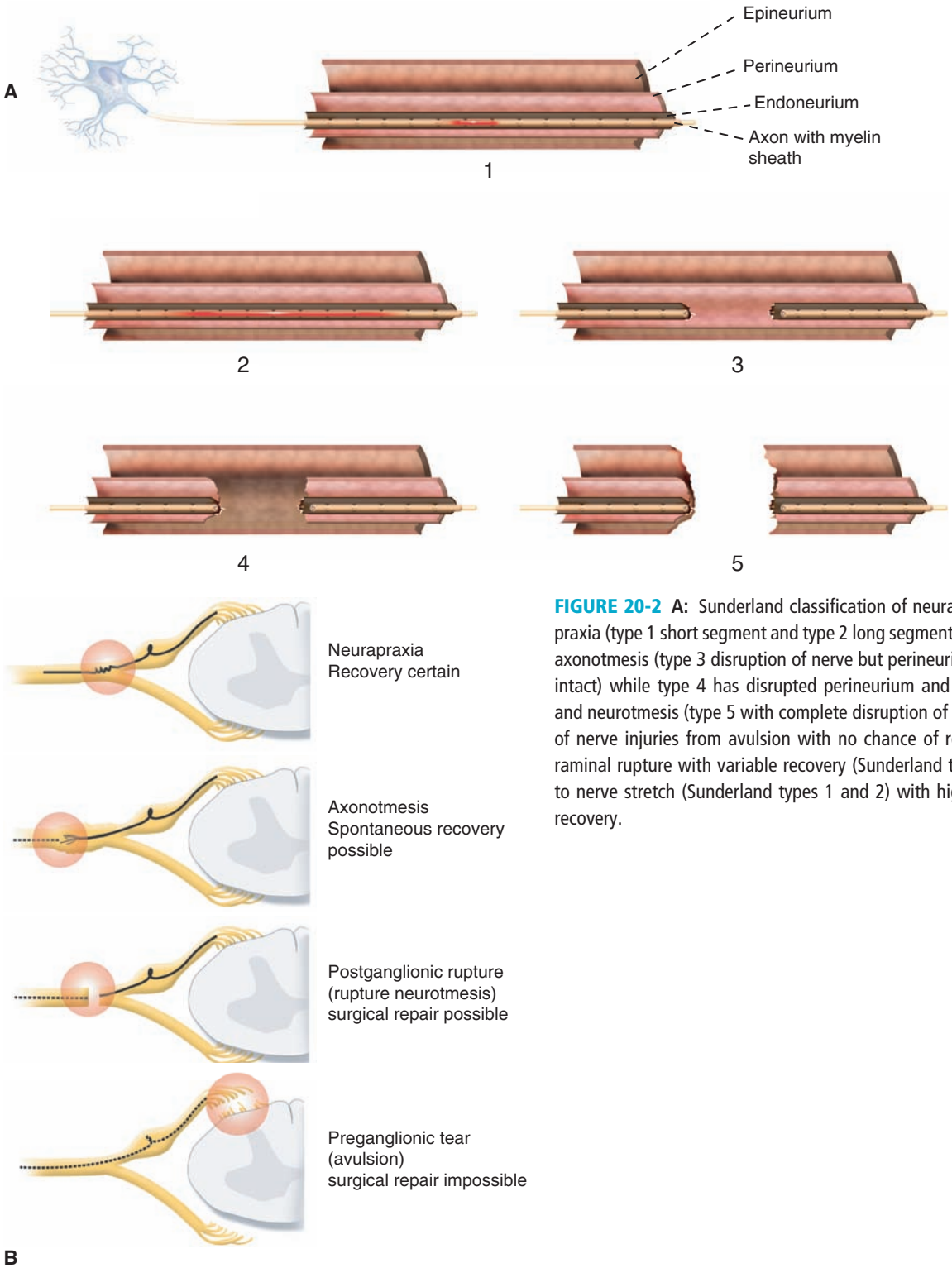


FIGURE 20-2 **A:** Sunderland classification of neural injury with neurapraxia (type 1 short segment and type 2 long segment neurapraxic injury), axonotmesis (type 3 disruption of nerve but perineurium and epineurium intact) while type 4 has disrupted perineurium and intact epineurium), and neurotmesis (type 5 with complete disruption of nerve). **B:** Sequence of nerve injuries from avulsion with no chance of recovery; to extraforaminal rupture with variable recovery (Sunderland type 3, and even 4); to nerve stretch (Sunderland types 1 and 2) with high likelihood of full recovery.

include congenital differences, central nervous system or spinal cord pathology, and infection.

Right from the start, the best information on the type of birth palsy is by physical exam. It is important to distinguish a preganglionic from a postganglionic lesion. Clear exam discriminators include a Horner syndrome (ptosis, miosis, enophthalmos, anhidrosis) and phrenic nerve palsy (elevated hemidiaphragm), which are associated with preganglionic injuries (Figure 20-3). Other concerning signs for avulsion include flail hand and loss of scapular control. The expectation in this situation is for very limited natural recovery since there is a complete disconnect between

FIGURE 20-3 Horner syndrome with ptosis, miosis, enophthalmos, and anhidrosis. There is a high correlation between an avulsion injury and the presence of a Horner syndrome.

the brain–spinal cord axis and the peripheral nerve muscle axis at each avulsion level.

Sequential physical examinations are still the most reliable method to define the type and extent of extraforaminal injuries. Recovery is dynamic. The nerves will tell you how bad the injury is and the expected natural recovery if you examine the child frequently over the first 3 to 9 months of life.[12,13] It takes patience and acquired skill to obtain an accurate exam. Utilizing more than one examiner for comparison and confirmation, such as a skilled plexus physical therapist, with each visit is beneficial. Observation of spontaneous movement, stimulated motor activity, and eliciting neonatal reflexes to assess muscle recovery are key components to an infantile exam (Figure 20-4). The systems most often used to

FIGURE 20-4 Typical posture of elbow extension (absent biceps), wrist flexion (absent wrist extensors), and digital flexion (absent finger extension).

Toronto Score Grading System		
Observation	Clinical Grade	**Numerical Score**
No joint movement	0	**0**
- Flicker of movement	0 +	**0.3**
- Less than 50% range	1 –	**0.6**
50% range of movement	1	**1.0**
- More than 50% range	1 +	**1.3**
- Good but not full range	2 –	**1.6**
Full range of movement	2	**2.0**

FIGURE 20-5 Toronto score for microsurgical indications. A score <3.5 is utilized in some centers as indicating nerve exploration and reconstruction. Others use the absence of biceps function as the indication for nerve surgery. Timing is debatable.

classify these injuries are the Toronto test score (0 to 2 for elbow flexion; elbow wrist, finger, and thumb extension) (Figure 20-5); modified Mallet classification (grades I to V for abduction, external rotation, hand to mouth, hand to neck, and hand to spine); Hospital for Sick Children Active Movement Scale (0 to 7 grades for 15 upper limb movements); and Narakas (I to IV) (see Figures 21-4 and 21-5 in Chapter 21).[14,15] Invasive radiographic studies including myelograms, CT myelograms, and MRI scans (including fast spin echo, MRI myelograms, and MRI neurography) have been used to differentiate avulsions from extraforaminal lesions.[16–18] These studies have high, but not perfect, accuracy. Electrodiagnostic studies are also utilized in some centers to define the severity of injury and prognosticate recovery. Unfortunately, there are multiple reports of discrepancies between electrodiagnostic and intraoperative findings. The neurophysiologic studies may underestimate the severity of injury and overestimate the prognosis of natural recovery.[19] These studies always require conscious sedation, and some require general anesthesia. At present, most centers still rely on physical exam findings to advise parents on treatment options.

Surgical Indications

Always keep an open mind and a compassionate heart.
—Phil Jackson

Amazingly, after over 100 years of publications on nerve surgery in infants with BPBPs, the role, timing, and type of nerve surgery is still controversial.[20–23] There is wide geographic variation. The timing controversy results in either potential unnecessary operations or missed opportunities to improve a child's condition by surgery. Depending on when a surgeon chooses to intervene with microsurgery (at 3, 4, 5, 6, or 9 months of life),[24–32] there is a significant difference in short-term economic cost and potentially

long-term economic cost and outcome. We still do not have the definitive answers that can be applied to any given case. This ambiguity and lack of consensus complicates life for parents trying to decide what is best for their child's future. The trends, however, are clear, and prospective study results are coming.

Inherent in any discussion of surgical indications is when *not* to do nerve surgery. Fortunately, the majority of BPBPs are transient. If partial antigravity upper trunk function including biceps function occurs in the first 6 weeks of life, ultimate normal recovery is expected. If biceps and upper trunk recovery does not begin by 3 months of life, then spontaneous recovery will be less complete. The crux of the ongoing debate centers on when between 3 and 9 months of life is the failure of biceps and upper trunk recovery an indication for infantile nerve surgery. Given the experience with secondary reconstruction procedures (e.g., tendon transfers), the question becomes which outcome will result in less long-term function: therapy and secondary transfers or nerve surgery and possible secondary transfers?

Clear indications for nerve reconstruction are (1) avulsion injury, (2) Toronto score <3.5 by 6 months of life,[33] (3) failure of return of upper trunk function as judged by partial biceps antigravity function by 6 months of life, and (4) failure of "cookie test" by 9 months of life. There clearly is some overlap in these groups. Surgeon and institutional preference still abounds regarding surgery between 3 and 6 months of life. Our bias is for (1) avulsion surgery at 1 to 3 months, (2) extraforaminal rupture surgery at 5 to 6 months, and (3) rare "fell through the cracks" patients at 9 months. The last patients now usually have nerve transfers.

SURGICAL PROCEDURES

Champions keep playing until they get it right.
—Billie Jean King

The surgical options for nerve treatment are decompression, neurolysis, neuroma resection and nerve grafting, and nerve transfers. Simply, decompression and neurolysis are a part of the surgical exposure, evaluation of pathoanatomy, and intraoperative decision making. They are not part of definitive treatment, though almost everyone performs neurolysis of scarred-in nerves to assess fascicular continuity by microdissection and electrical stimulation. There is no evidence that decompression and neurolysis alone improve the patient's future over natural history. Therefore, at present, your microsurgical options to hopefully improve your patient's life as an independent adult are neuroma resection and grafting and nerve transfers.[34–37] These same techniques are applied to the child and adolescent with a traumatic plexus injury. Direct repair to the spinal cord has not been feasible so far.[38]

As technically demanding as these operations are, the more complex aspect of the surgery is intraoperative decision making. There are treatment schemes that have been developed (Table 20.1) based on the available proximal donor and distal receipt sites, likelihood of neural recovery that will lead to functional muscle activity, and available secondary tendon transfers that will achieve satisfactory function. In general, recovery of shoulder stabilization, elbow flexion, and wrist extension are achievable goals in the more common extraforaminal ruptures in infants. Avulsion injuries are more challenging; but in infants, there usually is at least one nerve root to use as a proximal donor.

Table 20.1

Treatment recommendations in obstetric palsy

Ruptured/Avulsed Roots	Recipient Site	Functional Goal
C5, C6/0	Superior trunk	Shoulder, elbow, wrist control
C5, C6, C7/0	Superior trunk Middle trunk	Above plus Finger extension
C5,C6, C7/C8, T1	Posterior cord Lateral cord Medial cord	Shoulder control Elbow control Finger flexion + intrinsics
C5, C6/C7, C8, T1	Lateral cord Medial cord Suprascapular n.	Elbow control Finger flexion + intrinsics Shoulder control
C5/C6, C7, C8, T1	MCN n. Suprascapular n. Intercostal n. 2–5 to lateral cord	Elbow control Shoulder control Sensation
0/C8, T1	Graft from C6 to medial cord	Finger flexion + intrinsics
0/C5, C6	Graft from medial pectoral n. to MCN n.	Elbow control

Adapted from Green, Hotchkiss, Pedersen, Wolfe, eds.: Green's Operative Hand Survey, 5th edition, Philadelphia, Elsevier, 2005, 1333.

Also, in infants there is a reasonable chance of some recovery of hand function. However, even the most experienced surgeons are challenged when there is a mismatch between what is needed and what is available for reconstruction.

The tools available to aid intraoperative reconstructive decisions include (1) preoperative physical exam and MRI classification of injury, (2) microneural dissection to assess fascicular continuity, (3) intraoperative electrical stimulation of proximal nerves to assess distal muscle activation, (4) macroscopic and microscopic inspection of cut nerves, (5) biopsy of proximal nerve endings, and (6) somatosensory-evoked potentials (SSEPs). Motor-evoked potentials have been too difficult to standardize and quantify for their effective use in decision making.

Nonoperative Care of the Infant with BPBP

At the time of birth, it is difficult to predict the future for the infant and parents (avulsion injuries excluded, which have a poor prognosis). In the past, there was probably an overabundance of reassurance regarding full recovery. Now, there may be heightened worry about permanent disability. Providing balanced, discriminating information for parents about their child is important.

Infants are usually assessed in the first month of life to establish a baseline exam and to develop a relationship with the parents. Many of these families come in prepared for an extensive discussion after research and communication with other affected families and caregivers. Serial exams on a 1- to 3-month basis in the first year of life allow for proper classification of each child's injury and recovery. If and when these patients normalize their function, their care is discharged back to their primary care provider. If there is poor recovery, and microneural reconstruction is necessary, then trust and clear communication regarding expected outcomes has been established before extensive surgery is performed. Finally, in those who recover sufficiently not to warrant nerve surgery but who still have functional deficits, they are monitored with therapy until secondary surgeries may be appropriate. This can extend throughout their childhood with visits every 6 to 12 months.

Early therapy to maintain a full arc of joint motion is advised. This is particularly important for the glenohumeral joint. Muscle reinnervation is sequential and asymmetric; the adductors and internal rotators recover before the abductor and external rotators. The resultant muscle imbalance, if prolonged, can lead to contractures, joint deformity, and dislocation. There are similar concerns about contracture development with the hand. Early return of digital and wrist flexion before wrist and finger extension can lead to flexion contractures. Occupational therapy, including corrective splinting, is then beneficial. Finally, with biceps recovery, the children can develop an elbow flexion contracture if there is asymmetry between biceps and triceps strength or considerable cocontraction. This elbow flexion contracture may be addressed with therapy and at times splinting or serial casting.

Nerve Grafting for Upper Trunk Lesion

Failure of biceps, deltoid, and external rotation recovery alone or in combination with failure of wrist and finger extension by 5 to 6 months is a clear indication for nerve reconstruction. As mentioned in the indications section, this same clinical situation leads to microneural reconstruction at 3 or 4 months at other institutions (Figure 20-6).

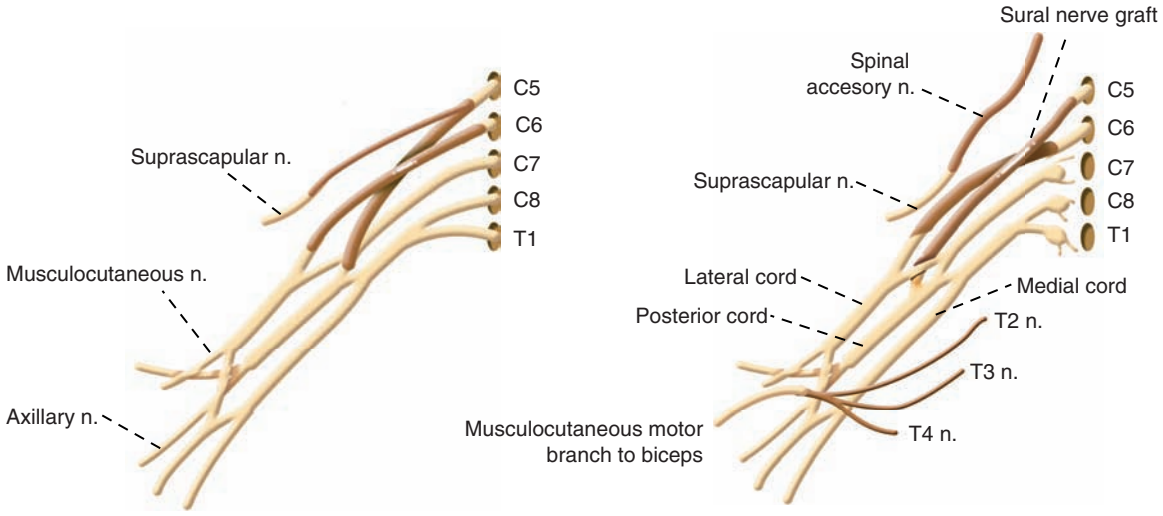


FIGURE 20-6 **A:** An illustration of a complete C5–C6 rupture with intact C7–T1. Reconstruction with cable sural nerve grafts from C5 to suprascapular and to posterior division of upper trunk; C6 to the anterior division of upper trunk. **B:** An illustration of C5-C6 grafting in combination with intercostal nerve (ICN) and spinal accessory nerve (SAN) transfers. C5 to posterior division of upper trunk; C6 to anterior division of upper trunk; SAN to suprascapular nerve; ICN to motor branch of musculocutaneous nerve to biceps.

FIGURE 20-7 **A:** Prepping and draping for exposure of neck, shoulder girdle, and entire affected arm as well as bilateral sural donor grafts if necessary. **B:** Transverse incision for supraclavicular exposure of upper trunk rupture. The coracoid is outlined by blue dot. This can be modified with a curvilinear supraclavicular flap for more exposure.

Surgery is performed under general anesthesia without neuromuscular blockade. Both lower extremities are prepped in anticipation of nerve grafting, typically utilizing the sural nerve as donor nerves. Supine, modified beach chair position is used with a roll between the scapulae. The head is tilted toward the unaffected side, and the shoulder girdle, arm to fingers, and chest are all included in the operative field. This wide field allows for versatility of all nerve grafting and transfer options (Figure 20-7A). Exposure of the affected brachial plexus is through a transverse supraclavicular skin incision centered between the transverse processes of C5 and C6 (Figure 20-7B) (see Sidebar). After scoring the skin, a diluted epinephrine solution is injected in the incision to lessen bleeding. The platysma and supraclavicular fascia are divided in line with the skin incision. The supraclavicular cutaneous nerves and spinal accessory nerve (beneath the sternocleidomastoid muscle proximally) are isolated and protected. Crossing branches of the external jugular vein are ligated while protecting the longitudinal aspects of the vessel. The omohyoid muscle is tagged and divided. If necessary for exposure and reconstruction, the transverse cervical artery (which usually crosses at C7) and suprascapular vessels are ligated and transected. The phrenic nerve is located on the anterior scalene muscle. Electrical stimulation while the anesthesia team momentarily holds the ventilation verifies diaphragmatic contracture. The nerve is followed proximally to identify C4 and C5. The more oblique C5 and C6 nerve roots are isolated between the anterior and middle scalene muscles. The upper trunk neuroma is usually at the junction of C5 and C6. Exposure and isolation of the more horizontal C7 is performed (Figure 20-8A). In each of these nerve root dissections, care is taken around the foramina to identify avulsions,

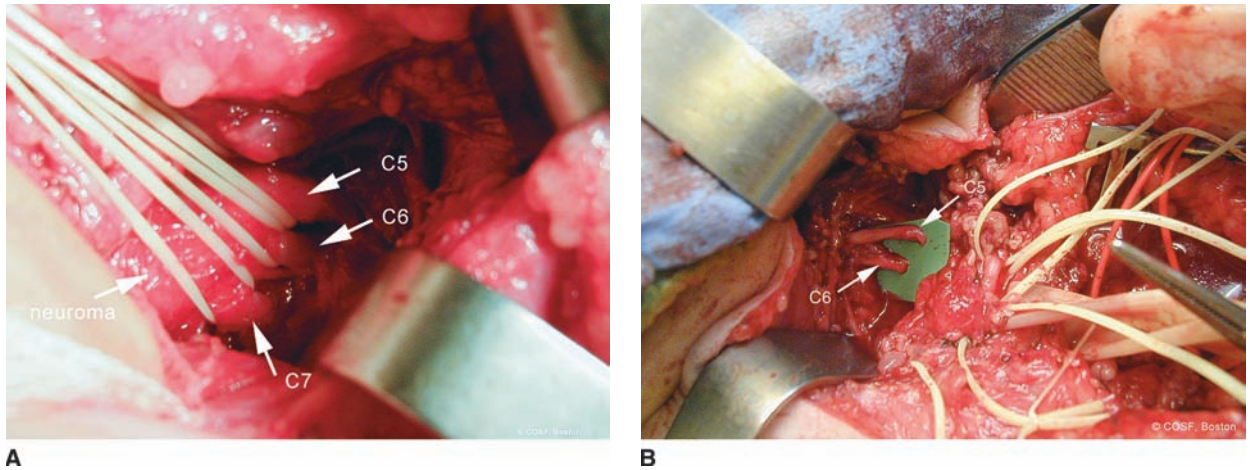
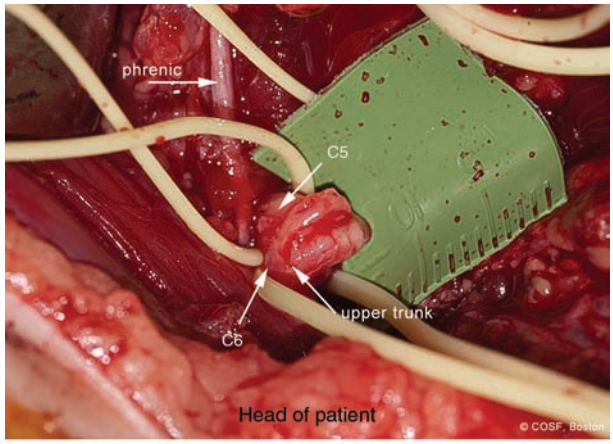


FIGURE 20-8 **A:** C5–C6–C7 nerve roots with elastic vessel loops around them as they enter neuroma involving upper and middle trunks. **B:** Transected C5 and C6 proximal to upper trunk junction in preparation for grafting.



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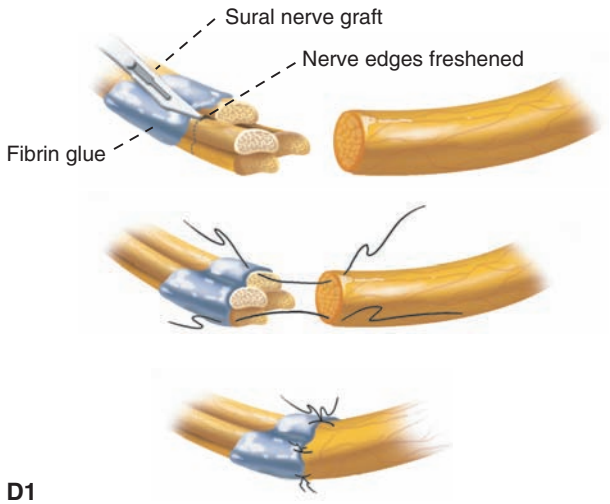

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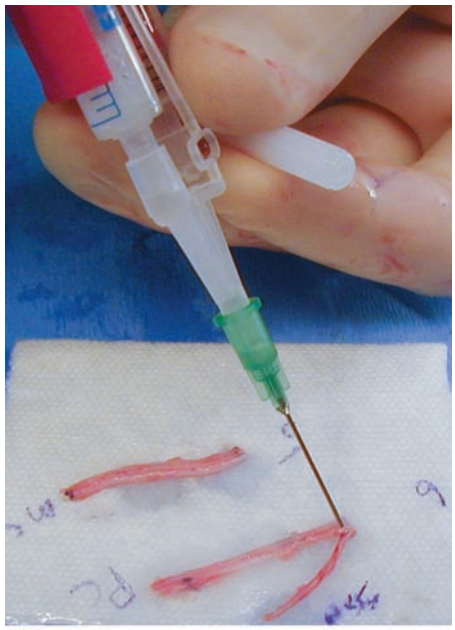

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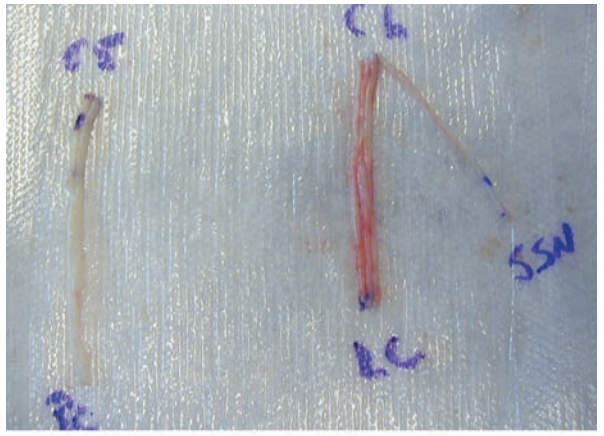

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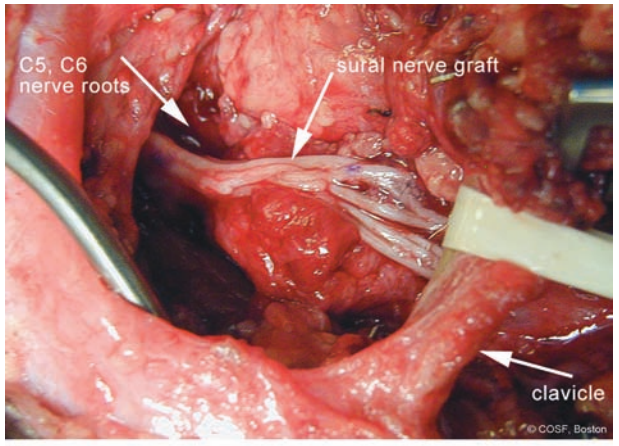

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FIGURE 20-8 *(continued)* **C:** Close-up view of transected C5 and C6 nerve roots with healthy fascicles. The phrenic nerve is seen on the anterior scalene muscle as it arises from C5 and descends to the thorax. **D:** Use of sural nerve grafts for reconstruction, depicted schematically in D1. In this case, sural nerves were used to graft C5 to posterior cord and C6 to suprascapular nerve and lateral cord (D2-D3) **E:** Completion of grafting from C5–C6 and C7 nerve roots to suprascapular nerve, anterior and posterior divisions upper trunk, and posterior division middle trunk.

assess neuromas in continuity, and protect against proximal bleeding. If there is any question about the viability of the C5 and C6 nerve roots for grafting, SSEP, transection with macroscopic and microscopic inspection, and biopsy are utilized. There is nothing worse than performing a major nerve reconstruction that fails to gain sufficient motor function due to the inadequacy of the proximal nerve segment. This is the critical intraoperative branching point between nerve grafting and transfers. The nerve roots are transected in sequence in preparation for grafting (Figure 20-8B, C).

SIDEBAR

Two decisions that face the surgeon in the operating room are (1) the type of skin incision and (2) mobilization or osteotomy of the clavicle. In general, the more severe the lesions, the more you need to see to decide and reconstruct. Surgical exposure of the brachial plexus can be by traditional Z-plasty incision or by transverse incision in the supraclavicular region (Figure 20-14A). Transverse incisions are more cosmetic. For us, extraforaminal upper trunk lesions are treated with the transverse incision that is between the palpable C5 and C6 transverse processes or a bit distal if we need to see C7. This allows excellent exposure of the C4–C6. C7 can be a bit of a stretch, and C8 and T1 can be seen in a limited way with more vigorous retraction. However, alternative exposure is safer if any real work needs to be done. More extensile exposure of C7–T1 can be obtained by converting this incision into a Z-plasty or by utilizing a second infraclavicular transverse incision with possible deltopectoral extension if needed.

If the neuroma extends under the clavicle, you need to see distally to reconstruct. This is always true for avulsions and may be true for injuries including C7. Your choices are either to mobilize the clavicle and work on either side of it or to perform a clavicular osteotomy for more complete exposure. For most of the C5–C7 injuries, we mobilize the clavicle with a circumferential Penrose drain. This includes partial detachment from the clavicle of the sternocleidomastoid insertion and pectoralis major origin. In infants, there is sufficient laxity in the sternoclavicular and acromioclavicular joints to allow for safe surgery. An elastic vessel loop is placed around the subclavian to axillary artery tree. In more severe injuries, we perform an oblique osteotomy of the clavicle with the periosteum intact. At the end of the operation, we repair the clavicle with nonabsorbable suture (Ethibond, Ethicon, Inc., Somerville, NJ) through drill holes in the bone and a tight periosteal repair. Clavicular nonunion is a risk and a painful problem if it occurs.

With the neural anatomy defined and neuroma isolated proximally, exposure distal to the neuroma is performed. In sequence, the anterior divisions of the upper and middle trunk to lateral cord and MCN nerve; the posterior division of the upper trunk to the posterior cord, radial, and axillary nerves; and the suprascapular nerve are isolated depending on each case. In the isolated C5–C6 upper trunk neuroma, complete exposure can be performed without clavicular mobilization/osteotomy (see Sidebar) or more extensile exposure. If C7 and the middle trunk are involved, both clavicular mobilization/osteotomy and more extensile surgical exposure may be necessary. The suprascapular nerve is identified as it exits the neuroma and heads to the suprascapular notch. Electrical stimulation will confirm its identity. The suprascapular nerve can be reconstructed by either a spinal accessory nerve transfer (see below) or nerve grafting from C5. The nerve is sectioned until macroscopic and microscopic inspection reveals healthy fascicles. Confirmatory biopsy can be used. Similar transections are performed for lateral and posterior cord reconstructions. The goal is to find healthy nerve as proximal as possible to increase the chance of success. Often in the isolated upper trunk lesion, this will be at the level of the anterior and posterior divisions of the upper trunk. With C7 involvement, it is usually more distal. Resection of the neuroma is performed as long as it will not damage healthy nerve. Measurements are made for length of cable grafts for each aspect of the reconstruction. This is all recorded on anatomic drawings on the operative field. To allow for redundancy and prevent undue tension, 10% to 20% (usually a centimeter) of additional length is desired for each graft compared to the distance measured within the operative field. The total length of donor graft needed is calculated and compared to the measured length from each ankle to knee region. Usually the full length of both sural nerves is needed.

Under tourniquet control, in sequence, each sural nerve is harvested. The first incision is longitudinal midway between the lateral malleolus and the Achilles tendon. The lesser saphenous vein is isolated from the nerve. A vessel loop is placed around the nerve, and distal branching points are identified. The nerve is then exposed atraumatically beneath the skin proximally. This can be done with a tendon stripper or long tenotomy scissors. It usually takes two to three transverse or longitudinal incisions to harvest the entire length, the last of which is frequently in the most distal popliteal fossa crease before the sural enters the medial sural and/or common peroneal nerves. In the midcalf, the nerve extends beneath the fascia. It also may have a smaller peroneal communicating branch that needs transection for full mobility. After sural nerve harvest is complete, the wounds are closed with absorbable suture, dressed, and the tourniquet is deflated.

Final tidying up of the plexus dissection and graft planning is then completed. The sural grafts are aligned in cables of appropriate length with planned redundancy.

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There is usually one, occasionally two grafts from C5 to the suprascapular nerve; multiple cables from C5 to the posterior division of the upper trunk; and multiple cables from C6 to the anterior division of the upper trunk. Again, the exact length of graft, proximal and distal insertion points, and number of cables is dependent on each case's operative findings and decisions. The cables are measured, cut to exact length, and aligned on the back table. Fibrin glue is used to connect them while leaving the ends open for repair (Figure 20-8D). In sequence, the nerve grafts are placed in the field. The coaptation sites are approximated with 9-0 or 10-0 epineural or fascicular suture and then fibrin glue completes the anastomosis. There are some situations where the alignment is precise without suture, and fibrin glue alone is used (Figure 20-8E). After completion of the grafting, the wound is closed in layers. Immobilization includes an infantile sling and swathe and a soft cervical collar along with lower extremity dressings.

◆ Nerve Transfers in Upper Trunk Lesion

Nerve transfers are less invasive, have a motor-to-motor direct repair, and occur closer to the motor endplate which shortens recovery time. There has not been a comparative study of grafting versus transfers. The ideal conditions for nerve transfer reconstruction of an upper trunk lesion are an intact spinal accessory to trapezius muscle; intact radial nerve to triceps and beyond; intact ulnar and median nerves to intrinsic and extrinsic hand function; and intact intercostals in a patient with absence of elbow flexion, shoulder abduction, and external rotation. This patient can be treated with neuroma resection and nerve grafting as noted above. Or, the lesion can be reconstructed with nerve transfers: (1) spinal accessory to suprascapular nerve; (2) long head of triceps motor branch of radial nerve to anterior axillary nerve branch to deltoid; (3) ulnar nerve extrinsic motor to biceps motor; and (4) median nerve extrinsic motor to brachialis motor. The T2–T4 intercostals could be substituted as a transfer for elbow flexion (Figure 20-9).[39–46]

FIGURE 20-9 Skin incisions outlined with supraclavicular transverse incision (indicated by *arrow*) for brachial plexus exploration and spinal accessory nerve transfer and curvilinear incision for either intercostal or partial ulnar nerve transfer depending on findings at exploration.

◆ Spinal Accessory Nerve Transfer

Cranial nerve XI exits the jugular foramen and divides into internal and external branches. The external branch supplies the sternocleidomastoid muscle first and then the trapezius. It crosses the posterior triangle between the superficial and deep fascial layers, supplies the upper trapezius with several branches, and courses under the anterior edge of the muscle as it descends. In the posterior triangle, it can be adjacent to lymph nodes, where it can be injured during lymph node biopsy. The spinal accessory nerve has variable connections with the cervical plexus, and this can be confusing. The nerve branches used for transfer are the distal branches that supply the middle and distal trapezius.

Dissection of the spinal accessory can be part of an entire plexus exposure (see above) or through a separate transverse incision proximal to the clavicle from the midclavicle to the acromioclavicular joint depending on the clinical situation. Mobilization of the spinal accessory is delicate so as not to dennervate the upper trapezius (the trapezius is important for ongoing shoulder elevation and function in these patients) or inadvertently harvest a cervical plexus branch rather than the appropriate motor branch (Figure 20-10A). Intraoperative nerve stimulation is very helpful in distinguishing the best branch for transfer while preserving function. Elevating some of the trapezius insertion into the clavicle can make the identification and dissection easier but does require care not to injure the nerve itself as it is on the undersurface.

The terminal motor branch of the spinal accessory nerve is transected distally and mobilized to allow for sufficient length and thus direct end-to-end repair with the suprascapular nerve (Figure 20-10B). Nerve grafts are usually not necessary and may lead to a less positive outcome. The suprascapular nerve is divided distal to the neuroma as it courses to the suprascapular notch. Its identification is confirmed by electrical stimulation. The size match of the two nerves is excellent. The transfer is completed with fine epineural sutures and fibrin glue. Postoperative immobilization protects against excessive neck motion. This procedure is usually not done in isolation but in conjunction with other nerve transfers or as a part of a grafting procedure for nerve regeneration to the limb. There are rare times where partial spinal accessory transfer is used for elbow flexion when the intercostals are damaged and the ulnar and median nerves are not functional.

◆ Partial Ulnar Nerve Transfer

The MCN nerve arises from the lateral cord distal to the coracoid process. Its first motor branch is to the coracobrachialis

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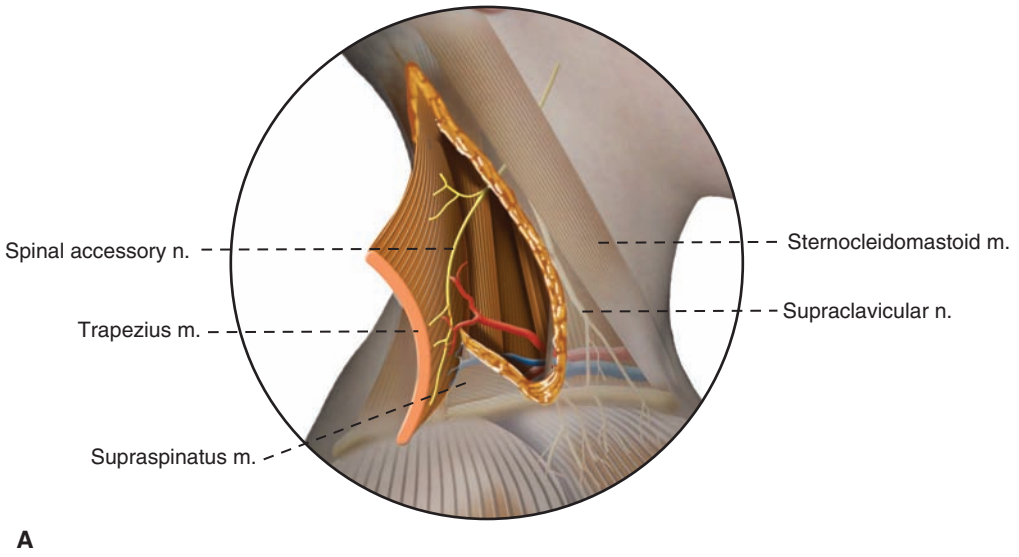


FIGURE 20-10 **A:** Spinal accessory partial nerve transfer outlined. The distal branches are utilized to avoid loss of trapezius muscle function and to be able to transfer to suprascapular nerve without a graft. **B:** Nerve transfer outlined with epineural repair.

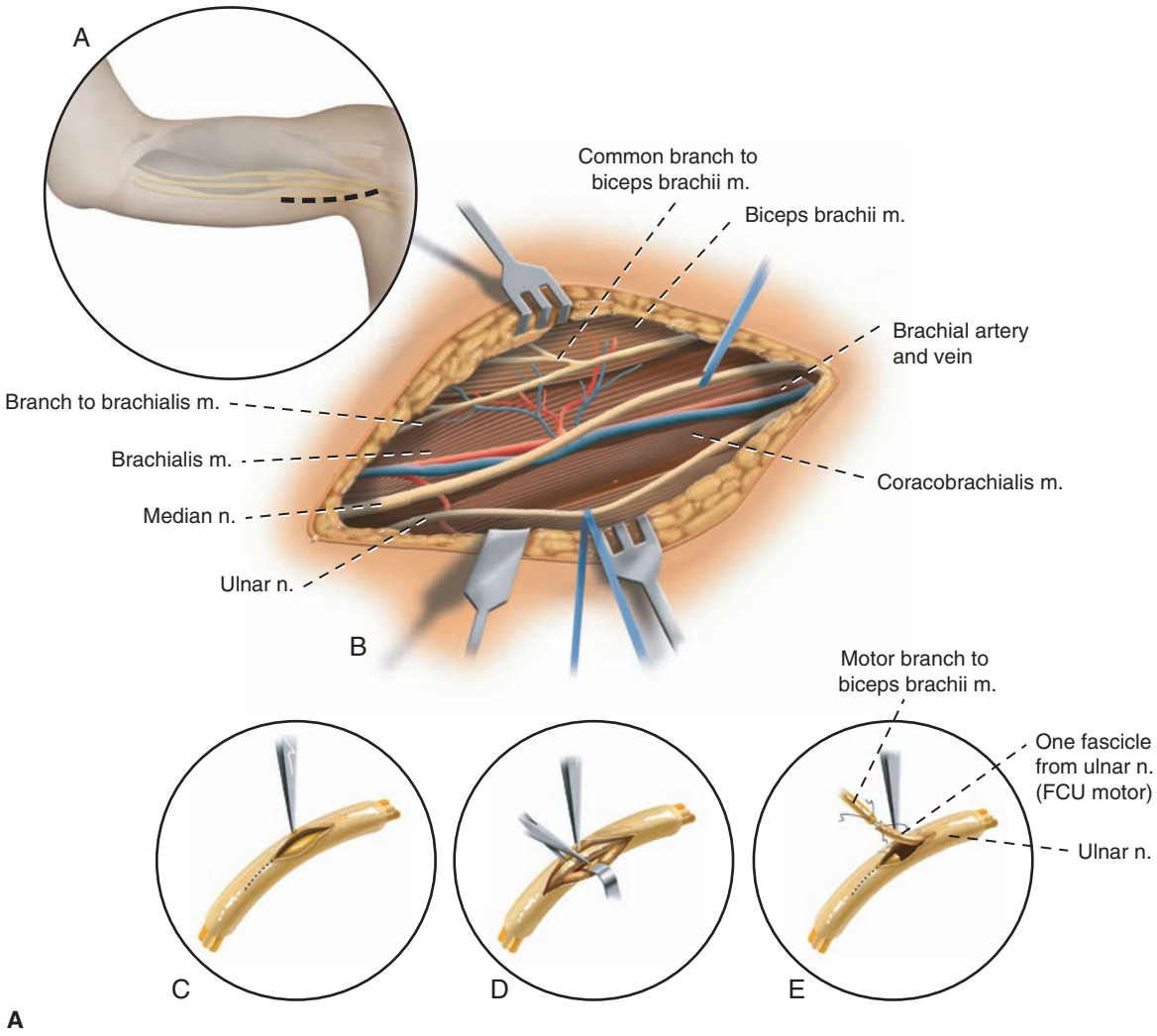
muscle, which it pierces. As the MCN nerve descends, it will either have a common trunk that divides into separate motor branches to the short and long head of the biceps or have individual motor branches that arise from the nerve separately.

The ulnar nerve is the terminal branch of the medial cord after its contribution to the median nerve. It lies inferior and medial to the axillary and then brachial artery as it crosses the upper arm. After isolation, microneural dissection is performed to distinguish motor from sensory fascicles and intrinsic from extrinsic motor fibers. The goal is to utilize a predominately extrinsic motor fascicle that has excellent length and width size to match the desired biceps motor recipient. The extrinsic fibers are usually posteromedial, and the intrinsic are usually anterolateral. Intraoperative nerve stimulation is used to confirm the proper fascicle (flexor carpi ulnaris (FCU) contracture should be seen) to avoid an intrinsic motor injury and functional loss to the hand (Figure 20-11D).

The close proximity of the ulnar to the MCN nerve in the upper arm allows for direct end-to-end nerve transfer without grafting (Figure 20-11A). Through a medial incision in the upper arm, isolation of each nerve is performed. Through an epineurotomy of the ulnar nerve, the extrinsic fascicle is isolated under the microscope, transected distally, and mobilized proximally for desired tension-free repair to a biceps motor or MCN branch (Figure 20-11B). Repair is done over or under the median nerve and brachial vessels depending on tension and compression concerns. Epineural and/or fibrin glue repair is performed in a direct end-to-end technique. The arm is protected in adduction for 2 to 4 weeks depending on the other care concerns. This transfer is usually not done in isolation except in rare, late-presenting cases. Now it is often done with a partial median extrinsic motor transfer to the brachialis motor to improve elbow flexion outcome.

◆ Partial Median Extrinsic Nerve Transfer

Similar to the ulnar nerve exposure and transfer noted above, the median nerve can be isolated in the upper arm



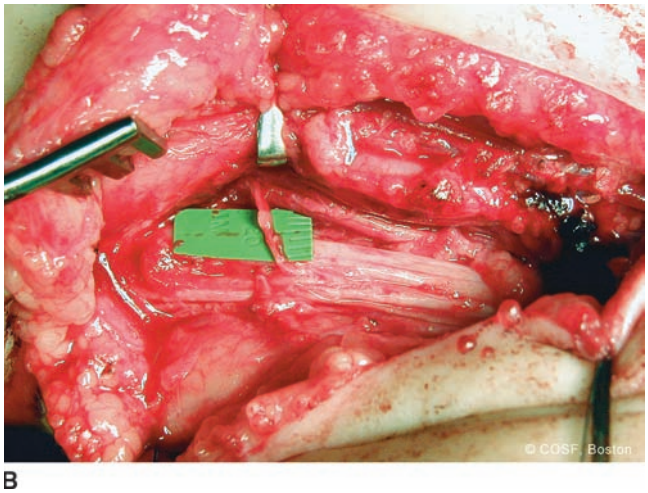


FIGURE 20-11 **A:** Illustration of Oberlin partial ulnar nerve transfer with direct motor fascicle to motor fascicle repair. **B:** Photograph of intraoperative repair. **C:** Skin incision utilized is outlined along the medial axillary line into the medial upper arm.

D

FIGURE 20-11 *(continued)* **D:** Ulnar nerve intrinsic motor loss after partial ulnar nerve transfer at another institution.

through the same medial incision. The median nerve forms from the medial and lateral cord terminal contributions and courses the upper arm adjacent to the brachial artery and vein. After isolation and protection of the vessels, the median nerve is dissected free. Through an epineurotomy, extrinsic fascicles can be isolated. Again electrical stimulation will confirm a predominately extrinsic motor fascicle of appropriate size match and avoid intrinsic injury.

The brachialis motor branches are distal to the biceps motor branches from the MCN nerve. Therefore the skin incision has to extend distally for this dual transfer. Similar to the ulnar nerve transfer, the motor to the brachialis is transected proximally and mobilized to tension-free proximity to the median nerve. The median extrinsic fascicle is transected distally and mobilized proximally for direct end-to-end repair. Epineural suture or fibrin glue repair is performed. Protection of repair is in an adducted position for 2 to 4 weeks depending on other care situations for the patient.

◆ Intercostal Nerve Transfers

Intercostal nerve transfers have been used extensively for reinnervation of MCN nerve and biceps muscle function.[35–37] Like all the other nerve transfer donors, intercostal nerves has also been applied for other nerve and muscle reinnervation with variable success as well as for free muscle transfer reinnervation. In addition, the T2 and intercostal brachial sensory nerves can be used for hand sensory reinnervation in extreme injuries. For MCN reinnervation, T2–T4 or T3–T5 intercostal nerves are used. The goal is to use the motor branches only and to do a direct end-to-end repair without grafting. The motor branch can be followed anteriorly toward the costochondral junction for maximum length for direct repair.

The incision can be transverse across the upper chest centered over the middle of the three ribs for planned nerve transfer. Or, incision can be part of a more extensile exposure depending on the complexity of the operation and the chest size of the patient (Figure 20-11C). The intercostal nerves are located beneath and behind each rib in order of V-A-N (vein, artery, nerve) from proximal to distal. Posteriorly at the midaxillary line, the long thoracic descends with the thoracodorsal vessels on the serratus anterior muscle and needs to be protected. The periosteum of each rib is incised from the anterior axillary line almost to the costochondral junction. The periosteum and intercostal muscle are elevated from the inferior and posterior surfaces to identify the nerve. The underlying pleura is precariously close and needs careful attention and protection. In an infant, often a small curved or right-angle retractor is used to elevate the rib and provide room for safe dissection. The nerve is followed anteriorly until terminal branches occur. After anterior distal transection, the nerve is circumferentially dissected back to the axillary branching point of the motor and sensory nerves. If more length is necessary, an epineural separation of the lateral sensory and medial motor branches can be carried out more posteriorly.

Similar to previous descriptions, the MCN nerve is dissected free distal to the coracoid. The proximal transection is determined for maximum motor reinnervation and tension-free end-to-end repair with the intercostal motor branches. This may require mobilization of the MCN proximally from the lateral cord. The microsurgical repair usually occurs in the axillae or on the serratus anterior muscle. The two to three intercostal donor nerves are initially glued together before direct epineural and fibrin glue repair (Figure 20-12). The repair needs to be tension free through full, passive shoulder and elbow motion in order to prevent postoperative gap formation and failure of the procedure. The arm is immobilized in an infantile sling and swathe in adducted position for 2 to 4 weeks.

◆ Long Head of Triceps Motor to Axillary Motor Nerve Transfer

The radial nerve has a separate motor supply to the long head of triceps apart from the lateral and medial heads. In a patient with an intact radial nerve but absent axillary nerve function, using the motor branch to the long head of triceps allows for direct motor-to-motor transfer to restore shoulder abduction without loss of elbow extension.

Both the radial and axillary nerves arise from the posterior cord of the brachial plexus. The axillary nerve courses with the posterior circumflex vessels around the humerus to the undersurface of the deltoid muscle. Along the way, it has anterior and posterior branches. The anterior branch provides motor supply to the anterior and middle deltoid. The posterior branch supplies the posterior deltoid and teres minor and usually has the separate sensory fibers to the lateral arm. The anterior branch is used for motor reinnervation of the deltoid with this transfer. This is usually done in conjunction with other nerve transfers.

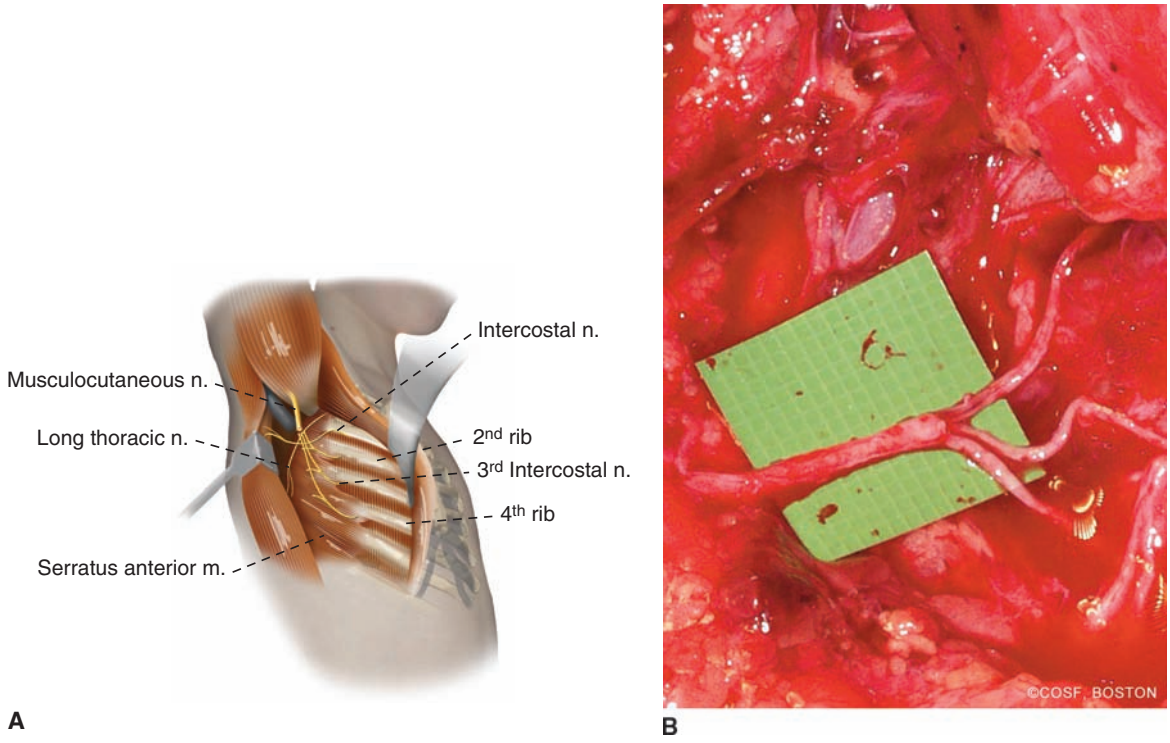


FIGURE 20-12 **A:** Illustration of intercostal nerve transfers with direct repair and no graft to MCN motor branch to biceps. **B:** Intraoperative direct repair of T2–T3–T4 to MCN.

Exposure for the nerve transfer is performed deep to the deltoid muscle in between the long and lateral heads of the triceps muscles. The quadrangular space (that transmits the axillary nerve) and the triangular space (boundaries of teres major superiorly, long head of triceps medially, and lateral head of the triceps laterally with the radial nerve and its triceps nerve branches) are identified. The teres major muscle is the key landmark, with the axillary nerve located above it and the radial nerve located below it. The nerve branch to the long head of triceps is isolated centrally in the triangular space and is dissected distally to its insertion point. It is transected as distal as possible and mobilized for direct repair to the anterior branch of the axillary nerve. These nerves are in close proximity. The anterior branch is isolated and confirmed by electrical stimulation. It is dissected proximally and transected just after its branching point. The two nerve ends can be repaired directly without grafting (Figure 20-13) with epineural suture and/or fibrin glue. The repair needs to be tension free throughout full shoulder and elbow motion to lessen the risk of operative failure. Postoperative care is protected sling and swathe immobilization for 2 to 4 weeks.

◆◆ Avulsion Injuries

Unfortunately, there are some infants and children with very severe nerve root avulsions. Fortunately, it is rare that all roots are completely avulsed. Nerve reconstruction is usually a combination of grafting and intraplexal and extraplexal transfers. Preoperative clinical exams, MRI scans, and electrodiagnostics can aid in decision making. However, in infants most of the definitive information comes with operative exploration and inspection. This may include SSEP and nerve biopsy analysis. This work is challenging. The required donors may not be available. Surgical strategy requires prioritization of potential recipients and anticipates less than full recovery of the entire limb. The length and amount of grafting can be extensive due to the wide zone of injury, and this may require additional grafting donors besides the sural. The length and amount of grafting may limit success. In adults, hand recovery is not feasible, but in children return of hand function is possible in limited ways. In the absence of a functional hand, even assistive, long-term outcome is poor. Brachiation against the chest may be the only assistive grasp or holding function of that limb. Therefore in infants we attempt to reinnervate the hand for both motor recovery and sensibility.

The techniques are not different than those described above. Plexus exposure is more extensile. This requires either two incisions or a traditional Z-plasty (Figure 20-14A). Clavicular mobilization or osteotomy is necessary. There is risk of chylothorax due to thoracic duct injury, respiratory distress due to phrenic nerve dysfunction or reinjury, and a pneumothorax due to dissection adjacent to the pleura. Averting these pitfalls requires gentle, meticulous dissection in a significant zone of injury and scar.

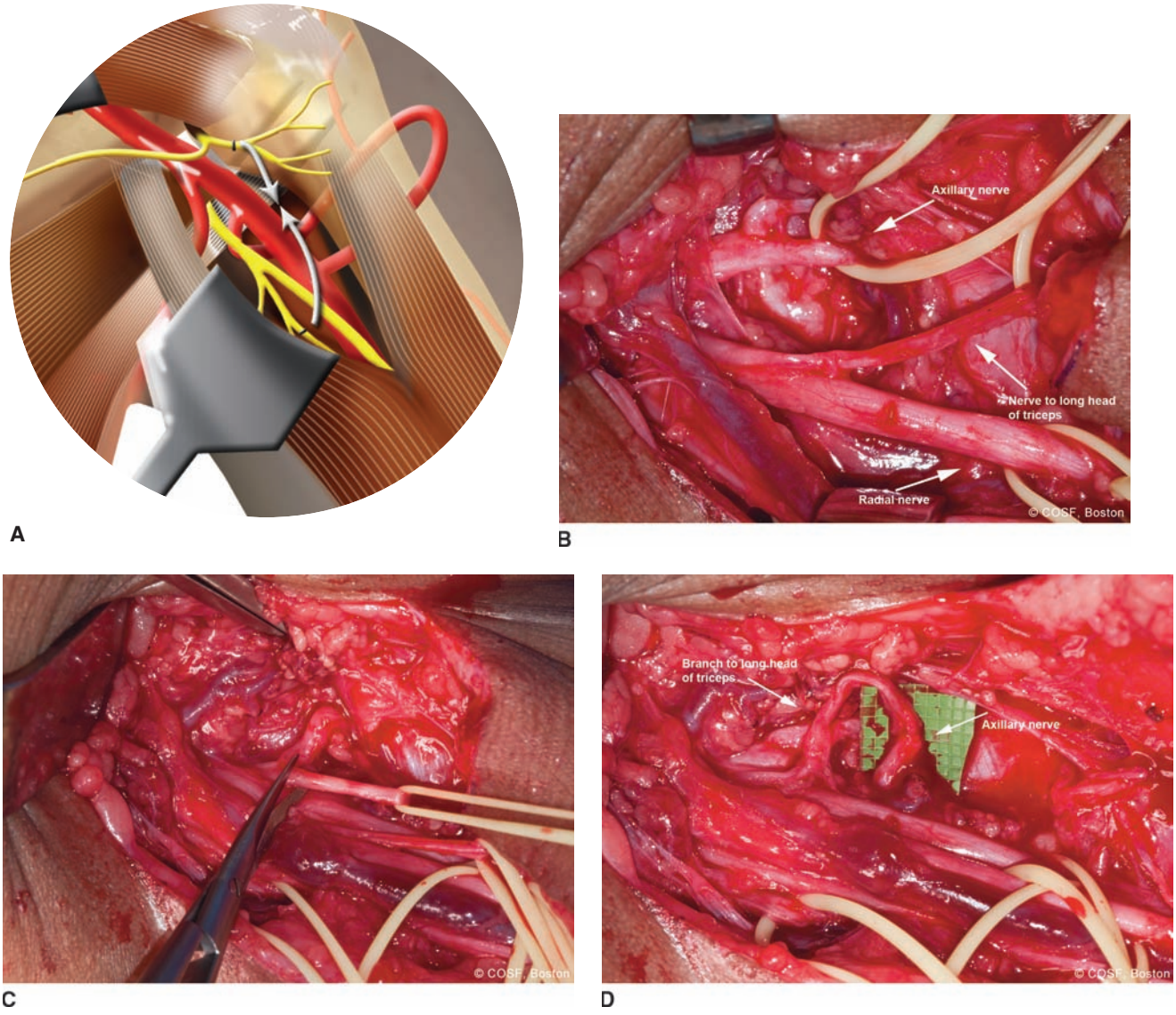


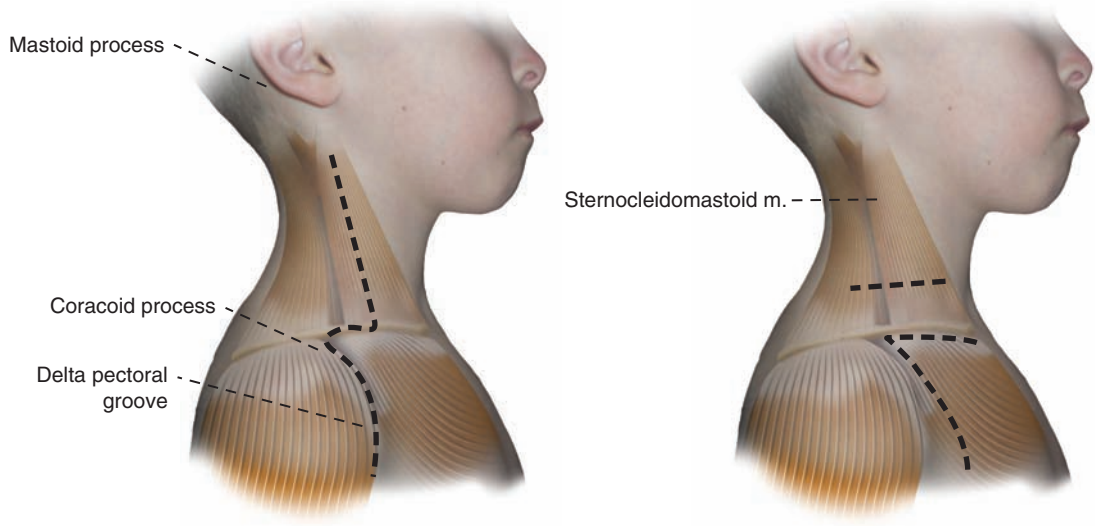
FIGURE 20-13 **A:** Illustration depicting partial radial nerve transfer of motor branch to long head of triceps to posterior axillary motor branch. **B:** Dissection of nerve fascicles for long head of triceps motor branch and axillary motor branch. **C:** The motor branch to the long head of triceps is transected. **D:** The nerve transfer is completed.

This surgery is best done early, at 1 to 3 months of life. This increases the chance of motor endplate recovery and is at a time of less fibrosis. These patients may require prolonged hospitalization and even intensive care monitoring if there are respiratory issues. The presence of phrenic nerve paralysis prior to intercostal transfers clearly poses a concern for poorer postoperative respiratory function. Your anesthesia and intensive care unit teams should be aware. During surgery, you may have to decide to utilize all the extraplexal nerves for transfer in the primary operation or save something in reserve for a possible free muscle transfer. This is not an easy call.

In these cases, recovery is more prolonged. Rather than seeing signs of neural recovery between 3 and 6 months following upper plexus rupture reconstruction, these grafts and nerve transfers may take 6 to 12 months to show signs of recovery. Recovery to antigravity strength may be more prolonged and, at times, does not occur. This makes re-exploration decisions harder.

Other Issues and Choices

Lack of clarity persists on the benefits of (1) vascularized versus nonvascularized nerve grafting and (2) contralateral C7 nerve transfers. In infants and children, we do not use vascularized ulnar nerve grafts for reconstruction. Others do.[16,47] This approach assumes no intrinsic hand function recovery if the ulnar nerve is to be utilized as a donor nerve. The anastomosis is between the transverse



A

B

FIGURE 20-14 **A:** More extensile exposure for avulsion injury is required by either traditional Z-plasty incision or two incisions. Either skin incision technique requires clavicular mobilization, which may include an osteotomy depending on the extent of the neuroma and reconstruction plan. **B:** Long-term photographs of avulsion patient treated with nerve grafting at age 5 months and shoulder tendon transfers at age 3 years. Hand to mouth, shoulder elevation, and external rotation noted.

cervical artery/external jugular vein and the superior ulnar collateral artery and vein. This is more of an adult operation.

Similarly there are rare, if any, indications for contralateral C7 or phrenic nerve transfers in infants and children. The results are variable and debatable. This is a rare case situation in which there are no nerve roots and insufficient ipsilateral extraplexal nerve transfer options. Details of these techniques are well described in other sources.[48,49]

Finally, there are some tragic situations in which only free muscle transfers have the potential to provide assistive arm and hand function to a severely affected limb. This includes failed nerve surgery and late-presenting severe cases. Single or double free gracilis muscle transfers, as advocated by Doi,[50,51] are used more often in adults. There are indications in children, most commonly to provide elbow flexion. In children these are usually performed late as opposed to early in adults in conjunction with nerve surgery. The technical descriptions for these multiple-stage operations are well described elsewhere. In our hands, they have been somewhat inconsistent in the late-presenting patient. Other free muscle options include latissimus and rectus femoris. Obviously if there is a regional pedicled transfer (such as Steindler flexorplasty) available, this would be preferred over free muscle transfer.

POSTOPERATIVE

The nerve reconstructions are protected against movement until there is sufficient healing to prevent rupture or gap formation. This is usually at 2 to 4 weeks. To be on the safe side, we immobilize for 1 month. This includes an adaptive sling and swathe using stockinette, heavy cotton padding, and size 3 BandNet (tubular elastic dressing retainer, Western Medical Ltd., Tenafly, NJ) to limit motion but prevent skin problems in a relatively insensate limb and hand. We include the neck in an adaptive infantile collar for grafting and spinal accessory nerve transfer procedures. In children with strong shoulder adductors and internal rotators, we use botulinum toxin A (Botox, Allergan Pharmaceuticals, Inc., Irvine, CA) to the pectoralis major and subscapularis muscles (1 to 2 U/kg) at the conclusion of the nerve surgery to prevent contractures. We do the same with tight finger and wrist flexors when wrist and finger extensors are absent. The sural nerve donor site dressings are removed at 2 weeks. At 4 weeks, we remove the arm and neck dressings and start unrestricted therapy. Our goal is to prevent contracture while awaiting recovery. The only time we use electrical stimulation is when we see signs of recovery and the child can tolerate the stimulation without pain. This is usually in the traumatic cases as a part of reeducation.

ANTICIPATED RESULTS

I've missed more than 9,000 shots in my career. I've lost almost 300 games. 26 times, I've been trusted to take the game winning shot and missed. I've failed over and over and over again in my life. And that is why I succeed.
—Michael Jordan

There is clearly a difference in expected results from upper trunk, to C5–C6–C7, to total plexus to avulsion procedures. The more severe the injury, the less complete the anticipated recovery with nerve surgery. The only recovery that matters is functional antigravity use. Contracture without functional use is more for us than it is useful for the patient. Without strength and useful active motion, patients will ignore that limb and go to their other side.

Fortunately, recovery of elbow flexion is extremely common. Recovery of shoulder stabilization is somewhat less with deltoid recovery higher than external rotators. Secondary tendon transfers to the rotator cuff are not unusual. Both wrist and finger extension also have a very good chance of antigravity recovery, but secondary tendon transfers and stabilization procedures have to be a part of the armamentarium of any plexus surgeon. Finally, assistive hand function can occur in approximately 40% to 60% of total plexus patients. Loss of sensibility is rarely a complaint in these children as they grow (Figure 20-14B).

COMPLICATIONS

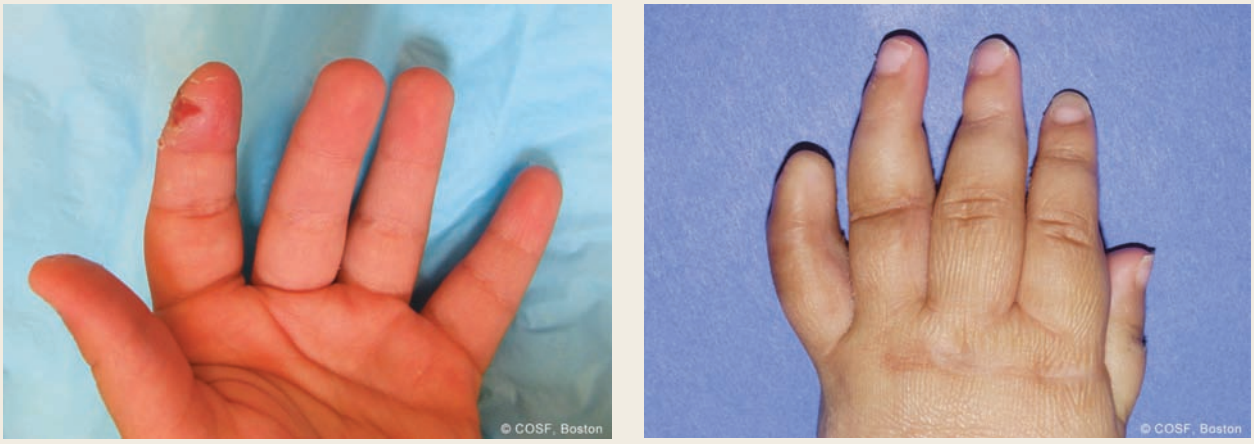
Infection is rare and usually superficial if it occurs. The end result may be a poor-appearing wound. Even without infection, incisions can hypertrophy. This is less common with transverse incisions. The most significant complication is failure of the procedure to restore useful, active function. In infants, this is rare but is very disappointing. Secondary reconstructions or reexploration and repeat nerve surgery may be indicated. Pain syndrome occurs rarely (see Coach's Corner). Serious complications, such as respiratory distress, pneumothorax, chylothorax, permanent elevated hemidiaphragm, and arterial or venous bleeding, are real possibilities. Meticulous, careful dissection and appropriate subspecialty backup and care are necessary to lessen the risk and treat these complications. Many of these operations can only be done in a tertiary care center.

CASE OUTCOME

This infant underwent brachial plexus exploration through a supraclavicular transverse incision at 5 months due to failure of adequate motor recovery in C5–C6–C7 distribution. The upper trunk neuroma was just beyond the C5–C6 junction. It extended into the middle trunk. Distal to the neuroma, the anterior and posterior divisions

COACH'S CORNER

In adults with traumatic brachial plexus injuries, a pain syndrome is anticipated and is very incapacitating. In infants, it is fortunately rare. It is seen in about 4% of cases. The trend is for it to occur more commonly after nerve surgery. The child is often inconsolable and fails all the pediatrician's "colicky baby" treatments. The telltale sign is self-mutilation of the affected digits and hand (Figure 20-15). These infants and children can literally chew away the terminal aspects of their digits with repetitive mouthing and limited sensory feedback. Recurrent wounds, infections, and eventual soft tissue loss can be a part of their pain syndrome. Protective dressings, distasteful lotions used for nail-biters, and pain service management with medications and blocks have been tried. Treatment of each infection is required. Eventually they outgrow the pain syndrome, often with neural recovery improvement. This is a disconcerting condition for the patient, family, and caregivers.



A B

FIGURE 20-15 **A:** Early self-mutilation with skin breakdown and resolved infection of the index finger after antibiotics. **B:** Long-term result of self-mutilation with autoamputation of distal aspect of small finger.

of the upper trunk were isolated. Transection of the C5–C6–C7 nerve roots, suprascapular nerve, and upper trunk divisions revealed macroscopic and microscopic healthy fascicles that were confirmed by nerve biopsy in the operating room. Electrical stimulation of the C7 nerve root through the middle trunk, posterior cord, and radial nerve showed triceps and wrist extensor muscle activation. Sural grafts were obtained from both legs. Nerve grafting with epineural suture and fibrin glue was performed: (1) C5 to suprascapular 4 cm single graft; (2) C5 to posterior division upper trunk three 4 cm cable grafts; and (3) C6 to anterior division upper trunk three 3.5 cm cable grafts (Figure 20-8E). The patient recovered antigravity biceps and deltoid function without issues. The rotator cuff function was less, and at 3 years he underwent secondary tendon transfers to the rotator cuff.

SUMMARY

About 10% to 30% of BPBPs will require nerve surgery. There is still controversy about the timing of surgery between 3 and 9 months. The indications are clearer for avulsion injuries and ruptures with failure of biceps recovery. Nerve reconstruction is by nerve grafting, nerve transfers, or a combination of both. These can be technically and intellectually demanding operations.

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CHAPTER

21

Brachial Plexus Birth Palsy: Shoulder Reconstruction

CASE PRESENTATION

An 18-month-old child with known brachial plexus birth palsy (BPBP) is referred for limitations of arm function. He has been enrolled in an early intervention physical therapy program with daily home exercises since early infancy. The parents' and therapist's notes indicate a return of elbow flexion at 4 months of age. They state he has never been able to reach his hand above shoulder level, and he reaches his hand to his mouth only with his elbow high in the air. He did have a clavicle fracture at birth, and the parents wonder if this is part of the problem.[1] On exam, he has limited passive external rotation (ER) to 10 degrees in adduction and 60 degrees in abduction. There is a bony prominence palpable in the posterior soft spot of his shoulder with internal rotation.

CLINICAL QUESTIONS

- How often does a child with BPBP have a permanent, incomplete recovery?
- What are the limitations of the shoulder with an incomplete recovery?
- What are the risks of glenohumeral deformity or dislocation?
- What radiographic tests are used to assess the glenohumeral joint?
- How is the deformity classified?
- What surgical techniques are used to treat the adduction, internal rotation contracture, and ER weakness?
- When is joint reduction indicated?
- Which techniques are used for joint reduction and stabilization?
- When are tendon transfers indicated?
- What are the indications for a humeral osteotomy?
- What are the long-term outcomes of these procedures? Expected complications?

THE FUNDAMENTALS

Muscle imbalance in a growing child can lead to bone and joint deformity. The glenohumeral joint is no different.[2] In children with incomplete recovery from BPBP, the adductor and internal rotator muscles are often out of balance with the abductor and external rotator muscle forces (Figure 21-1). The pectoralis major is dually innervated and will recover earlier than the opposing muscles in an upper plexus injury. The subscapularis, innervated by the upper and lower subscapular nerves off the posterior cord, also acts as a deforming force, through either unopposed muscle activity and tightness or, less likely, fibrosis. The latissimus dorsi (thoracodorsal nerve supply off the posterior cord) and teres major (lower subscapular nerve supply off the posterior cord) often recover in advance of the deltoid (axillary nerve off the posterior cord), supraspinatus, and infraspinatus muscles (suprascapular nerve off C5 or upper trunk). In addition, periarticular tightness and myostatic contracture can develop. This combination of forces leads to an adduction and internal rotation contracture in infancy or early childhood (Figure 21-2). Eventually, if unrestrained, this can cause progressive glenohumeral deformity and dislocation (Figure 21-3). Experiments using animal models have replicated this sequence from nerve impairment through muscle imbalance to joint deformity.[3]

Etiology and Epidemiology

Between 10% and 40% of infants with BPBP will have an incomplete recovery. Some will have minimal deficits; others will have profound, permanent disability. The C5–C6 (–C7) children with an incomplete recovery are more at risk for glenohumeral dysplasia and dislocation[4] than either the total plexus or the minimally affected patients. Publications on shoulder dislocations and deformity date back to Stimson and Fairbank and include many modern publications.[5–7] Cumulative knowledge is now extensive. Glenohumeral dysplasia and dislocation are clearly high risk for children with continued imbalance and contracture.[8] Close monitoring, evaluation, and treatment

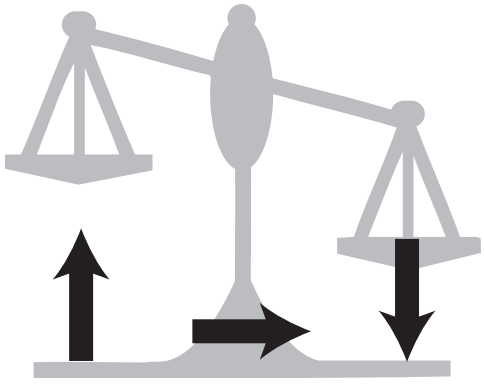

FIGURE 21-1 The return of internal rotator strength before ER muscle activity leads to an imbalance about the glenohumeral joint. This can progress to deformity and dislocation.

are required. Through the radiographic advances of MRI scans, confirmed by ultrasound and arthrograms, it is clear that deformity starts very early in life and is progressive if untreated.

Clinical Evaluation

Assessing individual muscle strength in an infant can be challenging. The Medical Research Council (MRC) muscle strength grading system (0 to 5) is too exacting, as infants and toddlers cannot follow verbal instructions for resistive testing. Recognizing that muscle strength has to be inferred from observed or stimulated movement in infants and children, Gilbert and Tassin modified that MRC system to a four-point gradation: (0) no muscle contracture, (1) muscle contracture without movement, (2) movement with gravity eliminated, and (3) complete movement against weight of extremity (Table 21.1). Other classification systems include the modified Mallet scale (Figure 21-4, Table 21.2) and the Hospital For Sick Children Active Movement Scale (Figure 21-5).[9–11] These later systems have been shown to have inter- and intraobserver reliability.

Assessing passive range of motion is an essential part of comprehensive shoulder evaluation in these patients.

FIGURE 21-2 The affected left arm of this child with incomplete recovery reveals restrictions in ER and above horizontal shoulder function that is typical for these patients. He has to reach his mouth with his shoulder maximally abducted. He cannot reach the top of head and can only reach the left side by tilting his neck forward and to the side. His humeral head is dislocated.

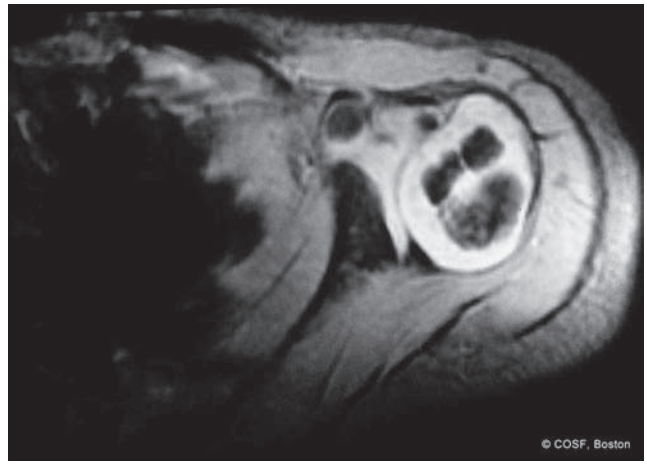

FIGURE 21-3 MRI of the affected glenohumeral joint reveals posterior subluxation of the humeral head and glenoid deformity with an early pseudoglenoid or biconcave joint. The humeral head is already beginning to change shape, and the position of the biceps insertion reveals the presence of an internal rotation contracture.

Table 21.1

Gilbert and Tassin's modified MRC classification for motor strength

Muscle grade	Strength
0	No contracture
1	Muscle contracture, no movement
2	Some movement, gravity eliminated
3	Complete movement against gravity

From Gilbert A, Tassin JL. Surgical repair of the brachial plexus in obstetric paralysis. *Chirurgie.* 1984;110(1):70-5.

Table 21.2

Modified Mallet classification

Functional Parameter	Class I	Class II	Class III	Class IV	Class V
Global abduction	None	<30 degrees	30–90 degrees	>90 degrees	Normal
ER	None	<0 degrees	0–20 degrees	>20 degrees	Normal
Hand-to-neck ability	None	Not possible	Difficult	Easy	Normal
Hand-to-mouth ability	None	Marked trumpet sign[a]	Partial trumpet sign[a]	<40 degrees of abduction	Normal
Internal rotation	None	Not possible	To S1	To T12	Normal

[a]A trumpet sign consists of abduction of the shoulder with simultaneous flexion of the elbow.
From Mallet J. Paralysie obstetricale du pexus brachial. Traitment des sequelles. Rev Chir Orthop. 1972;55(suppl):8-166.

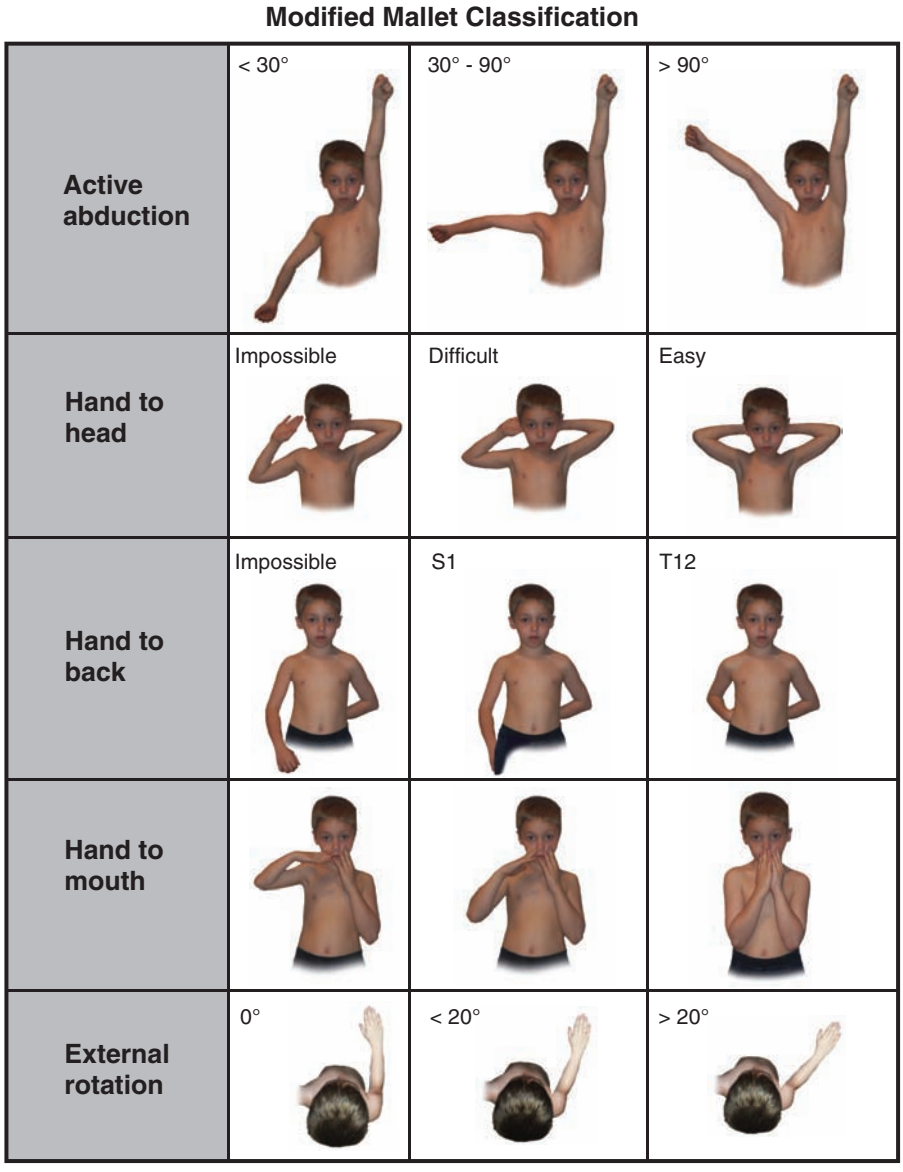

FIGURE 21-4 Modified Mallet classification for global abduction, ER, hand to neck, hand to spine, and hand to mouth. Each category is graded I to V with I, no function; V, normal function, and grades II, III, and IV depicted by illustration. Some children are not testable due to age and lack of cooperation at that particular visit. An aggregate Mallet score is a combination of the scores for all five categories, ranging 0 to 25.

Hospital for Sick Children Active Movement Scale

a. Shoulder abduction: ____
b. Shoulder adduction: ____
c. Shoulder flexion: ____
d. Shoulder external rotation: ____
e. Shoulder internal rotation: ____
f. Elbow flexion: ____
g. Elbow extension: ____
h. Forearm pronation: ____
i. Forearm supination: ____
j. Wrist flexion: ____
k. Wrist extension: ____
l. Finger flexion: ____
m. Finger extension: ____
n. Thumb flexion: ____
o. Thumb extension: ____

Gravity eliminated	Score
No contraction	0
Contraction, no motion	1
<50% motion	2
>50% motion	3
Full motion	4
Against Gravity	**Score**
<50% motion	5
>50% motion	6
Full motion	7

FIGURE 21-5 The Hospital For Sick Children Active Movement Scale grades each muscle movement from the shoulder to the hand by a score of 0 (no function) to 7 (normal function). A child must have full gravity-assisted function (score of 4) before antigravity scoring can be obtained.

Maintaining passive ER with scapular stabilization is integral to their therapy program. Conversely, those infants and children losing ER in adduction[12] and/or abduction[2] are most at risk for glenohumeral deformity (Figure 21-6). Before a fixed deformity develops, the shoulder instability can be palpated in the posterior soft spot with alternating internal (subluxation) and external (reduction) rotation. Later, the dislocated humeral head is palpable posteriorly with clear asymmetry to the opposite side anatomic situation (Figure 21-7). Scapular winging is present in all these children with muscle imbalance and contracture (Figure 21-8).

Advanced radiographic evaluation is now a significant part of treatment planning for these patients. Plain radiographs give limited information due to the major unossified areas about the shoulder at this age. Ultrasound in skilled hands provides definitive information on glenoid dysplasia and joint alignment similar to hip ultrasounds

FIGURE 21-6 With the scapula stabilized, this patient has limited ER in adduction. The glenohumeral joint needs investigation for deformity.

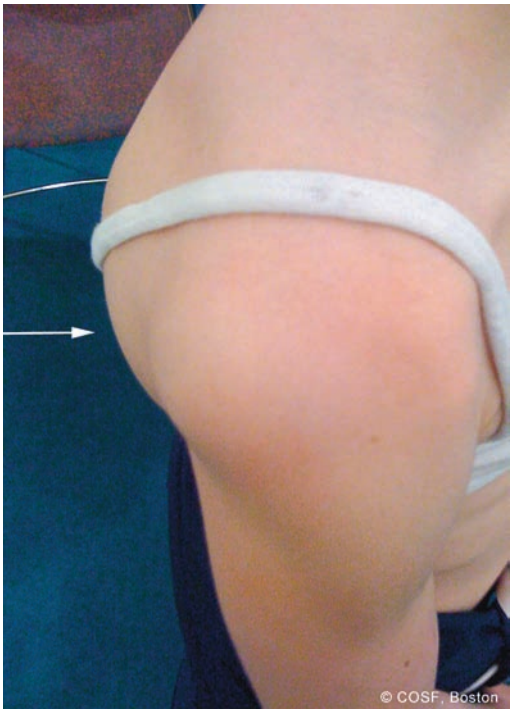

FIGURE 21-7 View of the affected right shoulder with obvious posterior dislocation of humeral head.

FIGURE 21-8 Marked scapular winging in this patient with dysplastic glenohumeral joint and shoulder contractures.

in developmental dysplasia. MRI scans are diagnostic (Figure 21-9).[13] CT scans are faster, cheaper, and give comparable information as MRI scans but have high radiation dosing and do not show the unossified glenoid apophysis[14,15] (Figures 21-10 and 21-11). Arthrograms also give comparable information[16–19] (Figures 21-12 and 21-13). The clinical continuum of dysplasia at the glenohumeral joint progresses from anatomic alignment and symmetric development, increased glenoid retroversion, humeral head posterior subluxation, and biconcave or pseudoglenoid (Figure 21-14) to a frank dislocation with a flat humeral head and glenoid (Figures 21-15 and 21-16). The degree of deformity can guide the surgeon on timing and the type of operative intervention. MRI scans are more capable than physical examinations of revealing the presence and degree of glenohumeral dysplasia.

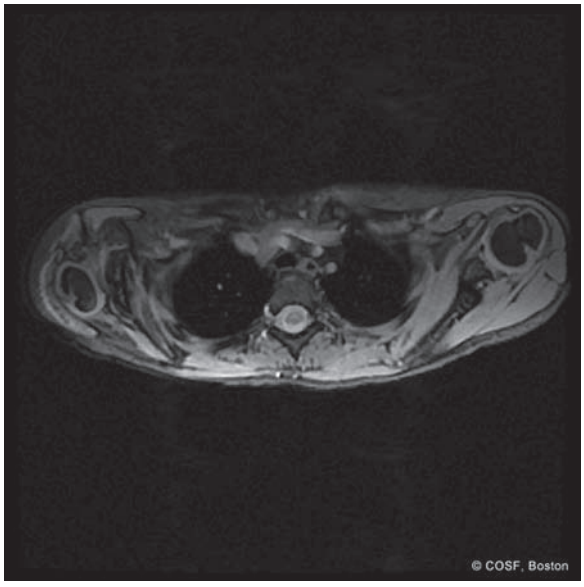

FIGURE 21-9 Obvious asymmetry between affected and unaffected glenohumeral joints by MRI scan. The affected side has marked glenoid deformity, posterior subluxation of the humeral head, and a pseudoglenoid. The unaffected side has anatomic alignment.

Surgical Indications

Indications for surgery about the shoulder in these children include (1) infantile dislocation, (2) persistent internal rotation contracture despite maximal nonoperative treatment, (3) limitation of active ER and above shoulder-level function with plateauing of neurologic recovery, (4) progressive or marked glenohumeral deformity, and (5) a combination of any or all of these (Figure 21-17). The age at intervention is dependent on the severity of the problem and when the patient presents for care. The spectrum can be from the first 6 to 12 months of life through adolescence. We advocate early intervention when indicated to prevent progressive deformity, allow for joint remodeling, and maximize function.

Almost all publications over the past 100 plus years indicate the problem is a combination of muscle imbalance, soft tissue contracture, and bone and joint deformity. The interventions recommended in those papers, public presentations, and patient consultations are various ways of addressing those issues. Surgical guidelines that emerge are (1) in the young child (6 months to 2 years) with resistant contracture but potential ongoing ER and abduction recovery, intervention for contracture release alone (botulinum toxin A [Botox, Allergan Pharmaceuticals, Inc., Irvine, CA] injection, subscapularis slide, arthroscopic joint release, coracoacromial ligament release) is indicated[20–23]; (2) in the slightly older child (2 to 5 years), a combination of releases and tendon transfers is indicated since active ER recovery is no longer feasible[15,24–27]; (3) joint reduction is indicated if there is moderate-to-marked joint deformity in the younger child (6 months to 5 years) with remodeling potential[28,29]; (4) bony surgery, such as humeral osteotomy, is necessary in older children with severe deformity.[30,31] Most of these methods achieve the same goal.[32] We have outlined broad guidelines, and each patient may require a variation depending on the physical exam, MRI scan findings, and social situation to achieve a successful outcome.

SURGICAL PROCEDURES

You don't suffer, kill yourself and take the risks I take just for money. I love bike racing.
—Greg LeMond, three-time Tour de France winner

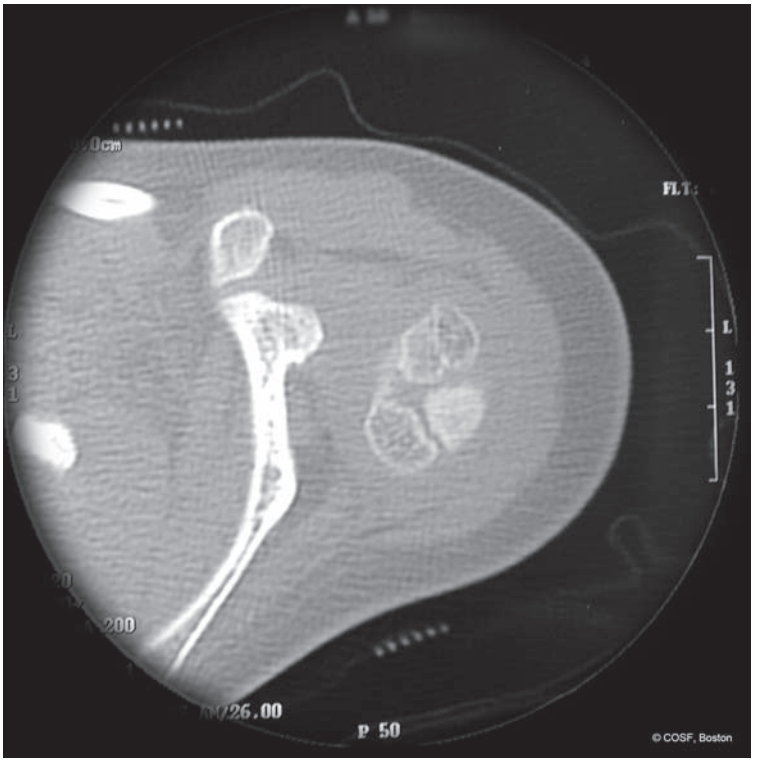

FIGURE 21-10 CT scan of dislocated humeral head with flattened glenoid.

Physical Therapy

Supervising therapy and monitoring recovery are important aspects of treatment of these children. Since glenohumeral dysplasia can start very early in life, prioritizing full-shoulder passive range of motion from month 1 is important. Stabilization of the scapula with passive abduction, ER in adduction and abduction, and forward flexion should become a many times a day routine for the families. Since in the first 2 years of life, diapers are changed on average eight times a day, this is an excellent opportunity and reminder for therapy. Loss of passive motion clearly correlates with the risk of glenohumeral deformity and dislocation. If adduction and ER approach 0 degrees, or abduction and ER approach <90 degrees (straight vertical), then further intervention is warranted. Depending on the situation, this may be a trial of more supervised therapy; Botox injections in the subscapularis, teres major, and/or pectoralis major muscles; or an MRI scan to assess deformity and joint alignment.

Botox Injection

Botox injection may be indicated in patients who are failing to maintain passive ER and joint reduction in the first 2 years of life despite vigorous, supervised appropriate physical therapy.[33] Since Botox is currently used off-label, proper informed consent must be obtained. The published beneficial effects of Botox injections in cerebral palsy muscle imbalance, and early, similarly positive results in BPBP, warrant its use in the suitable patient. Dosage is 1 to 3 U/kg, not to exceed 10 U/kg, injected in equally divided doses into the pectoralis major, subscapularis, and teres major. This is done under general anesthesia and sterile prep conditions. Percutaneous electrical stimulation can be used to isolate each muscle for injection. Following Botox injection, the

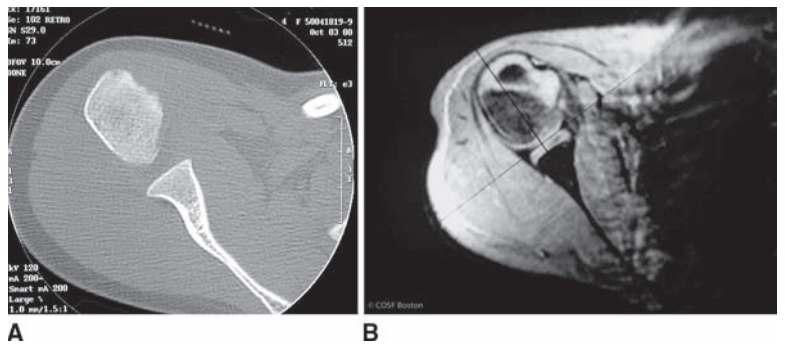

FIGURE 21-11 Normal glenohumeral joint with humeral head centralized and normal glenoid retroversion for age by CT (**A**) and MRI (**B**) (Type I glenoid).

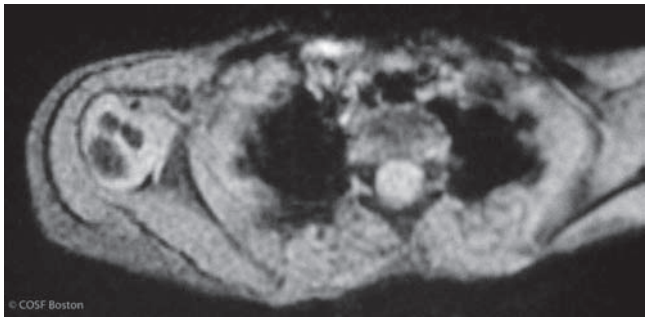

FIGURE 21-12 Type II deformity with mild increased retroversion and the beginnings of humeral head subluxation.

shoulder is reduced and casted. A shoulder spica is applied with the shoulder adducted approximately 30 to 40 degrees and externally rotated approximately 60 degrees. The elbow is flexed and the forearm is supinated. Postreduction and spica ultrasound or MRI scan is obtained to confirm reduction. The spica is maintained for 4 to 6 weeks depending on the age of the patient. Therapy is reinitiated.

Subscapularis Slide

Subscapularis release or lengthening to correct the internal rotation contracture and improve ER function dates back to Fairbank.[7] Options for dealing with the contracted subscapularis have included tenotomy, Z-lengthening, and muscle slide. Muscle slide, as described by Carlioz and advocated by Gilbert, improves passive ER with less risk of losing internal rotation power or postoperative ER contracture.[22] In the young child with a chance of ongoing

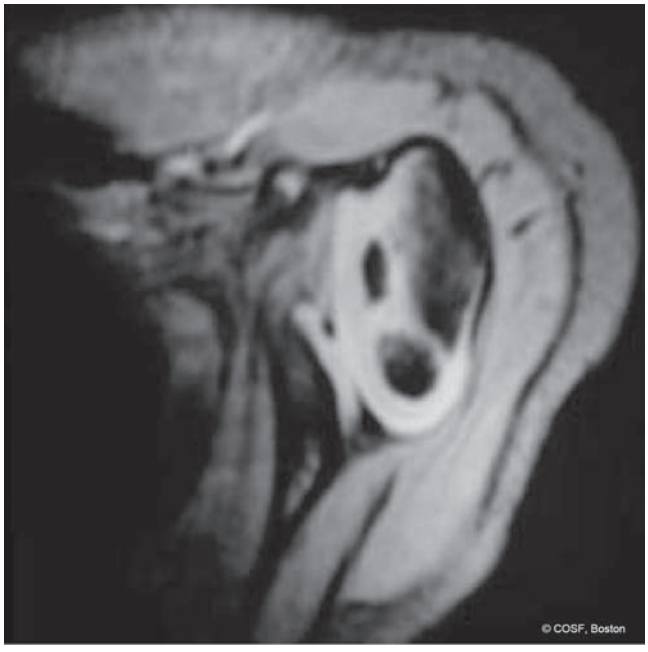

FIGURE 21-13 Type III deformity with increased retroversion and posterior subluxation of the humeral head.

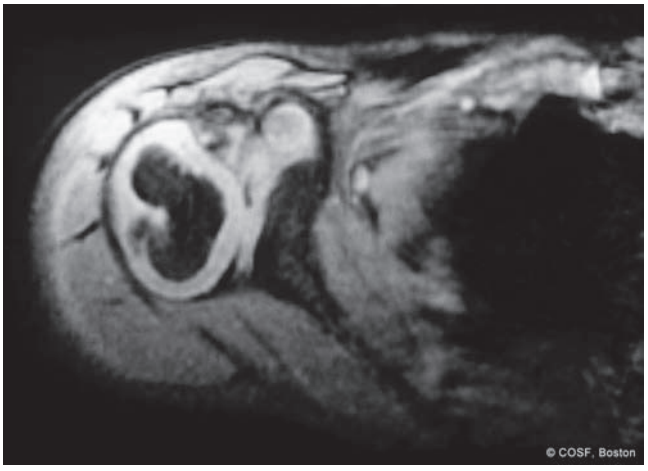

FIGURE 21-14 Type IV deformity with humeral head dislocation and the development of a pseudoglenoid, or biconcave, joint.

muscle recovery (6 months to 2 years), this can be done in isolation. In older children with mild joint deformity, it is done in conjunction with extra-articular tendon transfers.

In a lateral decubitus position (this can also be done semiprone or prone) with the affected arm up, care is taken to softly pad all neurovascular structures (including opposite brachial plexus, peroneal and ulnar nerves) and bony prominences. The entire shoulder girdle and arm are prepped and draped to allow for surgical exposure of the medial scapula and measurement of passive ER. A longitudinal medial scapular incision is utilized. Dissection is carried down the anterior medial border of the scapula. Using a Bovie electrocautery (Bovie Medical Corp., Clearwater, FL) and then a broad elevator, the subscapularis origin is released off the anterior scapula.

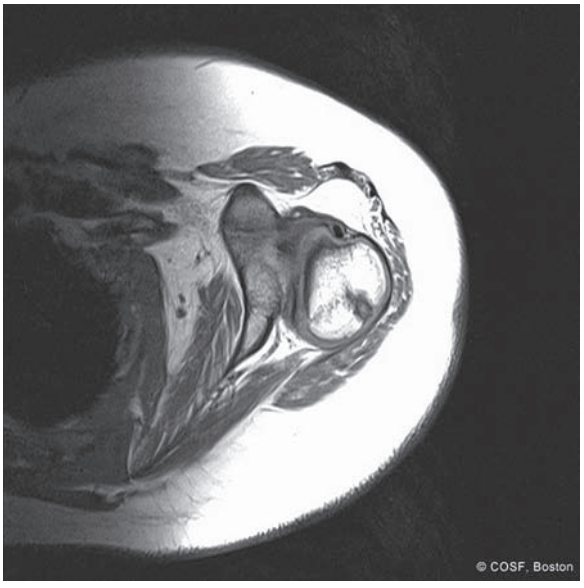

FIGURE 21-15 Type V deformity with flat glenoid, flat humeral head, and complete posterior displacement of humeral head.

Radiographic Classification Glenohumeral Deformity

Type I normal

Type II increased glenoid retroversion

Type III increased glenoid retroversion and posterior humeral head subluxation

Type IV Pseudoglenoid

Type V Humeral head and glenoid flattening

Type VI Infantile Dislocation

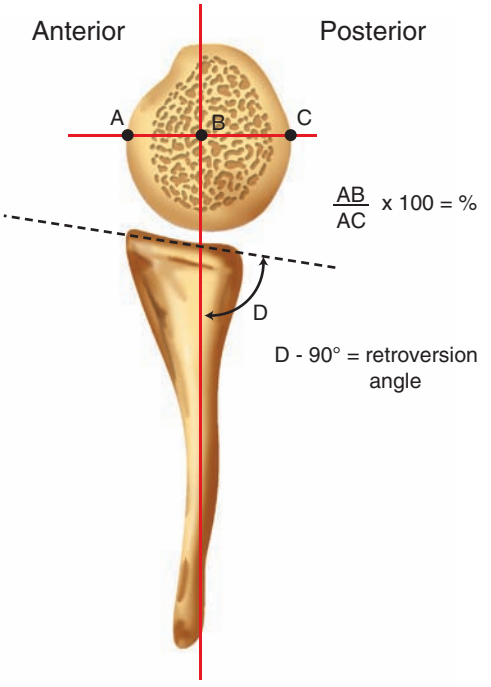

FIGURE 21-16 Measurement of glenohumeral alignment and deformity. Classification system.

Throughout its proximal to distal length, the entire muscle belly is mobilized from medial to lateral. Passive ER of the arm in adduction facilitates the correction. Generally the arm is contracted at 0 degrees or less of ER in adduction; and the goal is to achieve 60 to 80 degrees intraoperatively without undo tension. Once achieved, the wound is closed in layers with absorbable suture. A shoulder spica cast is used to maintain the corrected adduction and ER position for 4 weeks followed by intensive therapy.

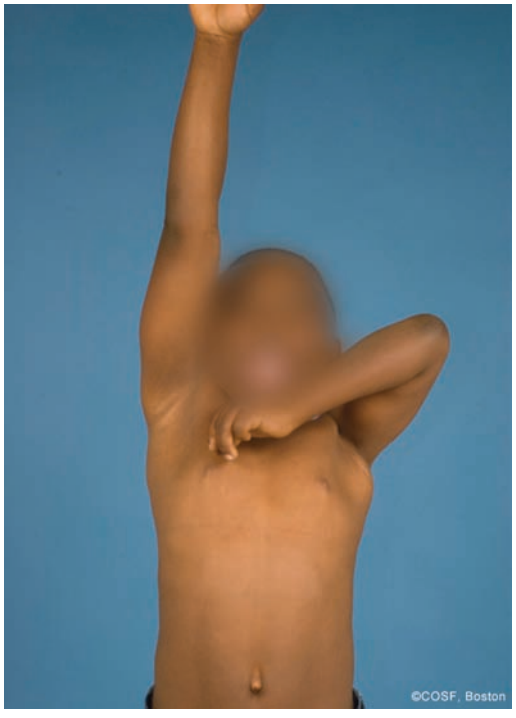

FIGURE 21-17 Typical patient with normal right arm elevation and affected left arm with multiple problems: internal rotation contracture, lack of ER and antigravity triceps strength, and a good hand.

◆ Arthroscopic and Open Joint Releases

Pearl introduced the use of arthroscopic techniques to achieve similar goals as open procedures.[23] The difference is that arthroscopic releases start from the inside out, while the open procedures come from the outside in. In a complete release, the procedure can achieve the same results using different techniques. However, in a partial release, different anatomic structures will be involved. The outcome in terms of undercorrection or overrelease could be different (partial vs. complete subscapularis release; partial, complete, or no joint capsule and ligament release). In addition, the application of each technique requires different skill sets. Open releases and reduction require ease and expertise at dissecting around and near the brachial plexus nerves. Arthroscopic releases and reduction require technical prowess and familiarity with appropriate-sized arthroscopic equipment for a young child. So far, the published results indicate equivalency of joint remodeling and clinical outcome.

◆ Arthroscopic Release and Reduction

This procedure is performed in a lateral decubitus position with the affected arm up. Care is taken to softly pad all neurovascular structures (including opposite brachial plexus, peroneal and ulnar nerves) and bony prominences. A

beanbag is used to maintain body position throughout the procedure. Prepping and draping includes the entire arm and shoulder girdle region. Through the posterior soft spot, an appropriate-sized spinal needle is used to inflate the joint with injectable saline and age- and weight-appropriate diluted epinephrine. The posterior portal is distal and medial to the posterolateral acromion between infraspinatus and teres minor and can be palpated with your thumb during internal rotation and ER. Confirmation of the needle in the joint is seen by free backflow. Full distention of the joint allows for atraumatic placement of arthroscopic equipment by separating the humeral head and glenoid. This is particularly important in such a small joint. Visualization is performed from the posterior portal. Manual distraction of the joint is necessary, and this requires an attentive, able-bodied assistant applying longitudinal traction on the arm. At present, there is no commercially available shoulder/limb positioning device suitable for infants and young children.

The posterior subluxation of the humeral head and increased glenoid retroversion are evident and correlate with MRI findings. The anterior portal is then localized with an outside-in spinal needle in the rotator interval between the medial labrum, inferior subscapularis, and superior biceps tendon. The operative release is performed from this portal. Mayo scissors, rongeurs, arthroscopic biters, and lasers have all been used for the release. A hooked Bovie electrocautery device is our instrument of choice (Figure 21-18). The release is on the anterior-inferior edge and involves the capsule, inferior, and middle glenohumeral ligaments. The overlying subscapularis is partially released. A back and forth between release and measurement of passive ER and joint reduction is performed until more than 40 to 60 degrees of tension-free ER with a reduced humeral head is achieved. Care is taken not to overrelease the joint or perform an entire subscapularis release due to concern about loss of internal rotation power and/or development of an ER contracture. Anterior-inferior glenohumeral instability can also occur with an extensive release. The axillary nerve is nearby and needs protection throughout the procedure. We identify the nerve beneath triceps and deltoid and protect it throughout its anatomic course. If the triceps fascia is impinging the nerve, we release the fascia to compress the nerve. At the conclusion, the portals are closed, and a shoulder spica cast is applied in adduction and ER to maintain reduction. The cast is discontinued at 4 to 6 weeks and therapy initiated.

◆ Muscle Tendon Releases and Transfers with or without Open Joint Reduction

Tendon transfers to restore ER function and improve abduction are standard in patients with incomplete recovery (Figure 21-17). The latissimus dorsi and/or teres major are most commonly used for transfers.[34,35] Insertion of the transfer into the greater tuberosity provides more improved overhead function than transfer into the humeral shaft.[24] If there is weakness alone without an internal rotation contracture (seen most often after microsurgery with failure of suprascapular nerve recovery), then a transfer alone will suffice. If there is a contracture and weakness, then both a release and a transfer are necessary. The release is usually a musculotendinous lengthening of the pectoralis major to improve abduction and ER (may not be necessary after microsurgery) and of the subscapularis to improve adduction and ER. Joint reduction and capsulorrhaphy are necessary for those patients with continued subluxation, dislocation, and/or contracture after extra-articular releases and detachment of the latissimus dorsi and teres major in preparation for transfer (Figure 21-19).

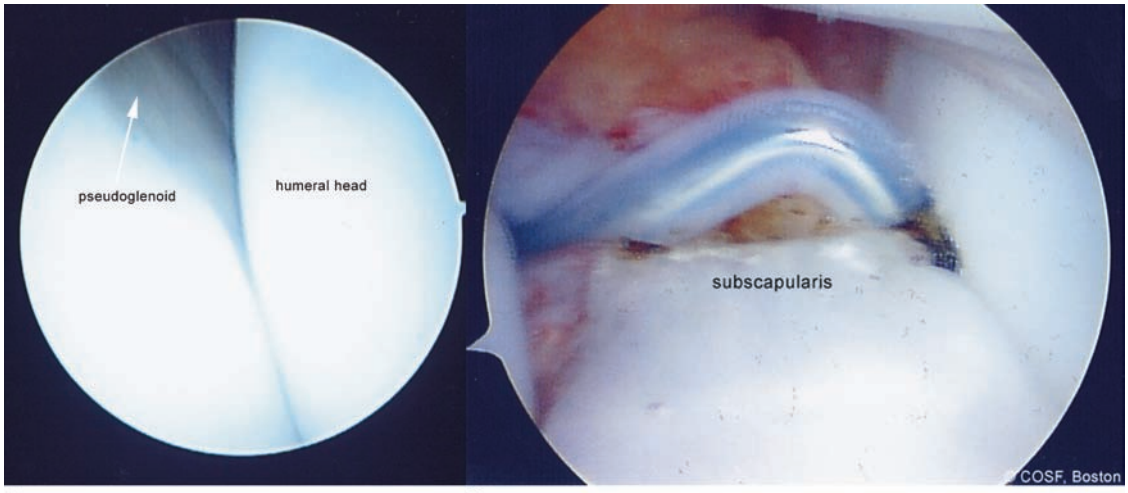

FIGURE 21-18 **A:** Arthroscopic view of glenoid deformity during partial reduction of the humeral head with maximum ER. **B:** Hooked Bovie electrocautery partial release of anterior capsule and subscapularis. You have to be careful not to overrelease with resultant loss of internal rotation movement and power.

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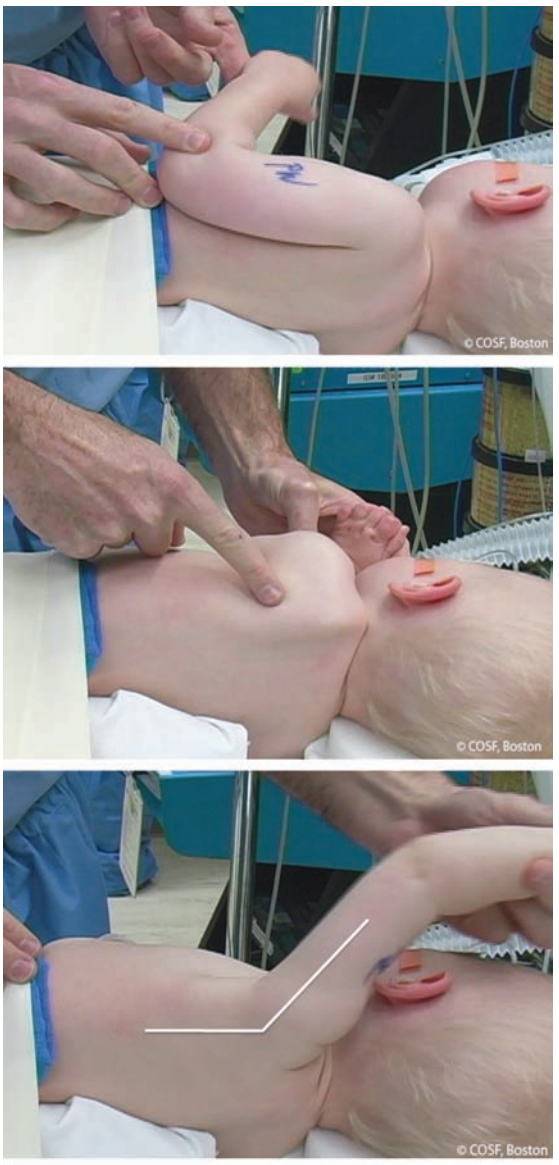

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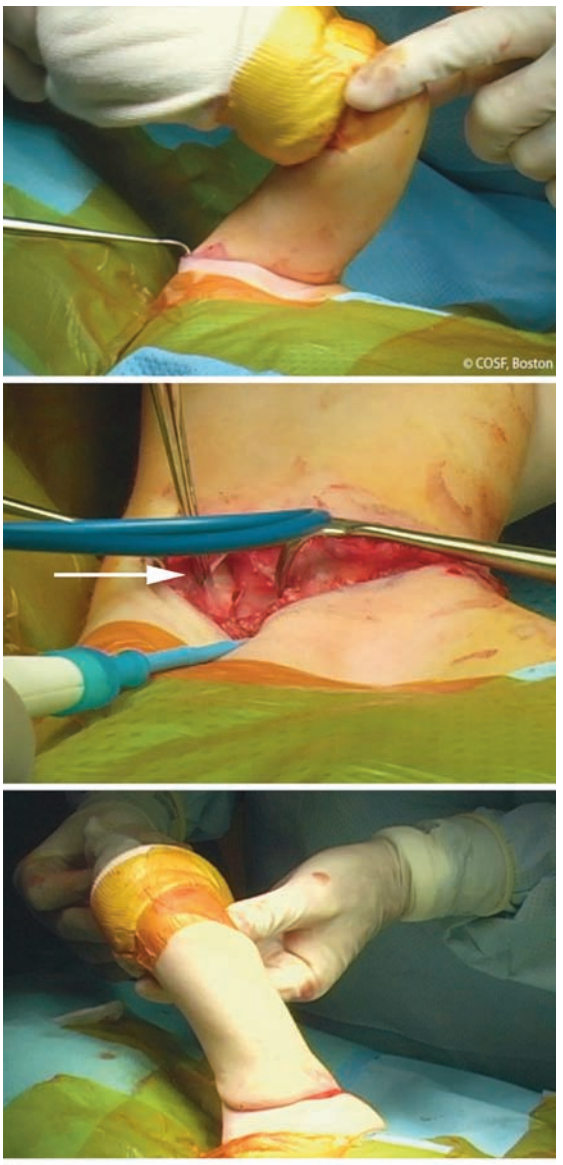

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B

FIGURE 21-19 **A:** Exam under anesthesia depicting limited ER in adduction, scapular winging with internal rotation, and limited scapulohumeral angle as depicted by lines. **B:** Transaxillary incision outlined. If an extra-articular rebalancing procedure is indicated, then only the anterior and posterior aspects of the incision are used. **C:** Musculotendinous release of pectoralis major (*arrow*) anteriorly with Bovie electocautery.

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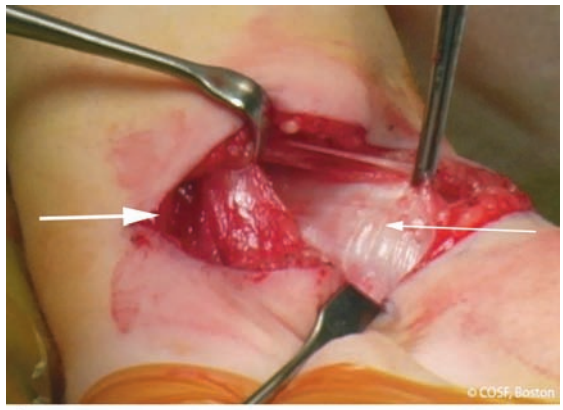
D



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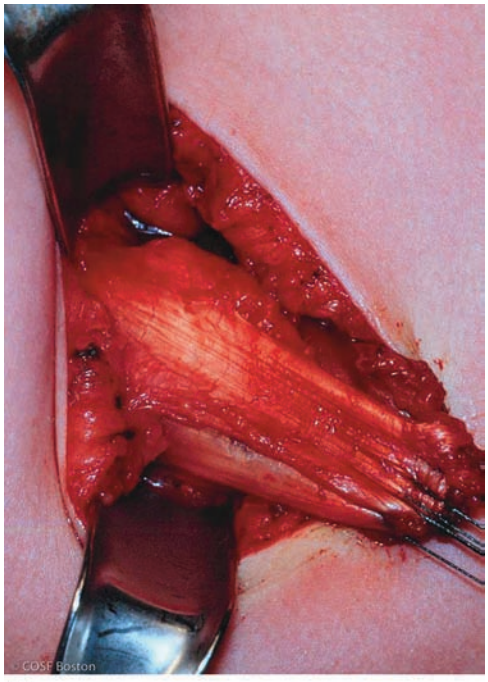

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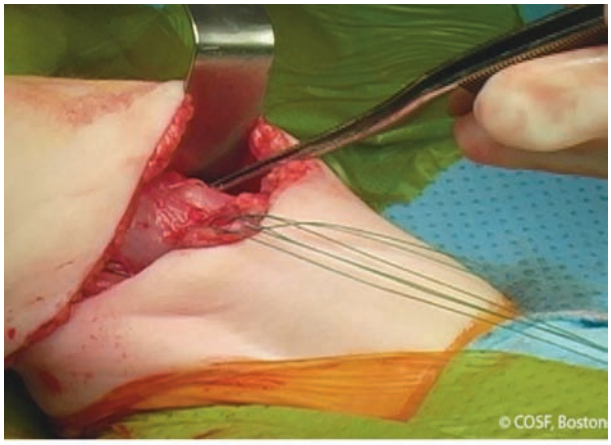

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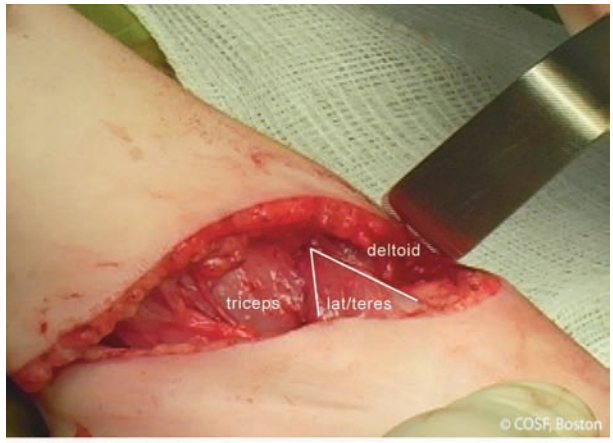


H

FIGURE 21-19 *(continued)* **D:** Release of fascia joining latissimus dorsi and teres major to axillary skin that allows better identification of the tendons. **E:** The *thin arrow* outlines the conjoint insertion of the latissimus dorsi and teres major to the humerus, posterior to the brachial plexus sheath (*thick arrow*) **F:** The tendon transfer is mobilized fully with sutures in place for insertion in tuberosity. **G:** The interval between the deltoid (superior) and triceps (inferior) is depicted by the forceps. **H:** The transfer is completed between the deltoid and triceps as outlined.

After induction of general anesthesia, an examination of the affected upper limb is performed with the patient in the supine position. Passive ER in abduction and adduction, scapulohumeral angle, and the presence of a Putti sign are noted (Figure 21-19A).

The procedure is performed in a lateral decubitus position with the affected arm up. Care is taken to softly pad all neurovascular structures (including opposite brachial plexus, peroneal and ulnar nerves) and bony prominences. A bean bag is used to maintain body position throughout the procedure. Prepping and draping includes the entire arm and shoulder girdle region. The incision is made in the axillary crease. If an extra-articular procedure alone is anticipated, the procedure may be performed through two smaller incisions: an anterior incision over the pectoralis major insertion into the humerus and a posterior incision from the latissimus/teres muscle to the posterior subacromial region. If more extensive release and joint reduction are required, then a single transaxillary incision is used throughout that length (Figure 21-19B). The preoperative MRI and exam under anesthesia will usually indicate the extent of surgery required to correct the problem.

The skin is incised, and subcutaneous flaps are raised. The posterior brachial cutaneous nerve is protected if encountered (see Coach's Corner). Anterior dissection isolates the pectoralis major muscle and tendon as they inserts into the humerus. With careful protection of the surrounding soft tissues, Bovie electrocautery is used to perform a musculotendinous fractional lengthening (Figure 21-19C). The posterior tendinous fibers are longitudinally released while preserving the integrity of the anterior muscle. Retesting of passive ER in abduction and adduction with scapular stabilization reveals the improved abduction and ER (Figure 21-19C). There is usually still limited adduction and ER and low scapulohumeral angle consistent with persistent subscapularis contracture and glenohumeral instability.

Posterior dissection of the latissimus dorsi and teres major insertion into the humerus is performed while protecting the brachial plexus; these tendons are often conjoined.[36] Visualization is facilitated by positioning the shoulder in abduction and internal rotation (Figure 21-19D). The upside-down look from the lateral decubitus position can be confusing and requires some getting used to. If you do not go medial enough, you will confuse the triceps with the latissimus. Also, there is a fascial connection between the posterior axillary skin and deeper soft tissues in the region overlying the latissimus dorsi; this fascial band should not be confused with the deeper tendons and may be released (Figure 21-19E). The tendon insertions of the latissimus and teres are detached from their humeral insertion. This may be done using Bovie electrocautery, understanding that the axillary nerve lies immediately cephalad to the teres major in the quadrilateral space (because the arm is abducted and "upside-down," the axillary nerve appears to be inferior to the teres major in the surgical field). Similarly, the radial nerve runs caudal to the teres major in the triangular interval, which appears "superior" with the limb in abduction and internal rotation. Maximum length is desired, and, therefore, release is performed in internal rotation. The neurovascular structures, particularly the axillary nerve, are protected. Nonabsorbable braided sutures (Ethibond, Ethicon, Inc., Somerville, NJ) are placed in the freed tendon ends. Adequate excursion of the musculotendinous unit is confirmed by pulling on these tagging sutures, releasing any adherent soft tissues or fibrous bands to assure full excursion. Care is made to ascertain that adequate decompression of the adjacent axillary nerve is achieved, including beneath the triceps.

Next, the interval between the deltoid posteriorly and long head of triceps anteriorly is developed via blunt dissection (Figure 21-19G). This interval is often difficult to develop and more posterior than the novice surgeon expects. Careful inspection of the muscle fiber orientation will distinguish the triceps from the deltoid. Furthermore, the ability of the surgeon to pass his/her finger easily into the subacromial space will confirm that the correct interval has been identified. After retractors are placed, the rotator cuff insertion onto the greater tuberosity of the humeral head may be palpated and visualized, especially with ER and abduction of the shoulder. Subacromial decompression is performed with a freer or "peanut" in the cases of prolonged contracture and dislocation.

Prior to completing the tendon transfer, joint stability and contracture are again assessed by remeasuring ER in abduction and adduction, as release of the latissimus dorsi and teres major can provide improved passive motion. If there is still restriction of adduction and ER, a subscapularis lengthening is performed. Posterior to the pectoralis major and anterior to the plexus, the subscapularis is indentified and the musculotendinous junction lengthened. This is often adequate. Formal anterior Z-lengthening is no longer performed. In cases of severe tightness, a posterior subscapularis slide is performed. Care is taken not to overrelease the subscapularis that could lead to loss of internal rotation power. Adequate release of the internal rotators is indicated by passive ER beyond 90 degrees with the shoulder abducted 90 degrees and beyond 30 to 45 degrees with the shoulder adducted against the thorax.

If there is still excessive tightness or persistent joint instability, then the anterior-inferior glenohumeral joint is accessed between the subscapularis anteriorly and the neurovascular structures posteriorly. The anteroinferior capsule is incised, allowing for easy glenohumeral joint reduction. Tactile confirmation of joint congruency is noted via palpation of the posterior glenohumeral joint line just posterior to the neurovascular structures. If excessive redundancy of the posterior capsule is noted, reefing of the posterior capsule with tendon transfer insertion is performed. This is performed with imbricating sutures. Like a tendon transfer, an initial suture is placed and both stability and arc of motion are tested. The goal is a stable joint with a near full passive range of motion. A formal

posterior capsular shift is no longer performed. No intraoperative imaging of the shoulder is routinely taken.

While maintaining joint reduction, the latissimus dorsi and teres major tendons are then sewn into the rotator cuff using the previously placed tagging sutures (Figure 21-19F and H). The shoulder is positioned in maximum ER to allow access to the greater tuberosity for suture insertion. Retesting of passive range of motion is performed prior to closure to be certain that (1) the joint is stable, (2) there is ER beyond the vertical in abduction and >30 to 45 degrees in adduction, and (3) there is no abduction contracture. The surgical wound is closed in layers, followed by instillation of local anesthetic in the subcutaneous tissues for postoperative analgesia. A sterile bandage is applied, and the operative limb is immobilized in an upper extremity spica cast. The extremity is typically positioned in mild shoulder abduction (40 to 45 degrees) and ER (30 degrees) and full forearm supination to maintain the glenohumeral joint in a reduced position, lessen the tension on the tendon transfer, and stretch the pronation tightness.

◆ Humeral Osteotomy

In adolescent patients with an internal rotation contracture, functional ER limitations, and a markedly deformed joint (type V), a humeral derotation osteotomy can lead to significant clinical improvement. By placing the hand in a more functional position, the scapula can facilitate better functional use.

In a modified beach chair position, central, stable positioning of the patient's midline is important to assess passive external and internal rotation in all planes before and after the osteotomy. Repeat exam of total arc of rotation and malalignment is made before proceeding. The entire involved upper extremity and shoulder girdle is prepped and draped; it is critical to be able to locate and palpate the midline structures (mouth, umbilicus, perineum) after draping. An incision the length of a six-hole plate is centered just proximal to the deltoid insertion. The distal half of the incision is curved medially to account for ER of the skin and soft tissues with osteotomy (Figure 21-20). This lessens the risk of a hypertrophied scar. (Others have used a more distal, medial incision to lessen this risk.) An extended deltopectoral dissection is performed. The cephalic vein is identified and protected, typically taking it laterally with the deltoid. Subperiosteal elevation between the pectoralis major and deltoid insertions is performed while protecting the posterior radial nerve (Figure 21-20). The six-hole nonlocking dynamic compression plate or plates (double-stacked semitubular plates for lower profile or in smaller patients) are applied with the center just proximal to the deltoid insertion. The proximal three screws are placed in standard fashion and then removed. The transverse osteotomy site is marked with an osteotome and Bovie electrocautery. Osteotomes may be used to score the humeral cortex along the side of the plate proximal and distal to the planned osteotomy level; these marks will later be used to assess the amount of rotation. (Alternatively, a smooth K-wire may be drilled into the humerus in an anterior-to-posterior direction, just distal to the plate; this pin can similarly be used to gauge the degree of ER introduced.) Usually the desired correction is about 70 degrees of ER of the distal fragment. Interestingly, this corresponds to the width of the plate in most patients. The previously placed plates are removed. The transverse osteotomy is performed with oscillating saw and osteotome, again protecting the radial nerve posteriorly. After the osteotomy is completed, care is taken to ascertain that the transverse cut is complete, with no posterior cortical irregularity or "bone spike," which may later impede rotation or block bony apposition. The plate(s) is reapplied loosely to the proximal fragment using the previously drilled screw holes. The distal humerus is rotated externally to match the vertical marks on the bone for planned correction. The proximal screws are tightened, the osteotomy site held reduced, and one distal screw is placed in compression. Manual testing of motion is then performed. The hand should still easily reach the groin, chest, and mouth with internal rotation while now having >30 to 40 degrees of adduction and ER and the ability to reach the hand to the occiput. When the appropriate amount of ER has been achieved, the remaining screws are placed distally. Intraoperative radiographs are obtained to confirm bone, screw, and plate alignment before wound closure (Figure 21-20). Appropriate adjustments are made as necessary. Closure is performed in layers with absorbable suture. Local anesthesia is injected. A sterile dressing and sling and swathe are is applied.

OTHER PROCEDURES

Other methods of approaching the limitations in ER function, internal rotation contracture, and joint deformity have included (1) coracoacromial ligament release, (2) acromial and distal clavicle osteotomy, and (3) glenoid osteotomy. Each method has its rationale. The coracoacromial ligament normally restrains anterior and superior translation of the humeral head. Release of this ligament has been shown in cadaveric study to increase abduction, ER, and humeral head translation. It has been noted that with long-standing internal rotation contractures, the acromion becomes elongated and turned downward, while the coracoid similarly is beaked. The degree of coracoid deformity correlates with the degree of posterior glenoid deformity.[12] Release of the taut, triangular coracoacromial ligament can be performed via a longitudinal incision lateral to the coracoid. This release can also be performed as part of an arthroscopic release and reduction. It is a tool for some patients and may be used in conjunction with other procedures but rarely in isolation. There is little evidence of the exact indications and results of this procedure, and we have performed it too few times to know.

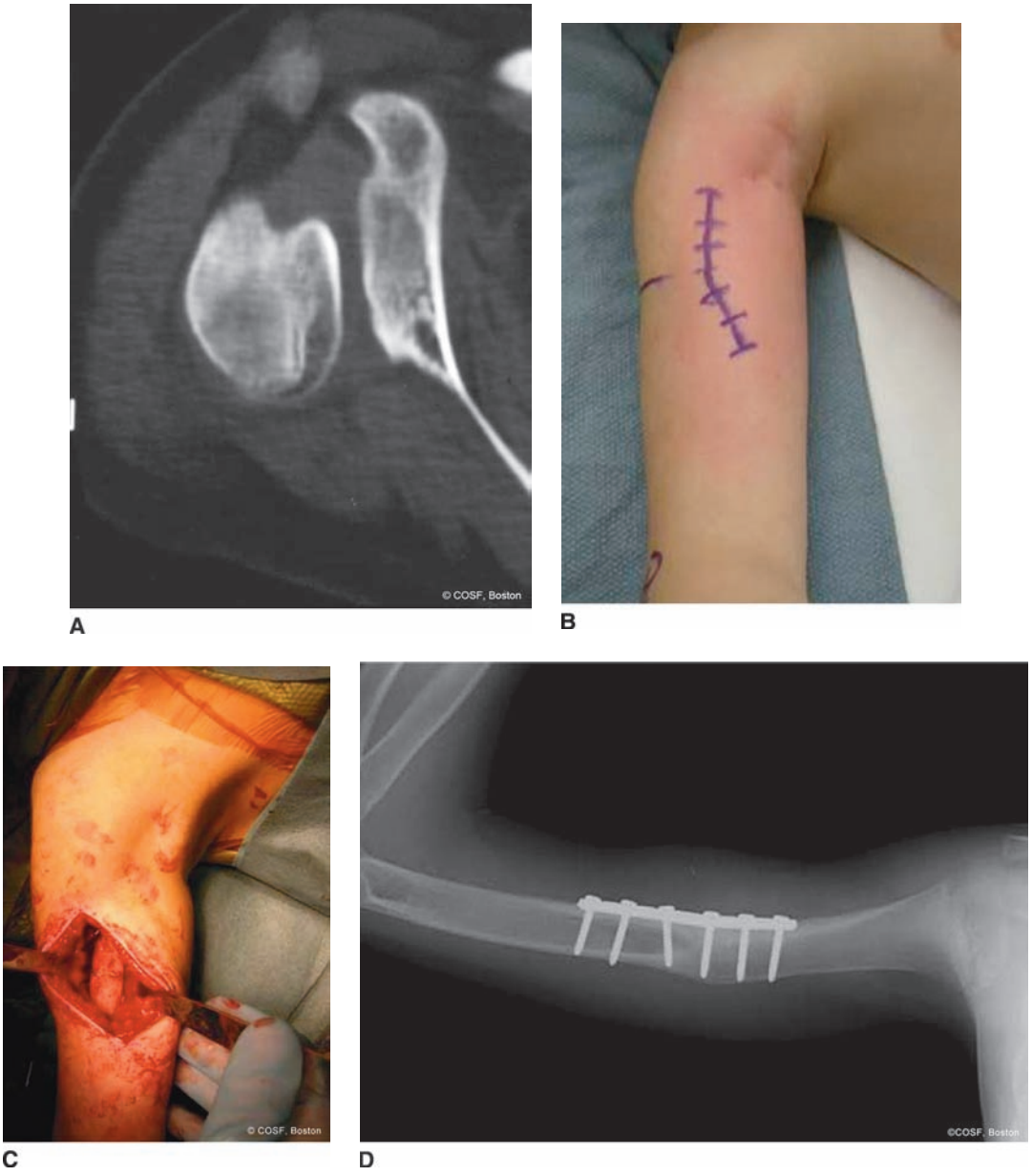


FIGURE 21-20 **A:** Preoperative CT revealing marked deformity of the glenoid with posterior dislocation of the humeral head. It was decided in this patient a humeral osteotomy would be best. **B:** Skin incision outlined with curvilinear aspect distally to account for ER of all tissues. This lessens hypertrophic scar formation. **C:** Transverse osteotomy performed just above deltoid insertion. **D:** Healed osteotomy with internal fixation noted.

In the presence of bony deformity, osteotomy makes sense. Similar to the hip, osteotomy of the primary deformity for joint reconstruction is rational. Rather than performing a humeral (femoral) osteotomy, a glenoid (acetabular) osteotomy makes sense. Unlike periacetabular osteotomies for hip dysplasia, considerable challenges remain in performing safe, reliable corrective osteotomies of the immature glenoid. While investigation continues, the results so far have been less promising.

Finally, it has been argued by Nath that the primary deforming force is the scapula (scapular hypoplasia, elevation, and rotation), and the acromioclavicular joint needs operative reconstruction to improve the internal rotation posture. His approach to the problem is a distal clavicular and acromial osteotomy along with a posterior capsulodesis.

POSTOPERATIVE

Joint reductions and/or extra-articular tendon transfers are immobilized in a shoulder spica cast in abduction, ER, and forward flexion for 4 to 6 weeks. The exact position of the arm depends on the joint alignment. Following spica cast removal, immediate passive and active range of motion is

started. Within 2 weeks of the cast coming off, there are no restrictions.

The vast majority of osteotomies are performed in older children. Therefore, immobilization can be with a sling and swathe for 4 weeks until there is sufficient radiographic healing. There are some rare, markedly deformed joints in children younger than age 5 who undergo humeral osteotomy because they do not appear to have remodeling potential, or a soft tissue procedure would result in too much loss of strength or cause an ER contracture. These children are immobilized in a spica cast for 4 weeks in an adducted and externally rotated position. After radiographic healing in both these cases, therapy is started. Return to sports is dependent on complete radiographic healing and restoration of motion and strength, usually at 3 months.

ANTICIPATED RESULTS

Winning is not everything, but wanting to win is.
—Vince Lombardi

An expected and consistent surgical outcome is improved ER and above shoulder-level function. Almost all the children improve their ability to move and stabilize their hand in space. This is evident by statistically significant improvement in modified Mallet hand-to-mouth (less of a trumpet sign), hand-to-neck (postoperatively able to reach their occiput without adaptive movements), and ER (able to move the hand away from body at their side) scores ideally without worsening internal rotation hand-to-spine scores. These improvements have been reported with indicated releases (subscapularis slide, arthroscopic release, and reduction), extra-articular lengthenings and tendon transfers, combined joint reductions and tendon transfers, and humeral osteotomies. One of the keys is picking the right operation for the right patient. These children should get significantly better though not perfectly symmetric. Their deformity will become much less noticeable and their function much improved.

It is now clear that joint remodeling can occur with intra-articular (arthroscopic or open reduction) procedures, with or without tendon transfers, if performed early (Figure 21-21). Extra-articular procedures alone will not result in significant joint remodeling, though they appear to stop progressive deformity. Humeral osteotomy is a salvage procedure as far as the joint is concerned and will not change the joint at all.

COMPLICATIONS

Rates of infection, further neurologic impairment, or worsening of the patient's condition are exceedingly low. Almost all of these indicated operations result in short- to intermediate-range improvement. There are reports that the early improvements with extra-articular tendon transfers can deteriorate during late adolescence.[37] It is unclear if the addition of joint reduction procedures to the tendon transfers will prevent that late deterioration.

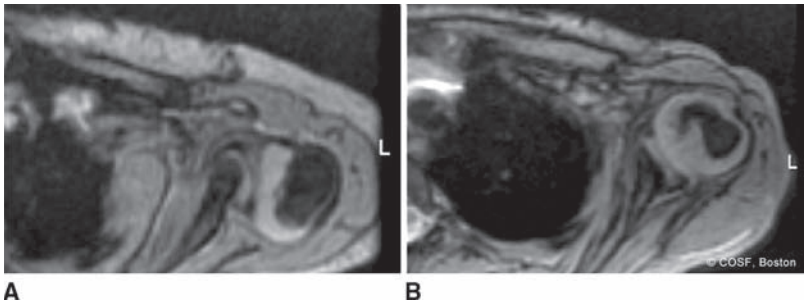
About 10% to 20% of joint reduction patients fail to remodel. Secondary procedures, such as a humeral osteotomy, may be necessary to improve adduction and external function. There have been abduction contractures post tendon transfers. These have been addressed with combined varus derotational humeral osteotomies. Another concern is overlengthening of the subscapularis and/or release of the internal rotation joint contracture. This can lead to loss of internal rotation power and/or an ER contracture. Resolving this may require an internal rotation osteotomy.

The risk of arthritis and adult shoulder pain is a potential concern. The radiographic changes can be impressive in some of these adults. However, at present, there is limited evidence to support this as a real clinical problem for these patients.

CASE OUTCOME

This is an operation that makes mothers cry with joy.
—Alex Mih, MD, when commenting on shoulder tendon transfers

A preoperative MRI scan revealed a type III deformity with increased glenoid retroversion, posterior humeral head subluxation, and the development of a biconcave or pseudoglenoid (Figure 21-21). The child's Mallet scores were II for ER, hand to spine, hand to mouth, and hand to neck with IV for abduction. A transaxillary approach was used for a combined joint reduction, pectoralis



A B

FIGURE 21-21 **A:** Preoperative MRI with profound deformity in a 2-year-old child. Surgery included open reduction, anterior releases, posterior tendon transfers, and capsular imbrication. **B:** One-year postoperative MRI reveals marked remodeling and joint reduction.

major and subscapularis musculotendinous lengthenings, and teres major–latissimus dorsi tendon transfers to the greater tuberosity (Figure 21-19). At 3 months postoperatively, he has passive ER of 35 degrees in adduction and 110 degrees in abduction. His Mallet scores were IV for hand to mouth, abduction, and ER; V for hand to neck; and unchanged II for hand to spine. These improvements remained unchanged at 2 years postoperative. The MRI scan at 2 years revealed near-complete remodeling.

SUMMARY

Shoulder reconstruction in children with incomplete recovery of BPBP is common. Surgery may include extra-articular tendon lengthenings and/or transfers, joint reduction, and osteotomies. The key is matching the right set of procedures to the right patient at the right time for the best short- and long-term outcomes. MRI scans are very helpful in decision making.

COACH'S CORNER

The surgical anatomy and dissection of muscle tendon releases and transfers can be daunting for the inexperienced surgeon. Familiar approaches to the shoulder and proximal humerus traditionally avoid dissection around the neurovascular bundles. In addition, the hyperabducted shoulder and transaxillary approach results in a disorienting "upside-down" view of the anatomic structures and relationships. Many of the structures at risk—including the axillary nerve in the quadrilateral space and radial nerve in the triangular interval—are only apparent after the adjacent musculotendinous units have been released. Finally, little has been written about the intermuscular planes and surgical exposures utilized for these procedures.

To conceptualize the approach to muscle tendon releases and transfers for BPBP, we propose thinking of the anatomy as six anatomic units forming five intervals (Figure 21-22). (This is analogous to the three "windows" in the ilioinguinal approach to the anterior column of the acetabulum described by Letournel.) From anterior to posterior, the anatomic units are (1) the pectoralis major, (2) the subscapularis, (3) the neurovascular bundle, (4) the conjoined tendon of the latissimus dorsi and teres major, (5) the long head of triceps, and (6) the deltoid. Each of these units forms the borders of the five intervals.

For the standard set of muscle tendon releases, each anatomic unit and interval

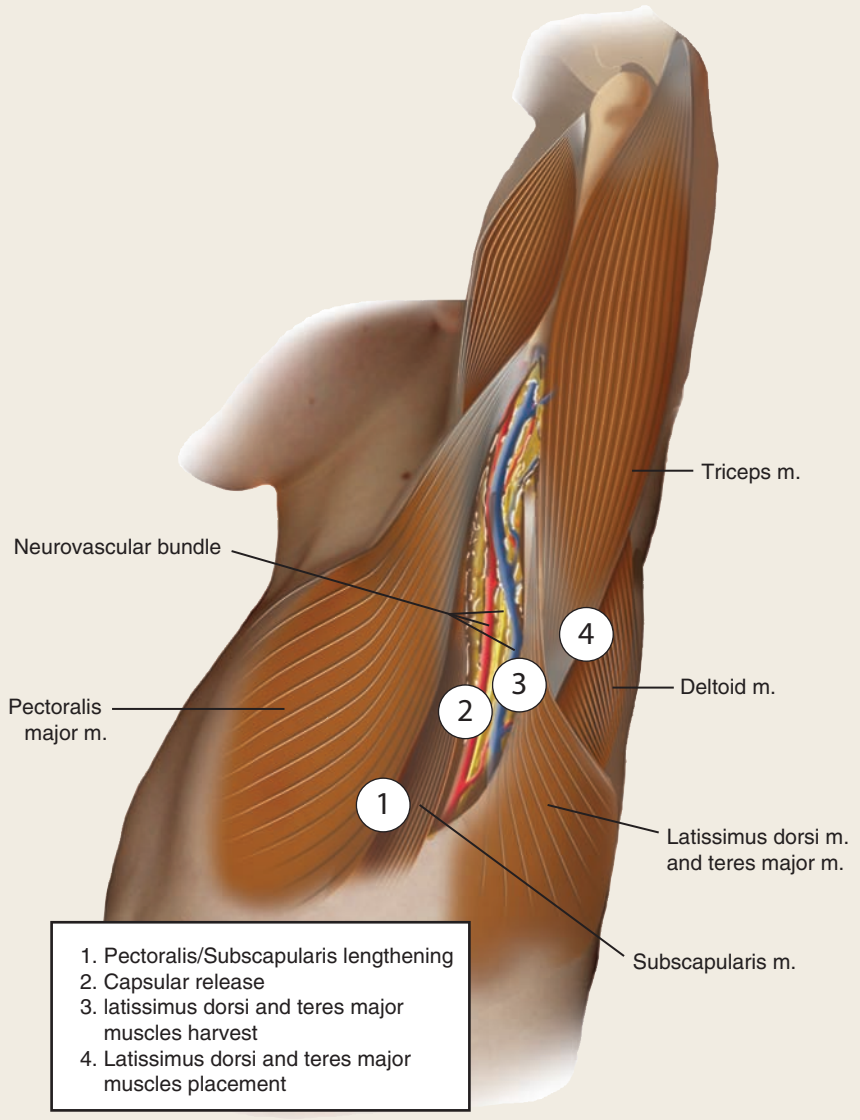


FIGURE 21-22 Schematic representation of the anatomic units and surgical "windows" utilized for muscle tendon lengthenings and transfers in BPBP.

COACH'S CORNER *(continued)*

must be developed. Identification of the first interval will allow for exposure of the pectoralis major tendon (which is on the posterior aspect of the insertion) for lengthenings. Development of the second window will allow for isolation of the subscapularis for its musculotendinous lengthening. Dissection in the third interval provides access to the conjoined tendon, which then may be safely released from the humerus. Blunt dissection in the fifth interval will provide access to the subacromial space and is the window into which the conjoined tendon is passed to complete the tendon transfer. If the anterior capsule needs to be released, it may be accessed via the second interval. Finally, posterior capsular imbrication may be performed via the third window.

The main nerve at risk during latissimus dorsi and teres major tendon transfers is the axillary nerve, which runs through the quadrilateral space. The quadrilateral space is bounded by the long head of triceps laterally, humerus medially, teres major inferiorly, and teres minor superiorly. Due to the "upside-down" view of the shoulder in the transaxillary approach, the axillary nerve appears to be "inferior" to the latissimus dorsi tendon and is at risk during the final portion of the tendon harvest. The radial nerve is also at risk as it runs through the triangular interval. Using the third window, dissecting on the anterior aspect of the conjoined tendon and harvesting the tendon directly off its bony insertion will avoid iatrogenic injury to the radial nerve.

While simple in concept, this simple organization of anatomic structures and surgical intervals may serve as a "trail map," allowing the surgeon to stay oriented and out of trouble during muscle tendon transfers.

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CHAPTER

22

Cerebral Palsy

CASE PRESENTATION

A 17-year-old male with hemiplegia presents to discuss the possibility of surgery to improve his functional use of his involved right hand and the aesthetics of his arm and hand before he leaves for college next year. He is past skeletal maturity. He has done extensive therapy in the past, including splinting during growth spurts. He did not feel botulinum toxin A (Botox, Allergan Pharmaceuticals, Inc., Irvine, CA) injections helped him. On exam, he has a 20-degree elbow flexion contracture with reactive biceps spasticity, a forearm pronation contracture without evidence of active supination, a wrist palmar flexion and ulnar deviation deformity with no active wrist extension evident, and a thumb-in-palm deformity. He does have active digital extension and, with this, has evidence of dynamic swan neck deformity of his index through small fingers. His two-point discrimination is between 5 and 10 mm. He is an A/B student in a mainstream classroom.

CLINICAL QUESTIONS

- What causes cerebral palsy (CP)?
- How often does it occur?
- How are the motor deficits in CP classified?
- What are the typical patterns of muscle imbalance in the upper limb?
- When is Botox indicated in the upper limb in a child with CP?
- What are the surgical indications for CP patients?
- What are the expected outcomes for hemiplegic upper limb surgery?

THE FUNDAMENTALS

Golf is a game that is played on a five-inch course—the distance between your ears.
—Bobby Jones

Children, and later adults, with CP never have normal motor function, and most have permanently altered sensibility. Aside from limb disorders, most have visual and cognitive abnormalities that clearly negatively impact function. Their problem is in their brain, and, as musculoskeletal and peripheral neurologic surgeons, we deal with the peripheral manifestations of their central nervous system (CNS) disorder. To completely fix their problem, someone would have to have the ability to resolve their brain disorder. That is not yet possible. However, with therapy, Botox, indicated surgery, and a multidisciplinary approach, collectively we can have a positive impact on their function and well-being. Our orthopaedic and hand surgery interventions are designed to improve their motor control and, therefore, increase their functional independence and aesthetics. A little can go a long way for these patients. We also need to counsel against unrealistic expectations or interventions that will not help improve their lives.

Etiology and Epidemiology

As defined by William Little in 1860, CP is a motor disorder due to a nonprogressive CNS lesion. The CP disorder occurs in about 1-6:1,000 live births, depending on geographic location and timing of study analysis. In the developed world, it is about 2:1,000 live births.[1–3] The disorder is more prevalent in lower socioeconomic classes. The CP disorder is the most common cause of spasticity of the limbs. Less common causes of spasticity include CNS tumors and their post-treatment sequelae, head injuries, encephalitis, embolism, and cerebrovascular accidents.

The causes of a neonatal brain injury are many. Epidemiologic and neuroimaging studies have shown it is *not* predominately due to birth asphyxia, as was once thought. Most neonatal brain injury is metabolic, whether from transient ischemia–reperfusion events or from defects in inherited metabolic pathways. Neonatal encephalopathy results in 15% to 20% of affected infants dying during the newborn period and an additional 25% having permanent disability.[3]

Causative timing for CP appears to be in utero in about 75% of cases, during delivery in about 5%, and postnatal in about 15%.[4] It is most common in premature infants (40% to 50% of all CP cases are premature infants), especially those with a birth weight <1,500 g. Overall

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prevalence of CP in premature infants born between 22 and 32 weeks of gestation is 8%, with 20% prevalence in the 24- to 26-week infants and 4% in the 32-week infants. An abnormal neonatal ultrasound is predictive of motor disability at 2 years, though up to 33% of CP patients had a normal neonatal ultrasound.[5] Multiple gestation pregnancies and intrauterine infections are other common risk factors. Coagulation and genetic abnormalities (such as factor V Leiden mutation) may be a risk factor for vascular thrombosis and spastic hemiplegia.[3,6] The relative risk of CP increases approximately four times with neonatal sepsis.[7] Neuroimaging can define the CNS lesion(s) and etiologic cause in >95% of cases.

Clinical Evaluation

The CP disorder is classified by (1) limb involvement (monoplegia [one limb], hemiplegia [same-sided arm and leg], diplegia [both legs], triplegia [three limbs], and quadriplegia/tetraplegia [all four limbs]) and (2) motor involvement (spasticity, flaccidity, athetosis, and other movement disorders). Most CNS lesions are in the motor cortex and corticospinal tract resulting in spasticity (70% to 80% of CP cases). An athetoid or dyskinetic movement disorder occurs in about 20% to 25% of CP cases and represents injury to the basal ganglia and extrapyramidal and/or pyramidal motor tracks. Ataxia is due to injury to the cerebellum and is seen in approximately 10% or less of patients with CP. Distinguishing spasticity from the less common athetosis is critical for management decisions, especially surgical indications. In this text, we will focus predominately on hemiplegia and less so quadriplegia, as they are the conditions that involve the pediatric hand and upper limb specialist. However, all of these patients require a multidisciplinary approach that includes pediatric orthopaedics, neurology, physiatry, nursing, social services, and physical and occupational therapy, among others. Their psychosocial, educational, and other medical issues (vision, seizures, developmental delays) are all major factors in their progress to be as functionally independent an adult as possible.

Physical exam findings vary by age.[8] Most patients have already had an accurate diagnosis and workup by the time of referral to the pediatric hand and upper extremity specialist. However, inevitably there are infants and children referred with an inaccurate diagnosis (brachial plexus birth palsy) who have a CNS lesion (hemiplegia). Understanding the discriminating fundamentals of a history and diagnostic physical exam is important. In the infant, there is usually progression from initial hypotonia to a hypertonic muscle exam. There will be persistent neonatal reflexes (asymmetric tonic neck, Moro) and delay in normal motor development. Understanding the basic time frames for gross and fine motor development is essential to recognizing the child who is outside the lines (sitting on average 6 months, walking on average 13 months with outside normal range of 19 months, fine motor pinch by 15 to 18 months on average). Provocative spasticity of the pronator teres (PT) in the upper limb; adductor, hamstrings, and gastrocnemius-soleus in the lower limb; and hyperreflexia of the involved limb may be all that is indicative of subtle hemiplegia. As trite as it may sound, believe a mother's intuition when she tells you that something is not right about her child.

Magnetic resonance imaging (MRI) is diagnostic, providing accurate anatomic information about the CNS lesion and, to some degree, the prognosis.[9,10] Treatable conditions, such as hydrocephalus or vascular malformations, are identified. In a large European study of CP patients, MRI scans showed that periventricular leukomalacia was the most common cause (42.5%) of white-matter damage, followed by basal ganglia lesions (12.8%), cortical/subcortical lesions (9.4%), malformations (9.1%), focal infarcts (7.4%), and miscellaneous lesions (7.1%). Only 11.7% of these children had normal MRI findings. There were good correlations between the MRI and clinical findings.[11] At this stage, almost all infants and children with CP will have at least one MRI scan as a part of evaluation and treatment planning.[12,13]

Established spastic hemiplegia has a classic exam for the upper limb: (1) adduction, internal rotation at the shoulder; (2) elbow flexion and forearm pronation; (3) wrist and finger flexion; (4) thumb-in-palm deformity; and (5) swan neck deformity fingers (Figure 22-1). Each posture represents asymmetric muscle tone, strength, and reactivity around that joint. The involved limb will be smaller in both length and girth.[14] Distinguishing spasticity alone from secondary joint contracture is important. This often requires a calm setting; gentle, repeated exams; and, at times, videotaped therapy sessions with standard protocols. Passive and active motion, voluntary control, involuntary movements, and degree of joint contracture are recorded with each visit and compared with previous visits. Grasp, pinch, and release functions are assessed and classified, specifically Volkmann angle for finger flexor tightness (Figure 22-2) and Zancolli classification of finger extension. Discriminatory sensibility by two-point, stereognosis (object recognition) and graphesthesia are recorded and compared to the uninvolved side in hemiplegia. The majority of CP patients have discriminatory sensibility deficits, and this affects motor use.[15]

Many classification systems are used for CP patients. The Gross Motor Function Classification System (GMFCS)[16] is now commonplace in most CP centers and is used to assess natural history and the effectiveness of therapeutic interventions (Figure 22-3). The Jebsen-Taylor test for hand function, the House classification (Figure 22-4),[17] the Melbourne Assessment of Unilateral Upper Limb Function,[18] the Assistive Hand Assessment, and the Shriner's Hospital Upper Extremity Evaluation (SHUEE)[19] are among the validated measurement tools for hand and upper limb function in children with CP.[20]

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FIGURE 22-1 Posture of severe spasticity with elbow flexion, forearm pronation, wrist flexion, thumb-in-palm, and mild digital flexion even in this extreme position of wrist flexion.

These instruments provide accurate assessment of therapeutic interventions. Of note, the parents' concept and children's self-concept of their functional capabilities have been shown to differ greatly by objective assessment.[21,22] This implies we need to gather as much information as possible from the child and to use other objective tools. Kinematic 3-D analysis and standardized videotaping of classification testing before and after intervention provide validated scoring and comparisons.[23–26] In a disorder as complex as CP hand function, validated instruments are imperative. Dynamic electromyography is used to define in-phase, out-of-phase, and continuous firing activity of agonists and antagonists at specific joints and muscles in certain centers. This can be useful with highly skilled interpretation to determine the best muscles for tendon transfers.

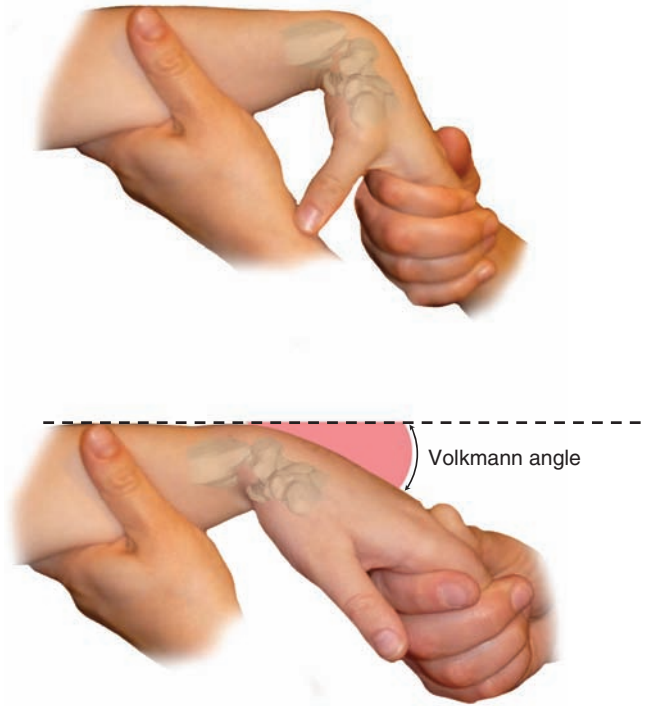


FIGURE 22-2 The wrist is brought from maximum palmar flexion into extension with the digits extended. The angle at which the digits go into a flexed posture is Volkmann angle.

Treatment Indications

Putting is like wisdom…partly a natural gift and partly the accumulation of experience.
—Arnold Palmer

The options for care of the hand and upper limb in CP patients include, among others: (1) natural history[27], (2) occupational and physical therapy, (3) splinting, (4) serial casting, (5) electrical stimulation and biofeedback, (6) constraint therapy, (7) botulinum toxin type A (Botox, Allergan Pharmaceuticals, Inc., Irvine, CA) injections, (8) surgery, and (9) a combination of any or all of the above. The goals for each child are to prevent contractures and to maximize grasp, pinch, and release motor functions. Ultimately, interventions are designed to improve functional independence as an adult[28,29] and a sense of well-being.

Almost all the children with CP have occupational and physical therapy as a part of their comprehensive care plan. Static splinting is used to prevent contractures due to muscle imbalance and hypertonicity. Most often this is at night or during leisure time so as not to impair functional activities. Daytime static or dynamic splints should truly improve function. These can include wrist extension support, thumb palmar abduction, and swan neck silver ring finger splints if warranted.[30]

Gross Motor Function Classification System (GMFCS) *Expanded and Revised*	
Level	**Description**
Level I	Walks without limitations.
Level II	Walks with limitations.
Level III	Walks using a hand-held mobility device.
Level IV	Self-mobility with limitations.
Level V	Transported in a manual wheelchair.
GMFCS - E & R © Robert Palisano, Peter Rosenbaum, Doreen Bartlett, Michael Livingston, 2007 CanChild Centre for Childhood Disability Research, McMaster University.	

FIGURE 22-3 GMFCS score illustration.

Constraint-induced movement therapy has been shown to improve motor efficiency and quality of movement in some hemiplegic patients.[31–33] The constraint methods have included casting, sling use, and restrictive gloves. Repeated constraint therapy has been used effectively.[34] However, there are limitations to the levels of evidence on this treatment method.[35]

Botox injections have been shown to be effective in children with no fixed contractures, good motor control, and a high motivation to rehabilitate.[36–38] The most typical injection sites are some combination of the biceps, PT, flexor carpi ulnaris (FCU), finger flexors, and thumb adductor. Standard doses are 1 to 2 U/kg. Both low- and high-dose injections have been shown to be effective. Injections have been performed by palpation and needle electrical stimulation localization. Injections have been administered in the office setting under topical anesthetic cream or local anesthesia or in the operating room under conscious sedation or general anesthesia. Botox injections have been performed by neurologists, developmental pediatricians, physiatrists, and surgeons, among others. Botox is used both as therapy and as a predictor of surgical outcome with reasonable but not unequivocal success at both.[39] However, there is a short duration of positive effect and a negative reduction in strength and functional capabilities post injection.[40–42] Repeat treatments can be used effectively without adverse effects.[43] In our institution, though costly, Botox injections are performed in the day surgery setting with conscious sedation and electrical stimulation localization by our physiatry team of physicians. Postinjection rehabilitation is intended to strengthen antagonists, stretch hypertonic agonists, and learn new functional motor patterns. Repeat injections are only for those who have had a positive effect.

Surgical Indications

The goals of surgery are to improve (1) function, (2) self- or assistive care and hygiene, and (3) aesthetics of the limb. This is done by muscle rebalancing and/or joint stabilization procedures at each affected anatomic level of the upper limb and hand. Although there are not absolute thresholds, ideally the hemiplegic patient should (1) have

House Classification		
Level	**Designation**	**Activity Level**
0	Does not use	Does not use
1	Poor passive assist	Uses as stabilizing weight only
2	Fair passive assist	Can hold onto object placed in hand
3	Good passive assist	Can hold onto object and stabilize it for use by other hand
4	Poor active assist	Can actively grasp object and hold it weakly
5	Fair active assist	Can actively grasp object and stabilize it well
6	Good active assist	Can actively grasp object and manipulate it against other hand
7	Spontaneous use, partial	Can perform bimanual activities easily and occasionally uses the hand spontaneously
8	Spontaneous use, complete	Uses hand completely independently without reference to the other hand

FIGURE 22-4 House classification.

an IQ > 70; (2) have some discriminatory sensibility or, in its absence, no visual impairment; (3) be between the ages of 5 and 25 years; (4) be highly motivated to perform postoperative rehabilitation; and (5) have no athetosis or flaccidity (see Sidebar). The quadriplegic patient should have marked contractures that have a negative impact on hygiene, dressing, and mobilization and/or communication. Pain from arthrosis may be a factor in severely contracted wrists in quadriplegia.

SIDEBAR

They say golf is like life but don't believe them. Golf is more complicated than that.
—Gardner Dickson

There is debate on timing of surgical intervention for hemiplegia upper limb reconstruction. Some surgeons advocate early surgery as it can correct the deformities and rebalance the muscles at a young age. Early surgery (ages 5 to 10 years) has the theoretic and, maybe, real advantage of increased affected side arm and hand use, bimanual skill acquisition, and, therefore, assistive and potentially even independent, hand function. The earlier in life you learn something, the easier it may be to do those activities. These potential advantages have to be balanced against the recurrence with growth and noncompliance risks. Early on in life, the parents are often more concerned than the child about the functional and psychosocial implications of a spastic upper limb and hand. The parents are the drivers of care and compliance with therapy and splints. Later, in adolescence, the young adults who are concerned about their functional level and appearance are motivated to change. This is a huge benefit in terms of compliance with a complex perioperative rehabilitation program that lasts many months. No matter how good you are as a surgeon, you will never perfectly rebalance the muscles, nor will you ever resolve their spasticity with a peripheral operation.

Growth will have a negative impact with ongoing muscle imbalance and spasticity. Unlike the lower extremity and foot where the floor will help maintain correction with each step and upright stance, the hand and arm are free to move without support. The imbalance of neural input and muscle activity can lead to recurrent deformity and loss of function. Second and third operations have less optimal outcomes than primary surgery. Therefore our bias is to do surgery during adolescence in a highly motivated patient whose SHUEE and Jebsen scores indicate a high potential for a positive surgical outcome.

SURGICAL PROCEDURES

The most rewarding things you do in life are the ones that look like they cannot be done.
—Arnold Palmer

Multiple anatomic level surgery is advocated in one anesthetic. Surgery should correct muscle imbalance by (1) lengthening or releasing tight spastic muscles; (2) augmenting weak, stretched muscles by tendon transfers or tenodesis procedures; and (3) stabilizing unstable joints by extra-articular muscle rebalancing, joint capsulodesis, or arthrodesis procedures. In higher functioning patients (House class 3 to 6), tendon transfers and lengthenings are more common, while in lower functioning patients (House 0 to 2), tenodesis and fusion procedures predominate (see Coach's Corner). We usually perform surgery in adolescents as they are then highly motivated and near the end of growth. This increases compliance, lessens recurrence, and makes sure the surgery is for the affected patient rather than their parent(s) (Table 22.1).

◆ Hemiplegic Spasticity Reconstruction

Tendon Transfers, Musculotendinous Lengthenings, Joint Stabilizations

Peter, I can't follow you hand surgeons with your alphabet soup operations.
—Mike Lynch as a third-year resident

Under general anesthesia and tourniquet control, the initial incision is transverse in the anterior cubital fossa for planned elbow release. Skin and subcutaneous flaps are elevated proximally and distally for more extensile exposure. Venous outflow is maintained. Dissection is carried down to the biceps tendon and radial tuberosity on the lateral side to avoid medial neurovascular injury. The lacertus fibrosus is isolated and released while protecting the underlying median nerve and brachial artery. The musculotendinous portion of the biceps tendon is isolated with a Penrose drain and lengthened. The underlying brachialis muscle is isolated and a musculotendinous lengthening is performed while protecting the antebrachial and radial nerves laterally and the medial neurovascular bundle (NVB) (Figure 22-5). The degree of passive elbow extension is tested and usually comes to near terminal extension. It is rare in hemiplegia, as opposed to quadriplegia, to need to perform an elbow joint anterior release, brachioradialis (BR) release, and/or Z-lengthening of the biceps tendon. The wound is closed quickly in layers with absorbable suture as precious tourniquet time is a-wasting.

A longitudinal incision is made in the forearm (Figure 22-6A). This is used to isolate the PT proximally and the musculotendinous portions of the flexor digitorum profundus (FDP), flexor digitorum superficialis (FDS), flexor pollicis longus (FPL), FCU, and flexor carpi

Table 22.1

Surgical treatment options in the spastic upper extremity

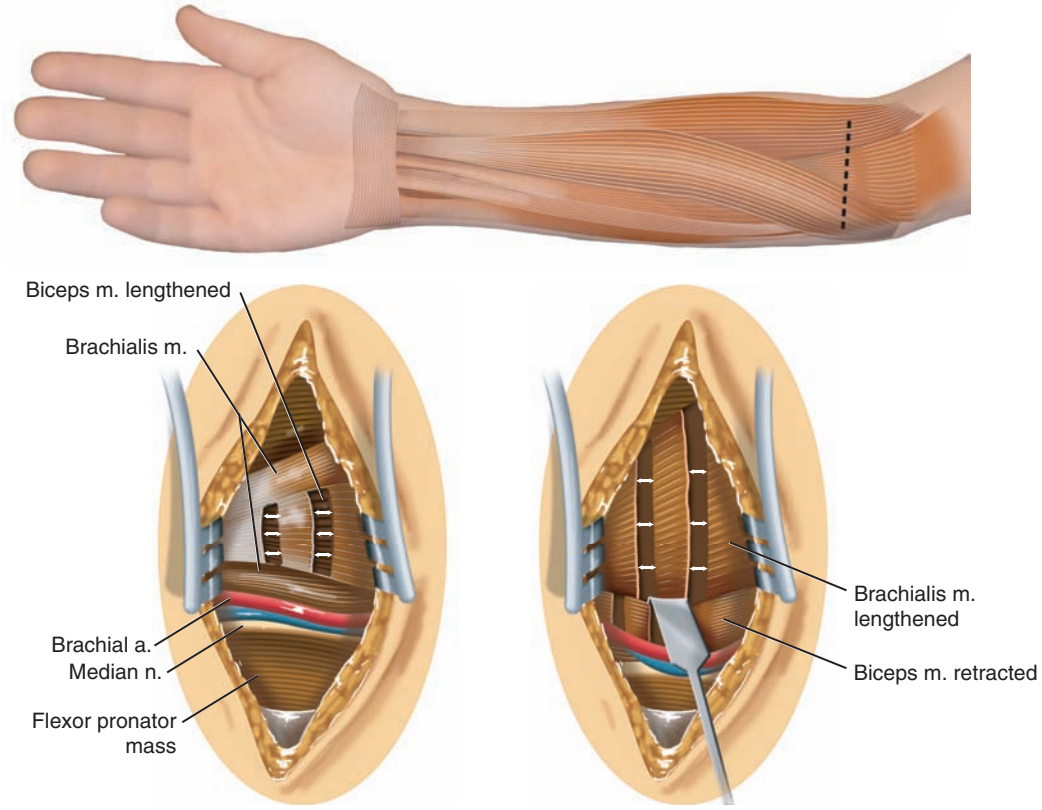
Deformity	Elbow Flexion	Forearm Pronation	Wrist Flexion/Ulnar Deviation	Thumb-in-palm	Finger Deformities
Procedures					
Tendon releases	Lacertus fibrosus release	PT release	Flexor pronator slide	Adductor release	FDS lengthening
	BR release		FCR tenotomy or lengthening	FPB release	FDP lengthening
	Biceps lengthening		FCU tenotomy or lengthening	FPL lengthening	Flexor pronator slide
	Brachialis lengthening				
Tendon transfers		PT rerouting	FCU to ECRB	PL to AbPL, EPB, or EPL	Lateral band rerouting (swan neck)
			FCU to EDC	BR to AbPL, EPB, or EPL	FDS tenodesis (swan neck)
			BR to ECRB	FCR to AbPL, EPB, or EPL	STP transfer
			ECU centralization	AbPL tenodesis	
				EPL rerouting	
Joint stabilization			Wrist fusion	MCP fusion	PIP fusion (rare)
			PRC	MCP capsulodesis	
				IP fusion	

PT, pronator teres; BR, brachioradialis; FDS, flexor digitorum superficialis; FCR, flexor carpi radialis; FPB, flexor pollicis brevis; FDP, flexor digitorum profundus; FCU, flexor carpi ulnaris; FPL, flexor pollicis longus; ECRB, extensor carpi radialis brevis; APL, abductor pollicis longus; EPL, extensor pollicis longus; EDC, extensor digitorum communis; STP, superficialis to profundus; MCP, metacarpophalangeal; PIP, proximal interphalangeal; PRC, proximal row carpectomy; IP, interphalangeal.
From Van Heest AE, House JH, Cariello C. Upper extremity surgical treatment of cerebral palsy. *J Hand Surg Am.* 1999;24:126

radialis (FCR). The PT insertion is identified below the BR while protecting the radial artery and radial sensory nerve. The supinator insertion is proximal, and the FPL origin is distal on the radius. The PT tendinous insertion is elevated sharply off the radius with a long, wide strip of periosteum. This requires sequential use of a sharp knife, cautery, and an elevator to maintain the integrity and length of the tendon as its insertion is naturally well attached to the bone and can be disrupted by careless dissection. A locked whip suture is placed in the tendon and periosteum. Care is taken to be certain there is free excursion of the PT while protecting its proximal neurovascular pedicle. A wide elevation of the interosseous membrane is performed at the level of planned rerouting transfer. With a curved passer, the PT is rerouted under the medial side of the radius and sewn into drill holes on the anterolateral side. The PT will now act as an active supinator.

In sequence, the FDS and FDP to the index, long, ring, and small fingers are lengthened (Figure 22-6A). Single or dual tenotomies can be performed. Oblique, separate incisions are performed until full passive digital extension is possible with the wrist in neutral. This is usually sufficient to correct digital flexion tightness without weakening grip, which can occur with Z-lengthenings and superficialis to profundus (STP) transfers. In a similar fashion, the FPL is lengthened and, if necessary, the FCR. Again, be careful not to overlengthen the wrist flexors in conjunction with FCU to extensor carpi radialis brevis (ECRB) transfer. This will prevent a wrist extension deformity and difficulty with release postoperatively. The palmaris longus (PL) may be released or used for transfer to the thumb as appropriate.

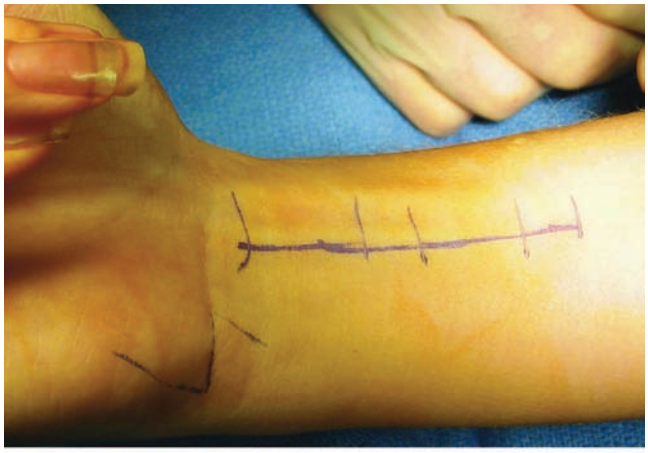
The FCU is isolated while protecting its proximal neurovascular pedicle and the ulnar artery and nerve as



A

B

FIGURE 22-5 **A:** Incision and technique for musculotendinous lengthening of biceps and brachialis for an elbow flexion contracture. **B:** Postoperative elbow extension from release along with FCU transfer, FDS and FDP lengthenings, and thumb release and transfers.



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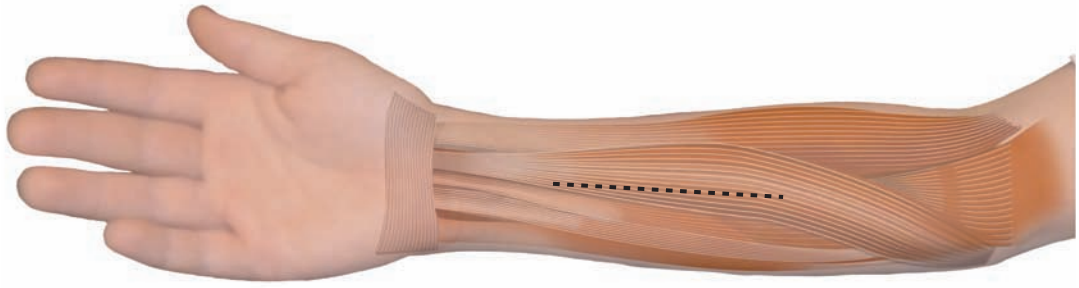

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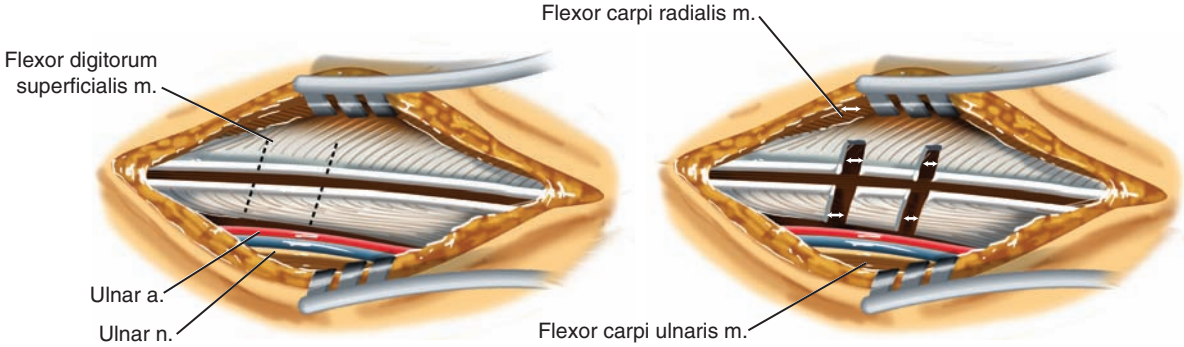
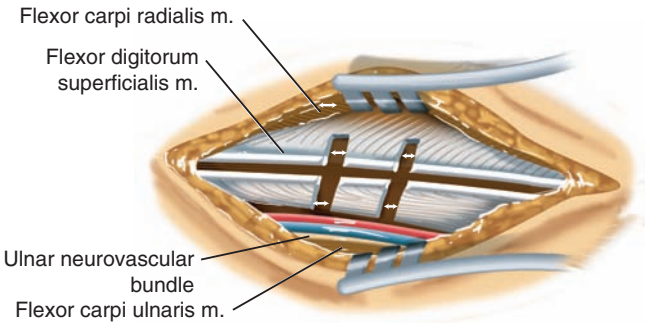
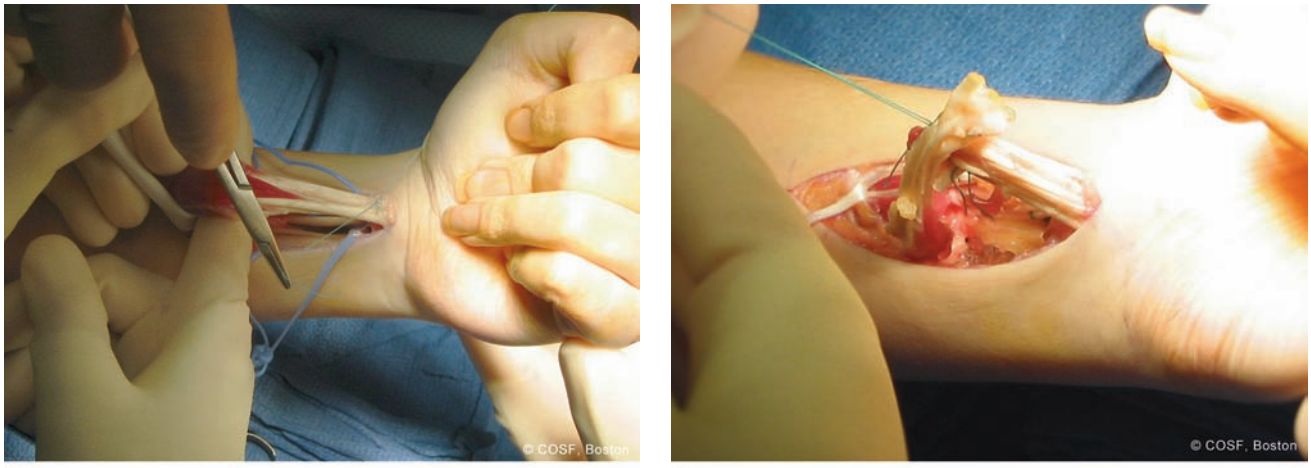


B1 B2



B3

FIGURE 22-6 **A1, A2:** Straight volar incision used for flexor tendon releases either by musculotendinous lengthenings or STP transfers. **B1, B2, B3:** Illustration of musculotendinous lengthenings of FDS, FDP, and, if appropriate, FPL and FCR. One or two incisions can be made in each tendon depending on the length needed.

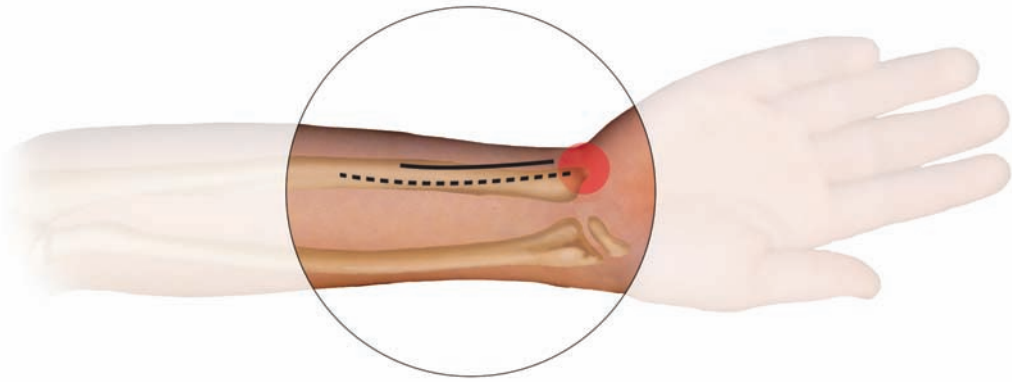


C D

FIGURE 22-6 *(continued)* **C:** The FDS tendons have been sutured together as distal as possible. The same is done with the FDP as proximal as possible. **D:** The FDS to FDP transfer is repaired with the desired cascade. (**A1** © COSF Boston.)

they enter Guyon canal distally (Figure 22-7). The FCU is released off its insertion into the pisiform and mobilized proximally for maximal excursion. There are typically multiple aponeurotic connections between the FCU muscle and surrounding fascia, which need to be released to obtain adequate FCU mobility. A locked whip suture is placed in the tendon in preparation for transfer to the ECRB.

A curvilinear dorsal incision is made over the first, second, and third extensor compartments in preparation



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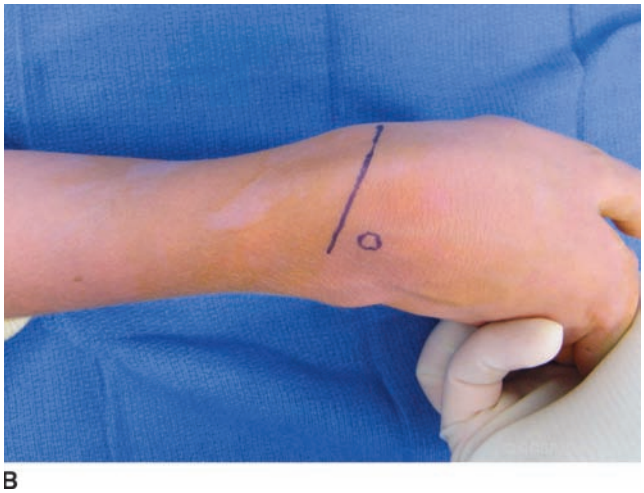


B

FIGURE 22-7 **A,B:** Straight ulnar volar incision adjacent to ulnar NVB (outlined by *dots*) ending proximal to pisiform (outlined by *open circle*). **B:** Oblique incision for exposure of EPL and rerouting from 3rd compartment (Lister tubercle noted by *circle*) to volar to 1st compartment; and ECRB for transfer FCU to ECRB.

C

D

FIGURE 22-7 *(continued)* **C:** FCU has been mobilized proximally while protecting neurovascular pedicle and is rerouted around ulnar border for weave inset in ECRB. This will improve both wrist extension and supination. **D1:** Postoperative wrist extension with fingers and thumb flexed (**D2**) and wrist, fingers, and thumb all extended. Oblique incision for FCU to ECRB transfer along with EPL rerouting.

for extensor pollicis longus (EPL) rerouting, FCU to ECRB transfer, and, if appropriate, BR transfer to the abductor pollicis longus (APL) or extensor pollicis brevis (EPB) (Figure 22-6A). After elevation of the skin and subcutaneous tissues, each tendon is isolated with a rubber loop. A subcutaneous tunnel is then made from the dorsum wrist to the proximal aspect of the volar forearm for passage of the FCU tendon. Routing the FCU around the ulna will improve active supination and lessen the risk of recurrent forearm pronation. At times, the tendon is too tight or active supination is not necessary, and then it can be passed through the interosseous membrane while protecting the anterior and posterior interosseous vessels. Once the FCU is passed to the dorsum, a final decision about FCR lengthening is made. If necessary, it is now performed in standard tenotomy fashion. The volar wound is then closed over a drain with layered absorbable suture. Again, remember the tourniquet clock is ticking away, and there is still a lot to do. No time for small talk.

The EPL is elevated out of the third compartment with release of the retinaculum at Lister tubercle. It is brought volar to the first dorsal compartment while protecting the radial sensory nerve and radial artery. This can be done with a retinacular flap, slip of APL as a pulley, or transection of the tendon and passage under the first compartment retinaculum. We tend to use a retinacular flap (Figure 22-8). The flap is readied but not yet sutured around the tendon.

If a transfer from the BR to the EPB or APL is to be performed, it is isolated and mobilized. The ECRB is also mobilized for a FCU Pulvertaft weave repair. These transfer repairs are performed at the conclusion of the thumb and finger portions of the case, but preparation now saves time later.

A two-part, four-part, or five-part Z-plasty reconstruction of the tight first web-space skin is performed (Figure 22-9). This skin has to be delicately handled as it is thin, and the NVBs are just beneath. At a minimum, the adductor and first dorsal interosseous fascia are released. Usually a more extensive release of the adductor muscle is required, at times leaving the deep muscle belly (oblique head) intact for voluntary pinch. A muscle slide of the first dorsal interosseous off the first metacarpal is performed while protecting the princeps pollicis artery at the base of the thumb. Further release of the abductor pollicis brevis or flexor pollicis brevis (FPB) may be necessary dependent on the type of thumb deformity. The Z-plasty flaps are rotated and closed with care to protect the vascularity of the flaps.

FIGURE 22-8 Illustration of EPL rerouting techniques.

If necessary, the swan neck deformities are now addressed (Figure 22-10A). This can be through lateral band rerouting, FDS tenodesis, or central slip tenotomy. The central slip tenotomy is made transversely just proximal to the proximal interphalangeal (PIP) joint, leaving the lateral bands intact.[44] The lateral band rerouting is made through ulnar midaxial incisions centered over the PIP joint. A longitudinal incision is made in the ulnar lateral band to separate it from the central extensor mechanism. The lateral band is sewn into the volar flexor tendon sheath or A2 pulley while protecting the ulnar digital NVB. The PIP extension is tested to be certain the tension is correct (Figure 22-10B). We tend to perform lateral band rerouting for dynamic, locking swan neck deformities. Those wounds are sequentially closed. Percutaneous pinning of the PIP joints in 20 degrees of flexion may be necessary for 3 to 4 weeks postoperatively to maintain correction.

Finally, the tendon transfers are sewn in. This is done after all the other wounds are closed. The FCU is passed through the ECRB under maximum tension and secured with nonabsorbable suture. Passive wrist flexion to 20 degrees with gravity is necessary to be certain the repair is not too tight. The EPL is sutured in its retinacular flap with absorbable suture. If necessary the BR or PL transfer is repaired as well. Wound closure is performed in layers, and a sterile dressing is applied. The tourniquet is finally deflated with a sigh of relief. The forearm is supinated, the wrist is positioned in 20 to 30 degrees of extension, the thumb-in-palmar abduction and opposition, and the fingers in protected flexion at the PIP joints with intrinsic stretch.

◆ Quadriplegic Realignment

Extensive Releases Elbow, Wrist, Hand, Thumb

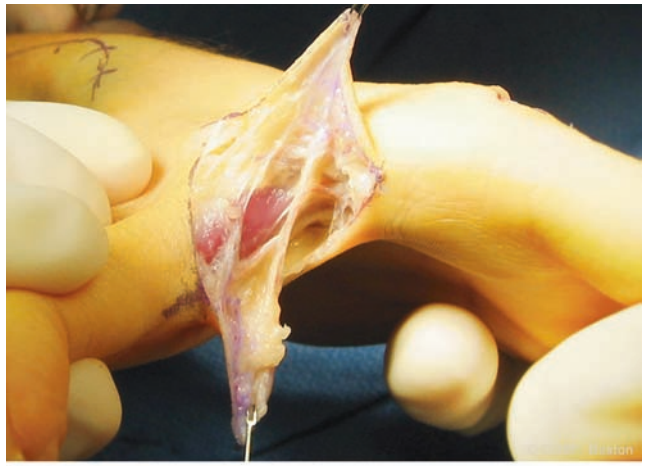
Proximal Row Carpectomy and Wrist Fusion

Quadriparetic patients can have more severe contractures and less function (Figure 22-1). They can also be more malnourished and have more medical problems. This can make their risk of surgical and perioperative medical complications higher. It has to be clear that there will be added benefit to the patient with surgical intervention given the risks. In general, surgery for quadriplegic patients is performed to improve hygiene (e.g., ability to trim fingernails; avoid skin breakdown in the palm, antecubital fossa, and axilla) and ease of nursing care (e.g., dressing, bathing, transfers from bed to wheelchair).

The elbow release is usually more extensive with a Z-lengthening of the biceps, BR release off the humerus while protecting the radial nerve, and often an anterior capsular release along with brachialis musculotendinous lengthening. Often the neurovascular pedicles are the tightest structures remaining, and care must be taken not to avulse them in long-standing severe contractures.

The pronator release and rerouting may also require release of the pronator quadratus and interosseous membrane given the long-standing contracture. At times, the

A



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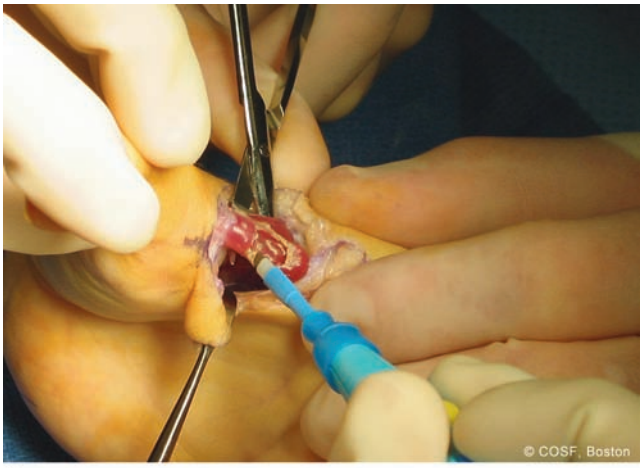

C

D

FIGURE 22-9 **A:** Outline of two-part Z-plasty for web-space release. **B:** Elevated Z-plasty flaps with vascularity to flaps maintained. **C:** Bovie cautery release of adductor. **D:** Postoperative first web-space release and tendon transfers for improved thumb function.

distal radioulnar joint is dislocated, and bony resection may be necessary though potentially excessive.

The digital flexion deformity usually requires STP transfer (Figure 22-6). This is performed by group isolation of the profundus tendons as proximally as possible and the superficialis tendons as distally as possible. Ethibond (Ethicon, Inc., Somerville, NJ) suture is used to secure the profundus tendons of the index, long, ring, and small fingers side-to-side in normal cascade. The tendons are transected proximal to the group suture. The FDS tendons are released distal to the group suture, often in the carpal canal, while protecting the median nerve. Before they can be repaired, correction of the wrist deformity is necessary. If a proximal row carpectomy (PRC) and wrist fusion are planned, then the FCR, FCU, and PL are released. If transfers are appropriate, then a modified hemiplegic surgery is performed with tenodesis and transfers.

The dorsal wrist is approached through a fourth compartment longitudinal incision. The extensor digitorum communis (EDC) tendons for each finger are isolated in a group. An H flap capsular incision is used to expose the

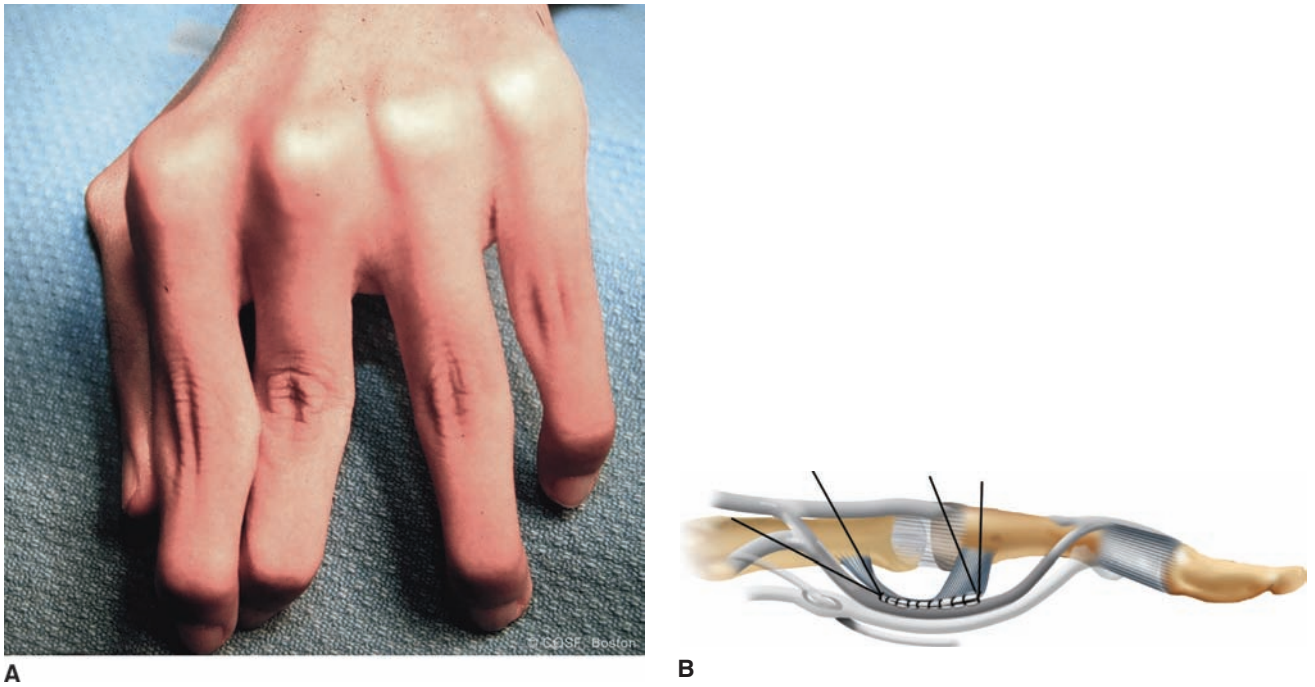

FIGURE 22-10 **A:** The patient with swan neck deformity. Note the dorsally subluxed lateral bands over the hyperextended PIP joints. **B:** Illustration of lateral band rerouting procedure.

wrist. If the proximal carpal row has significant cartilage wear, then a PRC is performed. The scaphoid, lunate, and triquetrum are removed in their entirety. The bone is morselized for bone graft. The scaphoid and lunate fossae of the radius are curettaged to bleeding bone. The proximal articular surfaces of the capitate and hamate are removed again to bleeding bone. Bone fixation can be by wrist fusion plate or intramedullary K-wires (Figure 22-11A). In the interest of time, and because it works, we use stout, smooth K-wires with the wrist in neutral to 20 degrees of extension. The bone graft is densely packed, and the capsule is closed. The retinaculum is repaired, and the redundancy in the EDC is ignored.

The STP procedure is then sewn in place to maintain appropriate tension and cascade to the digits. Since this is a poorly functioning hand at best, a "soda can" cascade seems to work for proper positioning with a wrist fusion. The FPL requires a Z-lengthening. The volar wounds are closed over a drain in a layered fashion. The volar skin can be tenuous and should be treated with "kid gloves" to lessen the risk of postoperative wound breakdown.

ALTERNATIVE PROCEDURES

Imagination has a great deal to do with winning.
—Mike Krzyzewski

Each child is unique. That is why extensive preoperative planning is necessary. Other muscles and tendons may have to be used to obtain optimum outcome for any given CP patient. Common modifications, among others, are (1) PT to EDC or FCU to EDC when active digital extension is lacking; (2) ECU to ECRB when the ECU is the main deforming force; (3) flexor pronator slide in less functional patients for correction of forearm pronation and wrist and finger flexion deformities; (5) metacarpophalangeal (MCP) joint arthrodesis (Figure 22-12A) (either as chondrodesis preserving physis or as true fusion in skeletally mature) or volar plate arthroplasty in unstable MCP hyperextension deformity; and (6) FPL abductorplasty and interphalangeal (IP) joint fusion when the FPL is the main deforming force of the thumb, and the EPL is weak or nonfunctional. You just have to be ready to do what is necessary and best. It is why CP reconstruction is black or double black diamond level work.

POSTOPERATIVE

The arm and hand are immobilized in a long-arm bivalved cast for 4 weeks for soft tissue–only surgery and 6 weeks for associated bone and joint surgery (fusions). Limb and hand positioning in the cast is individualized to protect tendon transfers. Generally forearm supination, wrist extension, digital extension, and thumb palmar abduction and opposition are used. Following cast removal, occupational therapy is performed in conjunction with a wrist and hand orthosis. Passive arc of motion is maintained, and active hand function is emphasized. Outcome

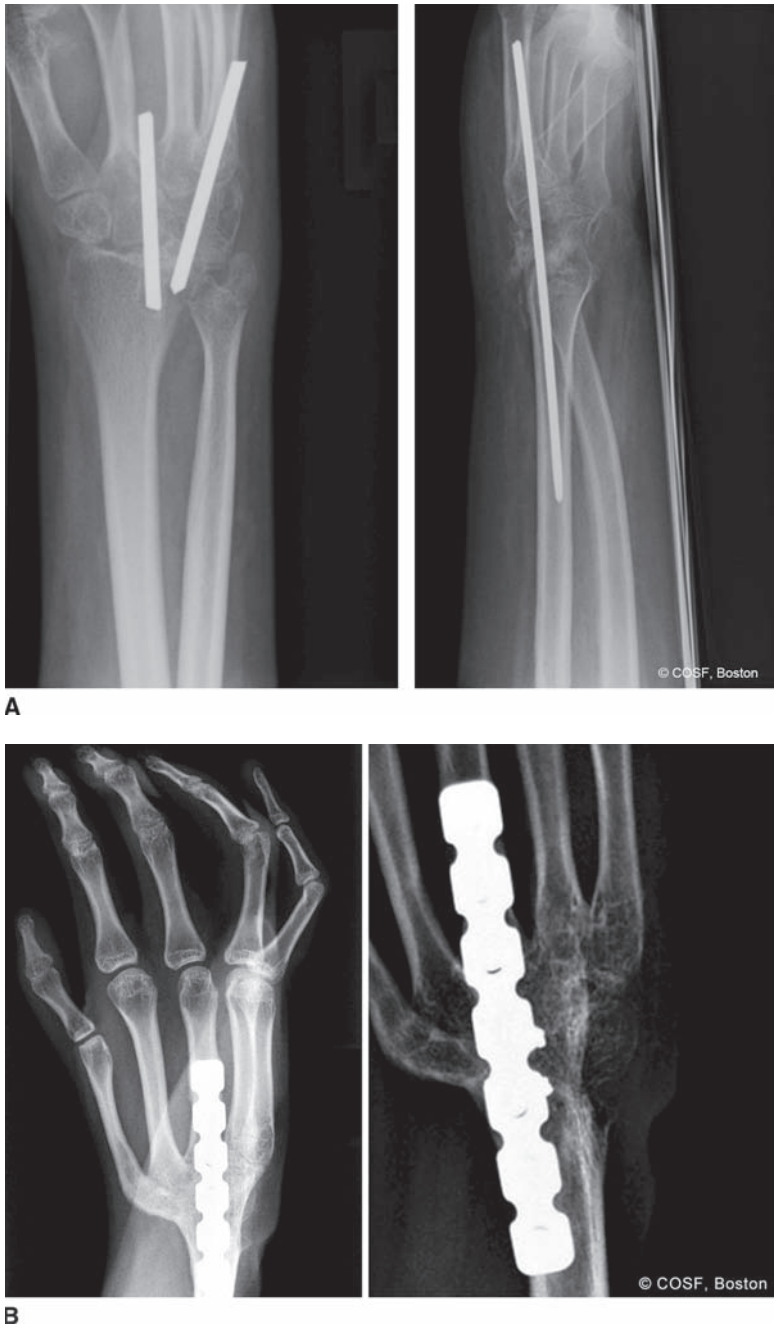

FIGURE 22-11 **A:** Postoperative wrist fusion with K-wires. **B:** Postoperative wrist fusion with plate.

is assessed at 6 months postoperatively. Maintenance care and exams continue as the CNS lesion remains unchanged by peripheral surgery.

ANTICIPATED RESULTS

Getting a dysfunctional limb in hemiplegia, or even more so with quadriplegia, to work better is not easy. That said, a little goes a long way in these patients. Improved joint positioning, especially wrist extension and forearm supination, during functional use is expected with hemiplegia surgery (Figure 22-13).[45–47] Overall functional improvement by House classification is expected in the two- to three-level range with multiple level surgery.[48]

COMPLICATIONS

The usual suspects occur more often with surgery in CP patients. Anesthesia and infection complications are higher in this population, especially the malnourished quadriplegic patient. Seizure disorders are more common in these children and increase the perioperative

risk. Careful patient selection, maximum medical and nutritional therapy before surgery, and multidisciplinary perioperative care can lessen both minor and major complications and their sequelae.

In our minds, the most preventable complication involves the failure of the surgery to achieve the desired result for the patient and family. Often this is a failure of communication. Surgical decision making has to be reality based, and communication has to be clear regarding the expected outcomes. "Step away from the car" before incision if everyone is not on the same page.

Failing to appreciate an athetotic patient can lead to disappointing results. Repeated exams, videotaping of function, and a high index of suspicion will avoid surgical disappointment or a worsening condition after surgery.[49]

Intrinsic spasticity can be unmasked by an extensive extrinsic rebalancing of the hand. This may require subsequent surgery with an intrinsic slide or ulnar motor neurotomy. An ulnar nerve block at Guyon canal will determine if an ulnar motor neurotomy will be successful.

CASE OUTCOME

Videotape analysis indicated this young man would benefit from multiple-level surgery. Under one tourniquet run of 2 hours and 10 minutes, he had (1) biceps and

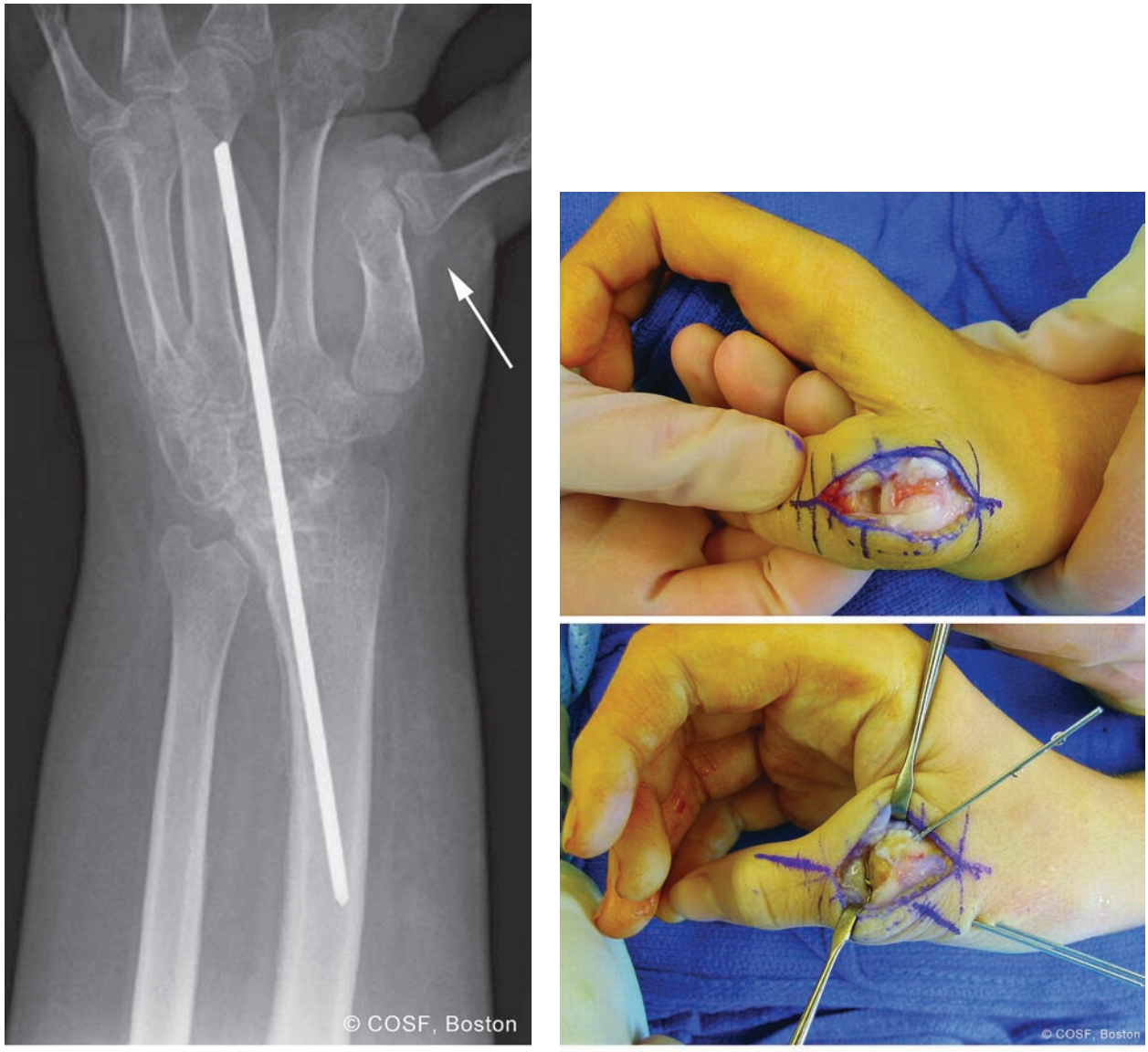

FIGURE 22-12 **A:** Postoperative radiograph shows wrist fusion in which soft tissue rebalancing of thumb MCP joint did not work at the time of wrist fusion. Note the MCP joint hyperextension and dislocation (*arrow*). **B1:** Exposed MCP joint with cartilage loss noted at the time of fusion. **B2:** Pins in place.

C

FIGURE 22-12 *(continued)* **C:** Postoperative x-ray shows MCP fusion.

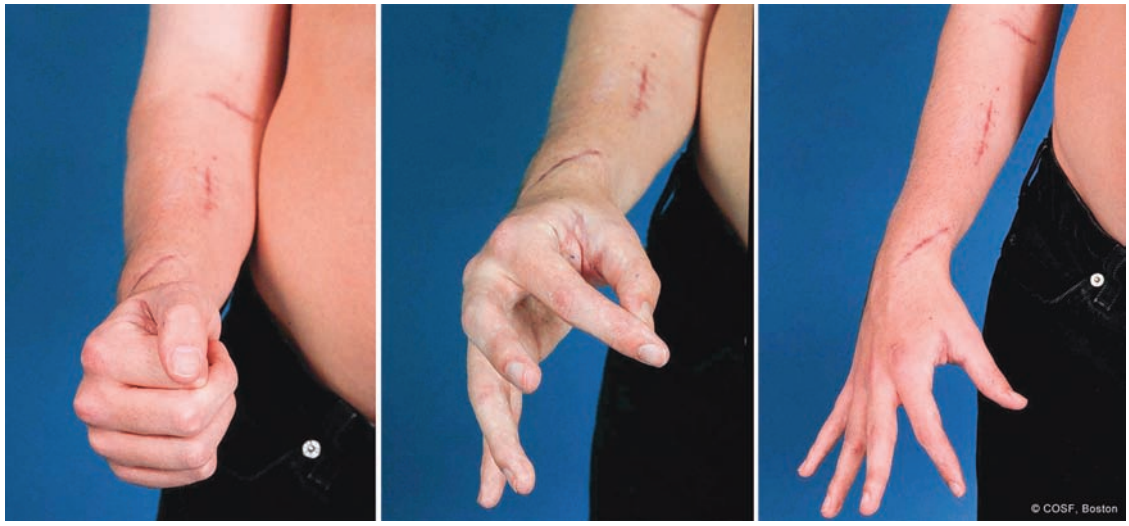

FIGURE 22-13 Postoperative grasp, pinch, and release function after transfers.

brachialis musculotendinous lengthening and lacertus fibrosus release; (2) PT rerouting tendon transfer; (3) FDS, FDP, FCR, and FPL musculotendinous lengthenings; (4) FCU to ECRB tendon transfer; (5) EPL rerouting tendon transfer; (6) BR to EPB transfer; (7) first web-space Z-plasty, adductor release, and first dorsal interosseous advancement; and (8) lateral band rerouting of index, long, ring, and small fingers. He had marked improvement in his assistive function and aesthetic appearance (Figure 22-13).

SUMMARY

CP is a complex motor disorder that limits function, affects self-perception and social integration, and is frequently associated with CNS cognitive, electrophysiologic, and visual disabilities. The goal of hand and upper extremity care is to improve grasp, pinch, and release functions while improving aesthetics. Properly selected treatments in the appropriate patient, including surgical intervention, can make a big difference in both the short and long term.

COACH'S CORNER

Visualize this thing that you want, see it, feel it, believe in it, make your mental blueprint and begin to build.
—Robert Collier

Multiple-level surgery of the upper or lower limb is advantageous for the CP patient. It involves one anesthetic, one rehabilitation, and one shot at getting the muscles balanced and joint alignment as close to right as possible in the operating room. It is a gamble with the costs of error high, and so it needs to be a very knowledge-based plan. You must use all the tools at your disposal such as parental insight, patient self-perception, therapist evaluation, and videotaped validated measurements. For us, the Jebsen-Taylor hand function test, House classification, and SHUEE are all a part of our pre- and postoperative videotaping. In a calm setting with friendly, knowledgeable therapists, the potential surgical patients are assessed for passive and active range of motion and functional tasks with standard camera placement. These videos and the standardized testing scores are then reviewed by the surgical and nonsurgical teams together to determine definitively: (1) if surgery is indicated at that time and (2) which specific procedures should be performed at each anatomic level for that particular patient. The ability to do this outside of the busy clinical setting, to wind and rewind the tape to be certain of what you see and think is best, is undoubtedly beneficial to the patient, family, and surgeon. Given the extensive amount of surgery required, and the time limits of tourniquet control, you must be committed to your surgical plan and work efficiently and skillfully once the limb is exsanguinated.

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CHAPTER

23

Arthrogryposis

CASE PRESENTATION

A 2-year-old female presents for evaluation of a stiff elbow. Prenatal diagnosis was made by prenatal ultrasound examination and pediatric orthopaedic consultation of arthrogryposis multiplex congenita (amyoplasia), and this was confirmed on postnatal genetic evaluation. She has had prior treatment of neurogenic clubfeet but is independently ambulatory and otherwise healthy. She has had elbows fixed in extension since birth, with considerable limitations in wrist and hand function as well. Radiographs of the elbow appear normal (Figure 23-1). The family now seeks treatment options to improve both function and aesthetics of the upper limbs.

CLINICAL QUESTIONS

- What is arthrogryposis?
- What causes arthrogryposis?
- How is it classified?
- What are the principles of treatment?
- What surgical procedures can be performed to improve hand and upper limb function in patients with arthrogryposis?

THE FUNDAMENTALS

Few conditions present as many clinical challenges for the pediatric hand and upper limb surgeon as arthrogryposis. The combination of functionally limiting joint contractures, hypoplastic or absent skeletal muscle, and normal to high intelligence motivate the patient and family to seek aggressive treatment. Unfortunately, to date, imperfect surgical solutions exist. Despite these challenges, a number of interventions may provide improved upper limb and hand function in selected patients. The ultimate goals of any musculoskeletal treatment are improved functional independence as an adult and as healthy and happy a childhood as feasible. Making the hand and upper limb "normal" is not possible and needs to be stressed early on in life, no matter how difficult it is for the family and patient to hear. As challenging as it may be, admitting our present limits can be very helpful for patients and families to focus their energy where it can do the most good.

Etiology and Epidemiology

Motion is life.
—Robert Salter

Arthrogryposis is a descriptive term used to describe a host of clinical conditions resulting in multiple congenital joint contractures.[1] The most common type is amyoplasia (also known as arthrogryposis multiplex congenita or classic arthrogryposis).[2–4] Other variants include distal arthrogryposis, which is characterized by hand and foot involvement with relative sparing of the proximal limb segments.[5,6] Arthrogryposis is also associated with a number of systemic or generalized conditions (syndromic arthrogryposis), including Freeman-Sheldon (so-called whistling face) syndrome.[5,7,8]

Although the primary condition involves failure of skeletal muscle formation and development, arthrogryposis manifests as multiple joint contractures. Indeed, "arthrogryposis" loosely translates into "abnormally curved" or "stiff joints." While the pathoanatomy and pathophysiology vary and continue to be investigated, it appears that the joints initially have full developmental potential but fail to form mobile articulations secondary to the absence of movement in utero. This theory has been supported by a number of chick embryo studies, in which paralytic agents were administered during development, resulting in abnormal joint morphology and stiffness.[9–12] The lack of joint motion results in articular cartilage abnormalities, failure of joint cavitation, and secondary fusions.

Amyoplasia is seen in approximately 1:3,000 live births.[13] It is thought to be sporadic, with no genetic or hereditary predisposition. In contrast, distal arthrogryposis is comprised of a number of autosomal dominant disorders, all of which are due to mutations in genes responsible for myofiber function, including TNNI2, TNNT3, TPM2, MYH3, and MYH8.[14–16]

FIGURE 23-1 Radiograph of the elbow, forearm, wrist, and hand of a patient with arthrogryposis. Note is made of the elbow extension and wrist flexion contractures. The osseous elements and joint spaces appear normal.

Clinical Evaluation

If you ain't looking at the big picture, you just ain't looking…
—Stephen Root

Amyoplasia is characterized by multiple, often symmetric joint contractures associated with marked muscle underdevelopment. The upper limbs will typically demonstrate posturing and/or contractures of shoulder internal rotation and adduction, elbow extension, wrist flexion and ulnar deviation, digital metacarpophalangeal (MCP) flexion, interphalangeal (IP) extension, and thumb-in-palm deformity. Associated musculoskeletal conditions include hip dysplasia, knee contractures, and clubfeet. Up to 10% of patients will have abdominal abnormalities.[17] Intelligence and cognitive abilities are normal or above average in distal arthrogryposis, amyoplasia, and many patients with syndromic arthrogryposis.

Careful history and physical examination are performed to assess the overall functional abilities and needs of the patient, particularly with regard to upper extremity and hand use. Passive range-of-motion measurements are made of the shoulder, elbow, forearm, wrist, and hand. The presence of active joint motion and strength, if any, is similarly noted. The functional status of the patient is very important to assess. These children will use head tilt, trunk sway, table stabilization, and leg and opposite arm assistance to improve functional independence. Do not just get lost in the specifics of each joint and muscle; see the child as a whole for what he or she can accomplish. If surgery is considered, radiographs are obtained of the affected joint(s), particularly in the older patient, to rule out joint fusions and/or secondary bony deformities.

Surgical Indications

We try to stress the little things because little things lead to big things.
—Steve Alford

Goals of treatment are to improve upper limb mobility and function in order to increase independence with activities of daily living and ambulation/locomotion. Occupational and physical therapy are essential components of treatment for these children and begin at a very young age. Surgical strategies for arthrogryposis focus on functional improvement and are performed in up to 25% of patients.[18] Indications include limited joint motion and upper extremity function refractory to nonoperative care in the motivated patient.[1,19–21] As with all systemic conditions in children, nonoperative and surgical treatment must be tailored to each individual patient.

Ezaki[19] has previously outlined the guiding principles of surgical treatment. First, any joint motion that is present should be preserved. Second, passive motion must be obtained before active motion is surgically provided. Third, the potential for bimanual hand/upper limb use must be prioritized, due to the relative weak grasp and associated wrist and digital stiffness. Finally, upper limb function should be maximized for use at the tabletop level.

The optimal timing of surgical intervention is unclear and remains individualized according to the overall needs and status of the individual patient. Considerations are made to (1) maximize upper limb mobility during the development of gross and fine motor activities; (2) optimize upper limb function by the time the patient is of school age; (3) prevent irreversible bone and joint changes; and (4) perform upper limb surgery in conjunction with other (lower extremity) surgical procedures whenever possible. Surgical treatment in these children most commonly addresses contractures of elbow extension, wrist palmar flexion and ulnar deviation, and thumb-in-palm deformity.

SURGICAL PROCEDURES

Splinting, Occupational Therapy

Occupational and physical therapy, including stretching and splinting, are critical components of upper extremity care in patients with arthrogryposis.[22] Indeed, the vast majority of patients will continue to undergo therapy and splinting treatments well into the second decade of life.[23] Modest gains in elbow, wrist, and digital motion will go a long way in improving function. The younger the age at which therapy is initiated, the more likely it is to be successful. However, it may take 18 to 24 months to achieve maximum outcome with therapy or to be truly determined as ineffective. For example, aggressive elbow flexion therapy can result in up to 90 degrees of passive motion in up to 80% of patients if consistently performed until 18 months of age, a huge advantage for these patients. It enables them, with functional adaptations such as table stabilization, trunk sway, and head tilt, to feed themselves and perform independent facial hygiene.

In addition, adaptive devices may further increase independence of feeding, dressing, personal hygiene, and other activities of daily living with considerable benefits to the patient.[24] This is particularly important as these patients approach school age, where adaptive tools may assist with keyboarding and tabletop activities, and independent hygiene and feeding are very important. The computer age has brought many technologic advances for these children, including voice-activated software and memory-recognition programs.

Elbow Release, V-Y Tricepsplasty

Given that the most important purpose of the elbow is to move the hand to and from the face, correction of elbow extension contractures remains a primary goal of surgical treatment.[19] Elbow surgery is indicated in roughly 20% of patients who fail passive motion therapy, with posterior capsulectomy and V-Y lengthening of the triceps being the procedure of choice in patients with amyoplasia (Figure 23-2). Preoperative radiographs must confirm the presence of sufficient joint space to allow for correction. Remember, passive motion must be achieved through therapy or surgery before consideration of active transfers.

Under general anesthesia and tourniquet control, a posterior midline incision is created, curved radially over the olecranon process. Skin flaps are raised and hemostasis obtained. Despite the apparently normal girth of the brachium, there is typically an abundance of subcutaneous fat with very thin and fibrotic triceps muscle mass. The ulnar nerve is identified, released, and protected at all times. It too will be atrophic and at times, almost fibrotic.

The medial and lateral margins of the triceps are identified, and the plane between the capsule and triceps developed. A long V-shaped incision in the triceps is created through the tendinous region, with the base distal and apex proximal. Care is made to make this "V" as long as possible to allow for adequate lengthening. The triceps flaps are then reflected proximally and distally, exposing the posterior elbow capsule. With release of the triceps alone, there is usually very little improvement in passive elbow flexion.

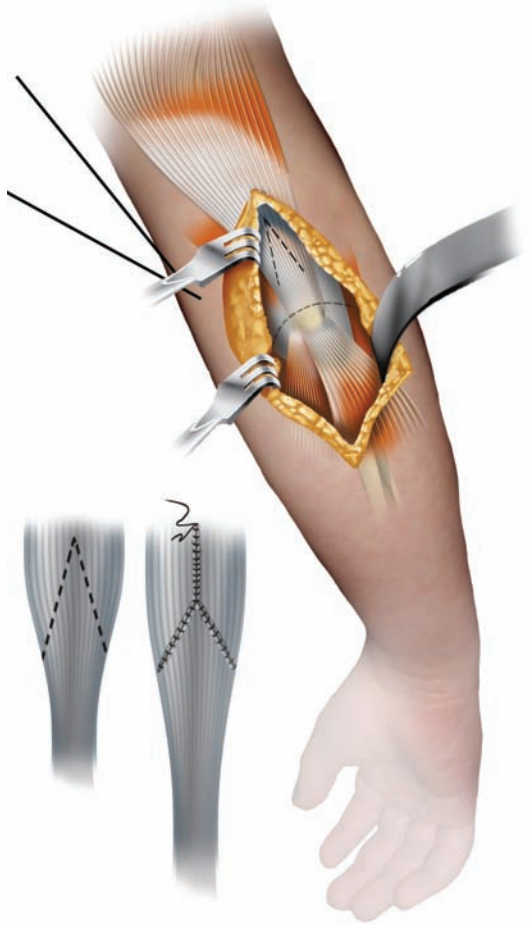

FIGURE 23-2 Schematic diagram depicting the technique of triceps V-Y lengthening and posterior capsular release for elbow extension contracture.

The posterior capsule is then transversely incised, with care made to identify and protect the medial and lateral collateral ligaments. The capsule is markedly thickened and densely adherent to the underlying bone. After capsulectomy, the elbow is gently and progressively flexed until at least 90 degrees of flexion is obtained. Overzealous or impatient forceful elbow flexion can lead to fracture through the osteopenic bone and should be avoided. If 90 degrees of flexion is not obtained, the posterior margins of the collateral ligament complexes may need to be released while preserving elbow stability.

The triceps is then lengthened and reapproximated in a V-Y fashion, using multiple interrupted 2-0 nonabsorbable sutures (Ethibond, Ethicon, Inc., Somerville, NJ). The elbow is again ranged to confirm maintenance of

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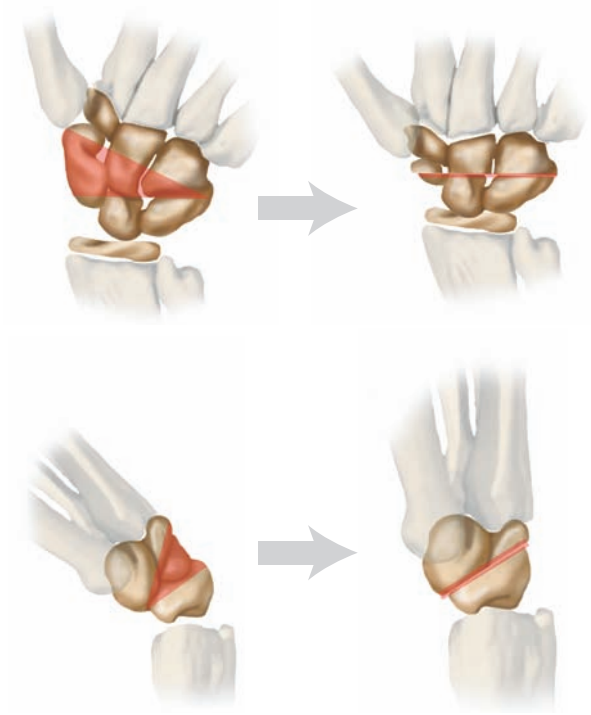
at least 90 degrees of flexion. The repair has to allow for at least 90 degrees of flexion and ideally up to 120 degrees. The ulnar nerve, if unstable, may be transposed subcutaneously. Subcutaneous tissues and skin are closed in layers, and a bulky soft bandage is applied. Postoperatively, the limb is immobilized in a bivalved long-arm cast in 90 degrees of flexion.

◆ Carpal Wedge Osteotomy

The wrist in amyoplasia is typically flexed and ulnarly deviated. Diligent splinting and therapy to achieve passive wrist extension to neutral is the goal of treatment in the first 1 to 2 years of life. In many amyoplasia patients, even when passive motion is achieved, extrinsic wrist extensor power is lacking. As active wrist extension also improves grip strength through tenodesis, insufficient passive or active wrist extension results in limited use of the wrist and hand for upper extremity activities. While a number of prior procedures have been proposed to improve wrist function, the carpal wedge osteotomy has proven to be a safe, effective, and reliable means of achieving more functional wrist position.

The carpal wedge osteotomy involves resection of a biplanar wedge of cartilage and bone at the level of the midcarpal joint, broader dorsally and radially to allow for correction of both the flexion and ulnar deviation deformity (Figure 23-3A). In theory, the carpal wedge osteotomy spares the radiocarpal and carpometacarpal (CMC) articulations as well as the distal insertions of the wrist extensors, thus preserving the potential for wrist motion.



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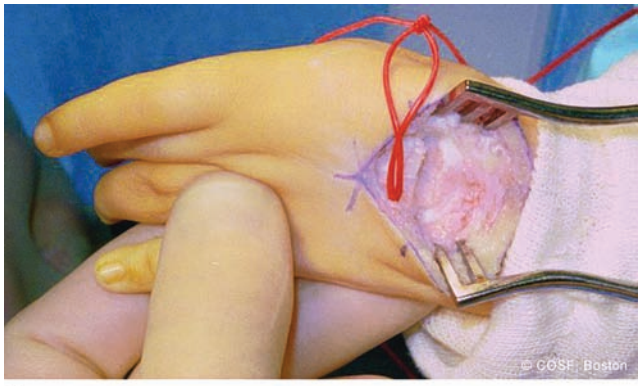

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FIGURE 23-3 Carpal wedge osteotomy. **A:** Schematic diagram of the carpal wedge osteotomy. Note that the wedge is broadest dorsally and radially to correct the flexion and ulnar deviation deformity. Care is made not to violate the radiocarpal or CMC joints. **B:** Intraoperative photograph depicting the wedge resection. **C:** Postoperative radiographs demonstrating the use of smooth K-wires to supplement fixation following carpal wedge osteotomy.

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Under general anesthesia and tourniquet control, either a dorsal longitudinal incision just ulnar to Lister tubercle or a dorsal transverse incision over the midcarpus from radial index to ulnar small finger regions (authors' preference) is created. Dissection through the subcutaneous tissue is made to the level of the extensor retinaculum, and flaps are raised, thus preserving the dorsal veins and cutaneous nerves. The third-fourth dorsal compartment interval is incised, allowing for radial elevation and retraction of the extensor carpi radialis longus (ECRL), extensor carpi radialis brevis (ECRB), and extensor pollicis longus and ulnar retraction of the extensor indicis proprius and extensor digitorum communis tendons. Often these structures are adherent to the underlying wrist capsule due to the lack of musculotendinous excursion from long-standing arthrogrypotic contractures. The wrist joint capsule is then incised transversely and flaps are elevated proximally and distally. Alternatively, a longitudinal incision may be made with radial and ulnar flaps. At this time, there should be adequate visualization of the entire carpus, though distinct midcarpal or intercarpal joints may not be seen due to the typical carpal coalitions that exist in the arthrogrypotic wrist.[19,25]

With care made to protect the adjacent soft tissues, preparations are made for the wedge osteotomy. Using a 67 Beaver or no. 15 blade (or rarely a small thin osteotome), the proximal cut is made perpendicular to the radiocarpal and ulnocarpal joints through the proximal carpal row. The distal cut is then created parallel and proximal to the CMC joints, with care being made to converge with the prior proximal cut, producing a trapezoidal-shaped wedge broadest dorsally and radially. The wedge is removed and the osteocartilaginous surfaces of the proximal and distal row are reapproximated, thus effectuating deformity correction (Figure 23-3B). Stability of the osteotomy can often be achieved with 2-0 nonabsorbable braided sutures (Ethibond, Ethicon, Inc., Somerville, NJ) placed through the periosteum or carpal cartilage, in essence achieving suture tension-band fixation. This may be supplemented by one or two percutaneously placed smooth K-wires, traversing the radiocarpal joint and osteotomy site in an oblique fashion (Figure 23-3C). The joint capsule is then imbricated and reapproximated using interrupted sutures (Vicryl, Ethicon, Inc., Somerville, NJ), supplementing the prior suture and pin fixation. Extensor tendons are relocated and the overlying retinaculum repaired. Subcutaneous tissues and skin are closed in layers, followed by application of a bulky soft dressing and bivalved cast.

In cases with extreme and rigid flexion deformity, the tight volar structures must be released and/or transferred to achieve adequate correction. In these situations, a volar longitudinal incision is made in the distal forearm overlying or just ulnar to the palmaris longus (PL) tendon. After skin flaps are raised, the PL tendon is transected (or less commonly Z-lengthened or transferred). Musculotendinous fractional lengthenings or intratendinous Z-lengthenings of the wrist flexors and/or digital flexors may need to be performed to obtain correction. Flexor lengthenings carry the risk of weakening grip strength in an already compromised patient. Furthermore, to assist with active wrist extension and perhaps prevent recurrent deformity, an extensor carpi ulnaris (ECU) or flexor carpi ulnaris to wrist extensor (ECRB or ECRL) tendon transfer may be performed in conjunction with the carpal wedge osteotomy. Problems with transfers include a lack of excursion and insufficient strength to be functional. Some of these transfers are, at best, tenodesis procedures.

Cast immobilization is typically discontinued at 4 weeks postoperatively, at which time the percutaneous K-wire(s), if present, are removed. Patients are transitioned to a removable splint and instructed on gentle range-of-motion exercises from the 4th to 6th postoperative week. Once radiographic healing is confirmed, more aggressive passive and active motion are pursued with the assistance of skilled therapy.

◆ Correction of Syndactyly and Thumb-in-Palm Deformity

The arthrogrypotic hand is characterized by stiff, flexed, "wax candle" digits and thumb-in-palm deformity. In some situations, there may be syndactyly between the short, abnormal fingers. Grasp, release, and pinch are all limited by these deformities, presenting great frustration to the patients, families, and treating surgeons. In patients with persistent functionally limiting deformities despite therapy and splinting, surgery may be considered to improve the position and function of the thumb and fingers.

It is not possible to restore normal digital motion and strength in patients with flexed, stiff, underdeveloped digits. Frank discussion with patients and families is needed to impart realistic expectations. In severe cases of camptodactyly, volar Z-plasties and/or full-thickness skin grafting combined with flexor digitorum superficialis (FDS) tenodeses transfer to the extensor mechanism or dorsal closing wedge osteotomies of the phalanges may provide improved resting position of the digits.[26] In general, simple dorsal capsulotomy and transient proximal interphalangeal (PIP) joint pinning results in early recurrent deformity.[20,27] More often than not, however, emphasis is placed on stretching out the MCP joints and improving thumb position. Syndactylies are reconstructed with techniques described in Chapter 2.

The thumb typically is positioned in metacarpal adduction and MCP flexion, with associated MCP joint laxity and hypoplasia of the thenar muscles.[28] First web-space deepening is typically performed to address the static thumb-in-palm deformity. Two-part or four-part Z-plasties may be utilized to release the tight first web skin. Through this skin incision, the tight fascia of the first dorsal interosseous and adductor pollicis may be released. In efforts

to maintain the correction achieved, opponensplasty using the FDS to the ring finger may be performed if there is sufficient FDS excursion and strength. If an adequate first web space can be reconstituted after these steps, flap closure is performed. Often, the volar skin overlying the thumb MCP joint may be deficient, and rotation flaps from the index have been proposed to address these soft tissue coverage issues.[29]

In cases where there is persistent thumb metacarpal adduction, additional steps are needed to correct thumb position. The thenars may be released from their origin via a separate incision along the thenar crease.[19] After identification and protection of the recurrent motor branch of the median nerve, the abductor pollicis brevis, flexor pollicis brevis, and opponens pollicis origins are then sharply released from their origins. Alternatively, an abduction-extension osteotomy may be performed at the base of the thumb metacarpal (while avoiding the physis) via a separate radial incision along the junction between the glabrous and nonglabrous skin, centered on the base of the thumb ray.[27,30,31]

◆◆ Elbow Tendon Transfers

In cases where passive elbow motion is achieved via therapy or operative releases, additional surgical procedures to provide active elbow flexion may provide further functional benefit.[32–34] A host of surgical procedures have been advocated, including triceps to biceps transfers, the Steindler flexorplasty, unipolar and bipolar pectoralis major transfers, bipolar latissimus dorsi transfers, and free functional gracilis transfers.[34–41] Unfortunately, all of these options have had problems, including limitations in assessing donor strength preoperatively, poor transfer function, diminishing transfer function over time, muscle imbalance, and resultant elbow flexion deformity.[35] These surgeries are not easy to perform; recovery is prolonged; and intensive rehabilitation is required. Obviously it is a major disappointment if an elbow flexion transfer fails to improve the patient's condition or, worse, leads to deterioration of function. At present, the transfer with a reasonable chance of success and least risk of complications is the partial triceps transfer.

Isolated long head of triceps to biceps (or to coronoid process or radial neck if no biceps tendon is present) transfers offer a number of theoretical advantages. First, the long head of triceps is anatomically distinct with an independent neurovascular pedicle allowing for surgical harvest and transfer.[19,42] Second, transfer of a part of the triceps allows for continued active elbow extension and potentially reduces the risk of postoperative elbow flexion deformity. Finally, prior clinical studies have demonstrated the ability of the long head to be activated independently from the other elbow extensors, facilitating its functional role.[43]

Surgery is performed under general anesthesia in the supine or lateral decubitus position, allowing for access to the ipsilateral upper limb and shoulder girdle.[35] A longitudinal incision is made along the posterior aspect of the brachium, which is curved medially around the olecranon process to avoid scar irritation. Skin flaps are carefully raised, and the ulnar nerve is identified, dissected free, and transposed. The long head of the triceps muscle is more easily identified in the proximal portion of the surgical exposure and may thus be separated from the underlying medial and adjacent lateral heads. Distally, the conjoined triceps tendon is identified and the medial third of the tendon sharply harvested with the long head of triceps muscle belly. (Often the triceps tendon distally is taken with periosteum and a strip of ECU fascia in an effort to provide additional length for the subsequent transfer.)

Once liberated, the long head of triceps tendon may be tagged and/or tabularized with a 2-0 or 3-0 nonabsorbable braided suture (Ethibond, Ethicon, Inc., Somerville, NJ). The medial skin flap is raised to allow access around the elbow to the anteromedial aspect. The previously tagged tendon is then passed to the level of the anteromedial proximal ulna, at or just distal to the coronoid process. The tendon may then be fixed to the ulna with periosteal sutures, osseous suture anchors, or bone tunnels with the elbow held in 90 degrees of flexion. After the transfer is complete, the wound is closed in layers, followed by application of a bulky soft bandage. The limb is then placed in a bivalved long-arm cast flexed 90 degrees for 4 weeks postoperatively. Following this, splinting and therapy are initiated. Splinting is continued intermittently until there is active control of the transfer.

POSTOPERATIVE

For elbow releases and triceps lengthenings, carpal wedge osteotomies, and tendon transfers about the elbow and hand, long-arm cast protection is maintained for 4 weeks followed by protective splinting until active control is achieved. Syndactyly surgery is protected for 2 weeks followed by splinting and therapy.

ANTICIPATED RESULTS

While none of the interventions described here result in normal upper limbs, surgical treatment of arthrogryposis can result in improvements in upper extremity position, motion, and use. Elbow releases and V-Y triceps lengthening reliably and safely improve passive elbow motion. Van Heest et al.[44] have reported on 29 elbows in 23 patients treated at two pediatric specialty care centers. The average age at surgery was just under 3 years. Passive elbow range of motion had improved from 32 degrees preoperatively to 66 degrees at mean 5.4 years follow-up. All were able to passively place their hands to their mouths, and none went on to subsequent tendon transfer surgery. Additional tendon transfers may improve upper extremity function in

patients with supple passive elbow motion and sufficient donors, particularly in patients over 4 years of age with dominant limb involvement.[33]

Ezaki and Carter[25] previously reported their results of carpal wedge osteotomy in 42 wrists of 24 patients. All osteotomies went on to successful bony healing. Average resting position of the wrist improved from 58.5 to 11.2 degrees of flexion, though the arc of passive wrist motion decreased overall by 10 degrees.

Results following surgical correction of hand and thumb involvement have been less encouraging. Yonenobu et al.[27] reported on 13 hands treated for thumb-in-palm deformity with combinations of Z-plasties, opponensplasties, tenodeses, and joint procedures. While all reportedly gained improved function, and cylindrical grasp was improved, range of thumb motion was not significantly altered. Recurrent thumb-in-palm contractures are common with Z-plasty releases alone.[20,27] In the same series of patients, eight hands underwent attempted correction of PIP joint flexion contractures. Interestingly, flexion did not improve, and extension improved modestly from an average of –65 degrees preoperatively to 33 degrees postoperatively. Others have had even more discouraging results from surgical attempts to improve IP joint motion.[20]

COMPLICATIONS

As with almost all neuromuscular conditions, complications may occur following upper limb surgery for arthrogryposis. Incomplete improvement in joint motion or resting position may be seen due to technically inadequate releases, suboptimal postoperative therapy and splinting, or unrecognized bony deformity unamenable to soft tissue correction. Neurovascular compromise may similarly occur, particularly in cases of aggressive joint releases performed without skeletal shortening.

Most commonly, the problem is failure to achieve the desired goal. This is particularly a worry with tendon transfer surgery. Ultimately antigravity strength and adequate active motion to improve function is desired. This is not always achievable, even when the patient, family, surgeon, and therapist do their best and "what is asked of them."

CASE OUTCOME

This patient underwent posterior elbow capsular release with V-Y triceps lengthening shortly after 2 years of age (similar to Figure 23-2). After postoperative casting and continued, aggressive therapy, passive elbow flexion improved to 85 degrees, allowing for tabletop positioning and additional functional use of the upper limbs. Although no active elbow flexion was seen, no additional procedures have been recommended as of yet to improve elbow motion.

SUMMARY

The treatment of arthrogryposis remains a challenge to the pediatric hand and upper extremity surgeon. To date, no solutions have been proposed that can correct or reverse the fundamental underlying cause of weakness and joint contractures in these patients. The importance of maximizing motion and function with therapy, splints, and assistive devices at an early age cannot be overstated. Surgical treatments to improve elbow motion, wrist position, and thumb position may provide improved hand and upper limb use to allow for independence.

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CHAPTER
24

Sternoclavicular Joint Injuries

CASE PRESENTATION

A 16-year-old right hand–dominant male presents for evaluation of right shoulder and chest discomfort after being checked into the boards during an ice hockey game. He has tenderness and swelling over the medial clavicle, and he reports some mild discomfort while swallowing. His parents report that his voice "sounds hoarse." Neurovascular examination of the right upper limb and hand is normal. A clavicle x-ray is taken and interpreted as being normal. Subsequent imaging identifies a posteriorly displaced sternoclavicular dislocation (Figure 24-1). A pediatric hand and upper extremity surgery consultation is requested.

CLINICAL QUESTIONS

- How do sternoclavicular joint (SCJ) injuries present?
- What are the anatomic stabilizers of the SCJ?
- How is the SCJ best evaluated radiographically?
- How are SCJ injuries classified?
- What are the indications for surgical treatment of SCJ injuries?
- How is surgical reduction and stabilization of acute SCJ injuries performed?
- What are the surgical techniques for chronic SCJ instability?
- What are the expected outcomes and potential complications of surgical treatment?

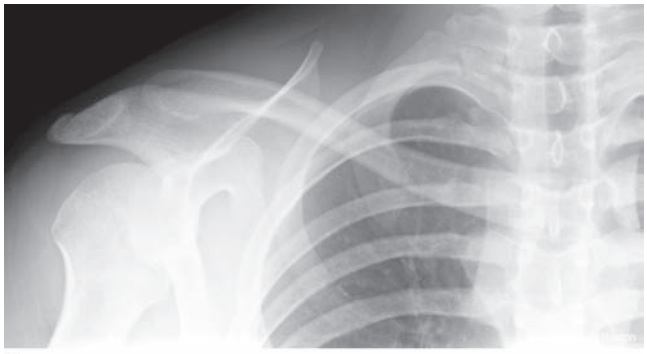
THE FUNDAMENTALS

The real superstar is a man or a woman raising six kids on $150 per week.
—Spencer Haywood

Fractures and dislocations of the SCJ are unusual but potentially devastating injuries in children and adolescents. Historically, most injuries have been observed or treated nonoperatively. Prior treatment principles were undoubtedly based upon fear of iatrogenic injury to adjacent anatomic structures and false assumptions regarding remodeling and longer term outcomes. Better understanding of the pathoanatomy, natural history, potential outcomes, and surgical reconstructive strategies of SCJ injuries has improved our ability to restore more normal shoulder girdle anatomy and mechanics in efforts to improve functional outcomes. We advocate surgical reduction and stabilization of acute traumatic posteriorly displaced SCJ injuries, as well as ligament reconstruction in cases of chronic post-traumatic instability associated with pain and functional limitations refractory to activity modification and therapy.

Etiology and Epidemiology

Fracture dislocations to the SCJ are uncommon injuries, representing <5% of shoulder girdle injuries.[1,2] Usually arising from high-energy mechanisms of injury (e.g., falls from a height, motor vehicle collisions, sports-related injuries), both direct and indirect trauma to the ipsilateral shoulder may result in SCJ injuries. Obtaining a history of prior trauma is critical, as atraumatic cases of SCJ instability do occur—particularly in children and adolescents—and the natural history and results of treatment are quite different than in traumatic cases.[3,4] In the majority of cases, displacement of the medial clavicle is anterior, typically resulting from a direct lateral blow to the shoulder with the shoulder extended. Posterior displacement is less common, usually resulting from indirect forces imparted on the shoulder girdle with the shoulder adducted and flexed or from a direct posterior blow to the medial clavicle.



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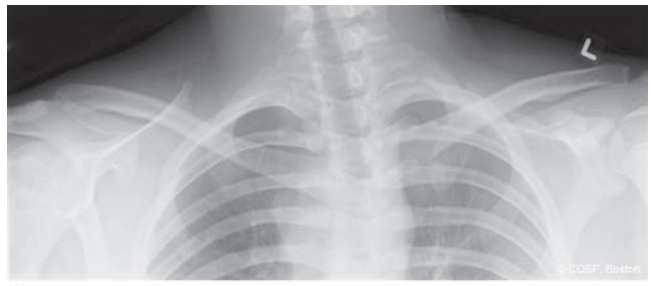

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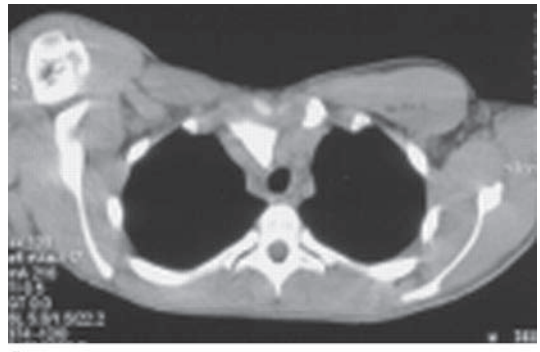

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FIGURE 24-1 Acute traumatic posterior SCJ dislocation. **A:** Anteroposterior clavicle x-ray demonstrates no obvious abnormalities. **B:** Serendipity view demonstrates asymmetry of the SCJ with posterior translation of the right clavicle. **C:** CT scan clearly demonstrates a posteriorly displaced medial clavicle.

Clinical Evaluation

Clinical complaints and physical examination findings depend upon the pattern of injury. With traumatic anterior displacement, patients will often present with pain localized to the SCJ, tenderness, ecchymosis, and an obvious bony prominence of the clavicular head (Figure 24-2). Ranging the shoulder causes pain and/or sensation of instability. Typically, there is no associated neurovascular compromise. However, most anterior SCJ dislocations or recurrent instability are atraumatic. The atraumatic anterior dislocators will not have swelling or ecchymosis but obvious instability on exam.

Conversely, physical examination findings in patients with posterior SCJ injuries may be subtle. While swelling and tenderness may be seen, often there is no obvious deformity. Posterior displacement increases the risk of mediastinal compression, and some patients may have dyspnea, dysphagia, odynophagia, or hoarseness.[5] In rare situations, signs of venous congestion, arterial insufficiency, or brachial plexopathy may be seen. A high index

A

B

FIGURE 24-2 Anteriorly displaced SCJ injury. **A:** Frontal and **B:** tangential clinical views of a left anteriorly displaced medial clavicle.

of suspicion is critical for accurate diagnosis and timely intervention.

Radiographic evaluation of the SCJ can be challenging, owing to the anatomy of the SCJ and overlying/adjacent skeletal structures. An AP chest radiograph may demonstrate asymmetry of clavicular length and abnormalities in the SCJ articulation, though these findings may be subtle. Dedicated radiographs of the clavicle are centered on the clavicular diaphysis and often lack the detail needed to make the diagnosis. For this reason, a number of dedicated views have been proposed to image the SCJ (Figure 24-3). Heinig has previously proposed a tangential radiograph of the SCJ, taken with the patient supine and the cassette placed behind the opposite shoulder.[6] The beam is angled in the coronal plane, parallel to the longitudinal axis of the opposite clavicle, providing a profile of the affected SCJ. Hobbs has proposed a 90-degree cephalocaudal lateral, taken with the patient seated and flexed over a table.[7] The cassette is placed on the table, against the chest wall, and the beam is directed through the cervical spine. Finally, Rockwood has reported on the use of the "serendipity view," so called due to the fact that its utility was discovered quite by accident.[2] With the cassette placed behind the chest, the radiographic beam is angled 40 degrees cephalic centered on the sternum, allowing for visualization of both SCJs. In cases of anterior dislocation, the affected clavicular head will appear superiorly displaced compared to the unaffected side. Conversely, with posterior displacement, the medial clavicle will appear inferior.

Given the difficulties with plain radiography in imaging the SCJ, three-dimensional imaging with the use of CT scans has increasingly become the standard of care for radiographic diagnosis (Figure 24-1C). With improved resolution and imaging techniques, the distinction between physeal fractures and true joint dislocations may be made (Figure 24-4). Furthermore, simultaneous assessment of compression or injury to the adjacent soft tissue structures (e.g., esophagus, trachea, brachiocephalic vessels) may be made.

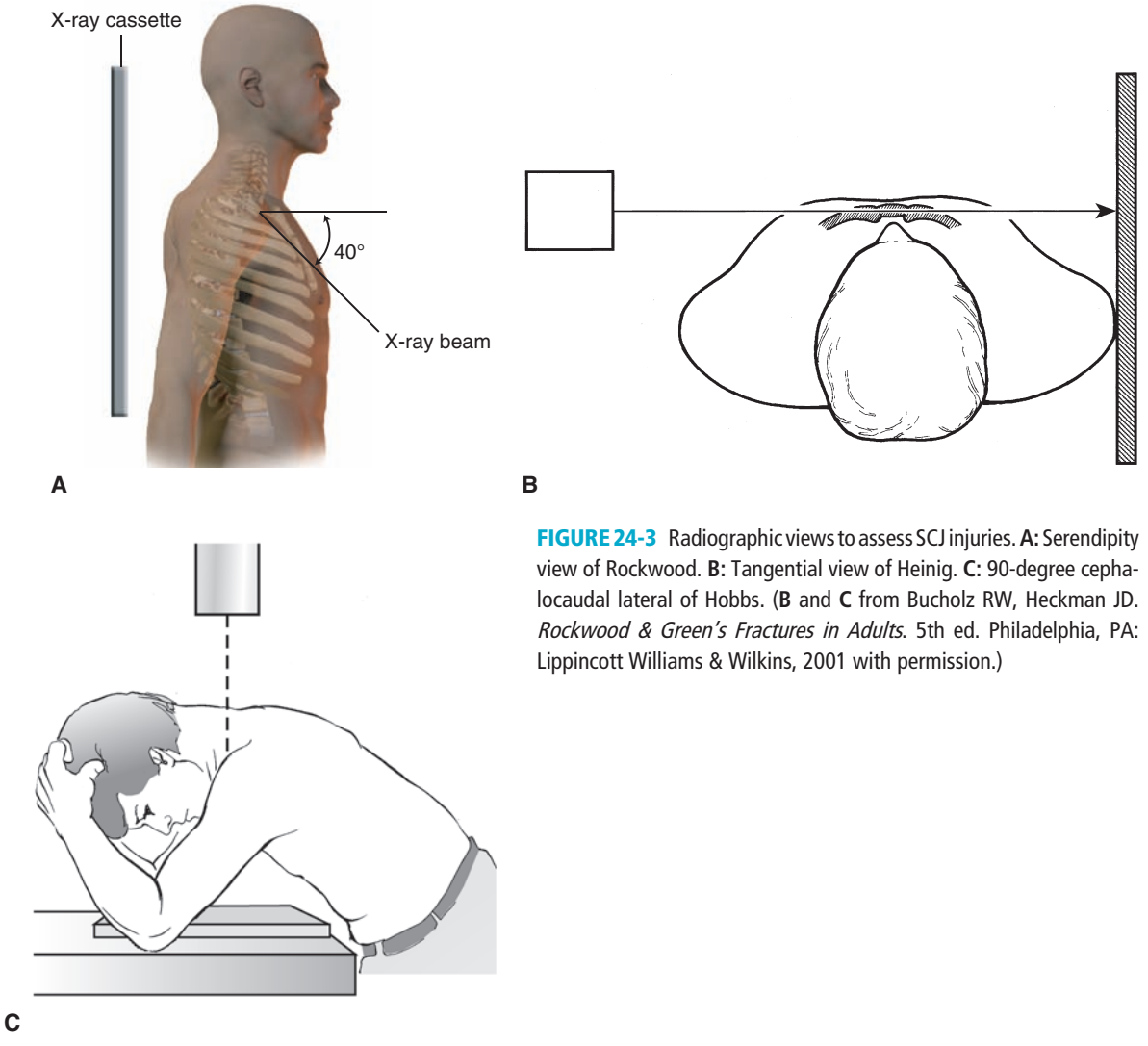
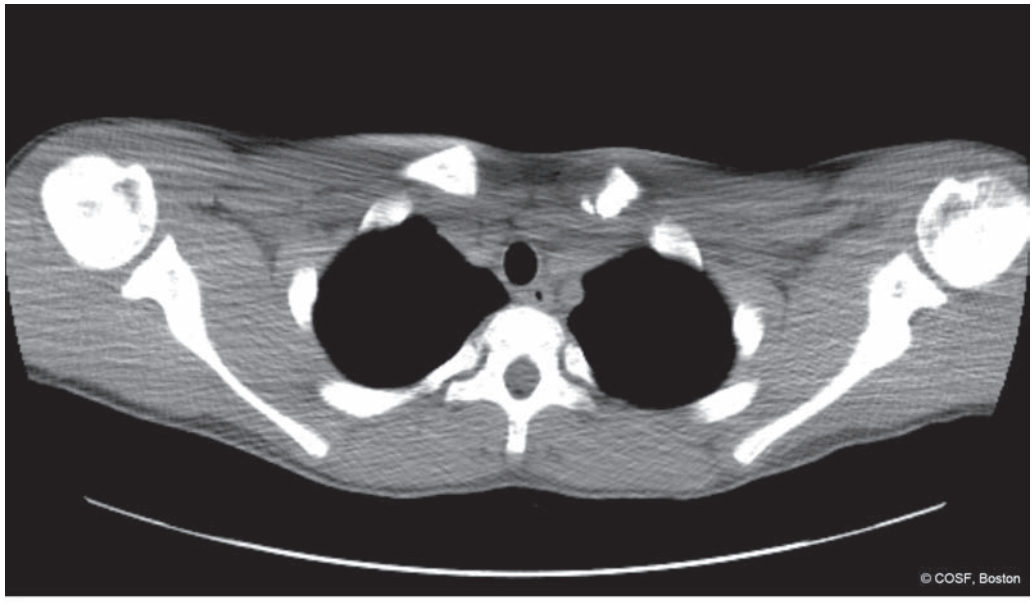


FIGURE 24-3 Radiographic views to assess SCJ injuries. **A:** Serendipity view of Rockwood. **B:** Tangential view of Heinig. **C:** 90-degree cephalocaudal lateral of Hobbs. (**B** and **C** from Bucholz RW, Heckman JD. *Rockwood & Green's Fractures in Adults*. 5th ed. Philadelphia, PA: Lippincott Williams & Wilkins, 2001 with permission.)



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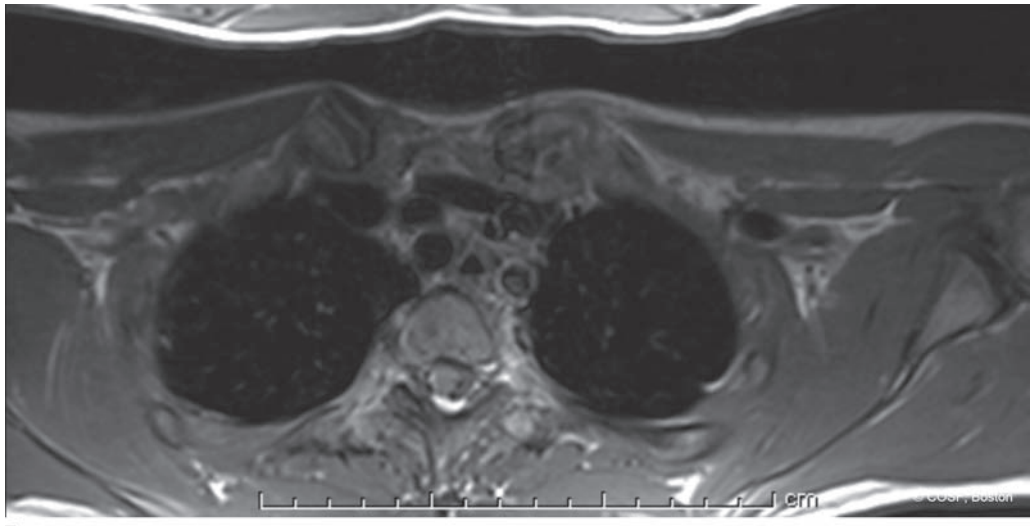

B

FIGURE 24-4 Medial clavicle fracture. **A:** Axial CT scan demonstrates an apparent displaced left medial clavicle fracture. **B:** Axial MRI scan demonstrates a medial clavicle fracture with a congruently reduced SCJ.

Surgical Indications

In general, a number of principles guide the treatment of SCJ fracture dislocations (Figure 24-5). First, the acuity or chronicity of an injury must be considered, as nonoperative or surgical treatment options are influenced by the time from initial injury. Second, the direction of displacement must be taken into consideration. While anterior injuries may cause little pain or functional compromise, posteriorly displaced injuries may result in compression of the adjacent mediastinal structures. Third, the severity of symptoms, if any, must be noted to weigh the risks and benefits of intervention. Finally, patient demands play an important role in the decision-making process, particularly in laborers or overhead athletes.

Unfortunately, there is a paucity of information regarding the natural history of untreated SCJ injuries. For this reason, treatment recommendations and results of surgical intervention have not been carefully compared with the natural history of the condition. As a result, symptomatic relief and avoidance of acute or late complications remain the factors driving treatment recommendations. In particular, unrecognized or untreated traumatic posterior SCJ injuries may lead to a host of potentially devastating complications. Tracheal stenosis, esophageal compression, pneumothorax, great vessel compromise, brachial plexopathy, thoracic outlet syndrome, sepsis, and even death have been reported in these instances. Furthermore, many

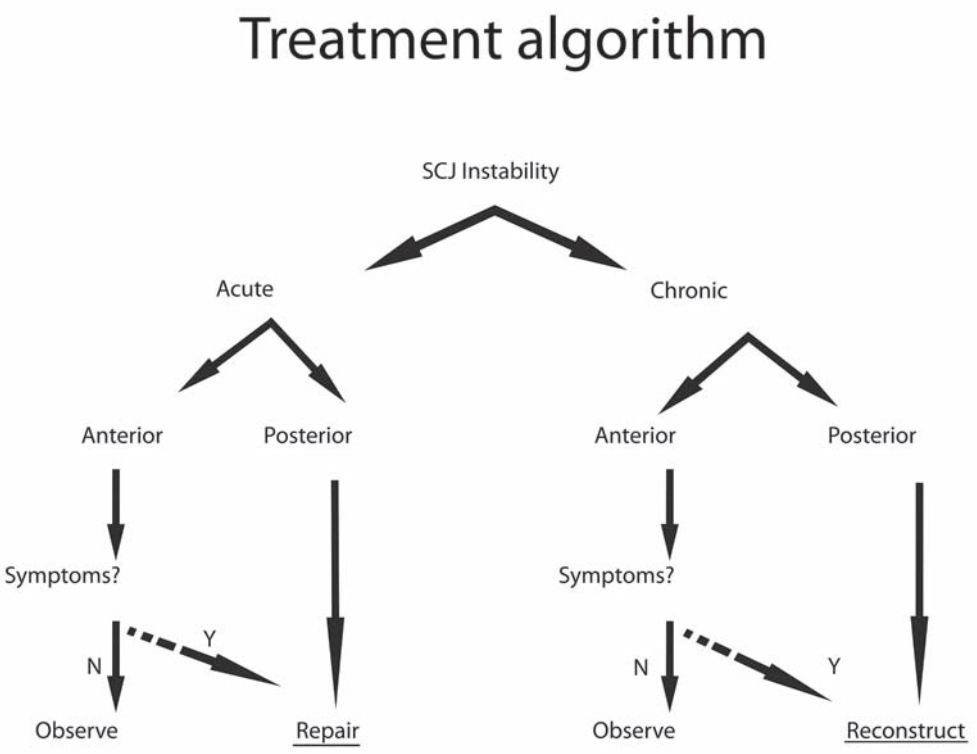

FIGURE 24-5 Proposed treatment algorithm for traumatic SCJ injuries.

of these complications can be seen in initially asymptomatic patients.[5]

Based upon these considerations, we believe indications for surgical treatment of SCJ injuries include (1) acute, traumatic posteriorly displaced injuries and (2) chronic, recurrent instability with pain and functional limitations despite activity modification and physical therapy. Surgical treatment is resisted in patients with atraumatic or voluntary anterior SCJ instability until there clearly is no other alternative (see Coach's Corner).

SURGICAL PROCEDURES

In general, surgical procedures for SCJ injury fall into one of three categories: repair, reconstruction, or resection. Each has advantages and disadvantages, and the choice of surgical technique is driven by the chronicity of instability, the direction of displacement, and the status of the articular surfaces of the clavicle and sternum.

Observation of Acute Anterior Dislocation

The optimal treatment of *acute anterior* SCJ fracture dislocations is controversial. Symptomatic management alone with sling immobilization followed by gradual return to activities has been advocated with the expectation of return of shoulder motion and strength.[8] Patients should be counseled about the likelihood of a persistent bony prominence in the region of the clavicular head. In young patients with physeal fractures, remodeling of bony deformity may be seen with continued skeletal growth. Others have recommended closed reduction under conscious sedation or general anesthesia. Reduction maneuvers involve scapular retraction and posteriorly directed pressure over the medial clavicle, followed by application of a figure-of-eight strap. While reduction may often be achieved, recurrent instability is commonplace. Surgical techniques of open reduction and ligament repair or reconstruction are not routinely utilized in acute, traumatic cases. Again, closed reduction maneuvers or surgical reconstructions should be generally avoided in patients with atraumatic or voluntary anterior SCJ instability. Our preference is to treat anteriorly displaced injuries symptomatically with sling immobilization and observation.

ORIF of Acute Posterior Dislocation

Treatment considerations are different for *acute posterior* SCJ fracture dislocations, in part due to the potentially disastrous sequelae of unreduced posterior injuries. Closed reduction has been proposed by many as definitive, particularly given the remodeling potential of the medial clavicle and thus its ability to accept a nonanatomic reduction.[2,9] Closed reduction is typically performed under general anesthesia via manipulation of the shoulders with abduction-traction, adduction-traction, or scapular

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retraction. Percutaneous techniques of controlling the medial clavicle (e.g., towel clip or screw) during reduction maneuvers have been advocated. More recent information, however, suggests that while an initial reduction may be achieved, recurrent instability is very common.[5,10,11] Furthermore, the safety of percutaneous techniques is a concern, given the proximity of the medial clavicle to the mediastinal structures. For these reasons, we advocate formal open reduction and suture fixation, with or without ligament repair or reconstruction, for acute posterior SCJ injuries (Figure 24-6).

Under general anesthesia and with appropriate general surgery or thoracic surgery backup, patients are placed in the modified beach chair position with a rolled towel or bump between the scapulae to facilitate scapular retraction. The affected upper limb and entire hemithorax is prepped and draped into the surgical field. A transverse incision centered on the SCJ is utilized, and the platysma is divided in line with the surgical incision. Subperiosteal elevation is performed in a lateral-to-medial direction over the clavicle, allowing for both clavicular head and SCJ exposure. The clavicle diaphysis is clear centrally. Dissection medially will reveal the medial clavicle disappearing into the chest. Fortunately, the posterior periosteum is almost always intact and protective in adolescents. Diagnosis of a true joint dislocation versus physeal fracture is made after inspection of the zone of injury. Using gentle manipulation, the dislocation or fracture may be anatomically reduced. A small towel clip or fracture reduction clamp is used during clavicular mobilization and scapular retraction to assist in the reduction maneuver. After extraction of the clavicle from the mediastinum, a quick conference is held with the anesthesiologist to make certain hemodynamic stability is maintained. Awareness of the normal anatomy is critical, as

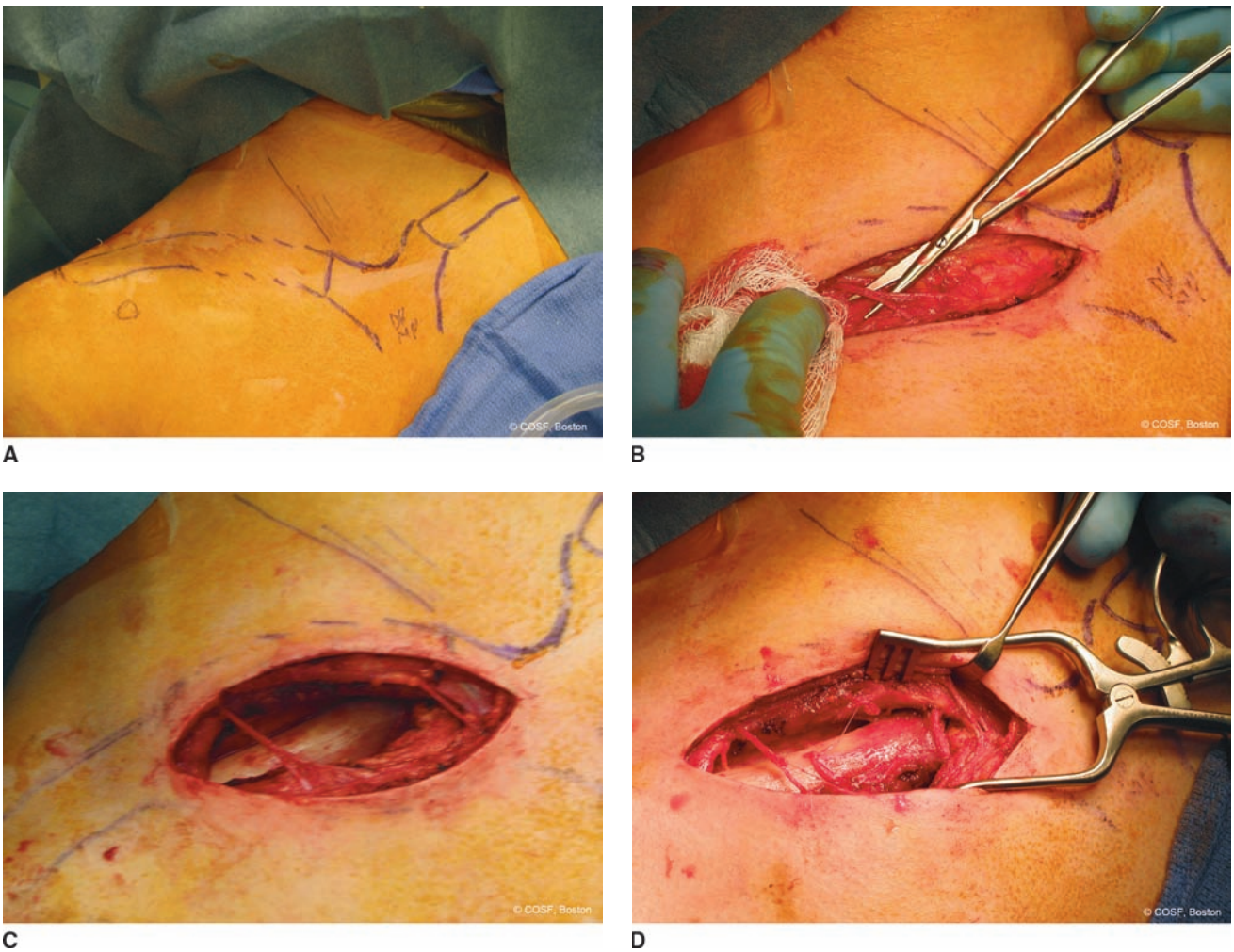

FIGURE 24-6 Surgical reduction and stabilization of the acute posterior SCJ fracture dislocation. **A:** The patient is placed in the modified beach chair position and the ipsilateral limb and chest wall are prepped into the surgical field. Surgical landmarks are palpated and marked. **B:** Through a transverse incision, the supraclavicular nerves are identified and protected. **C:** After incising the deltotrapezial fascia, the clavicle is subperiosteally exposed laterally and followed medially to expose the posterior SCJ injury. **D:** Gentle traction will allow for SCJ reduction.

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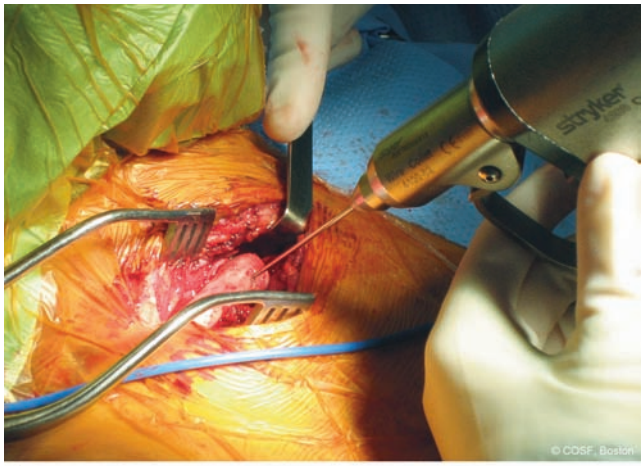

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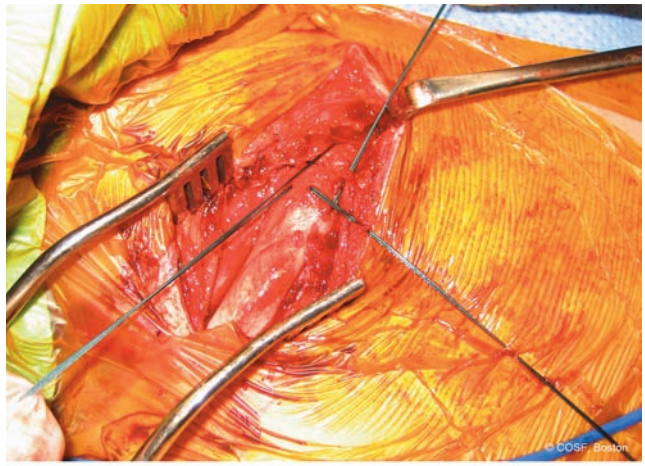

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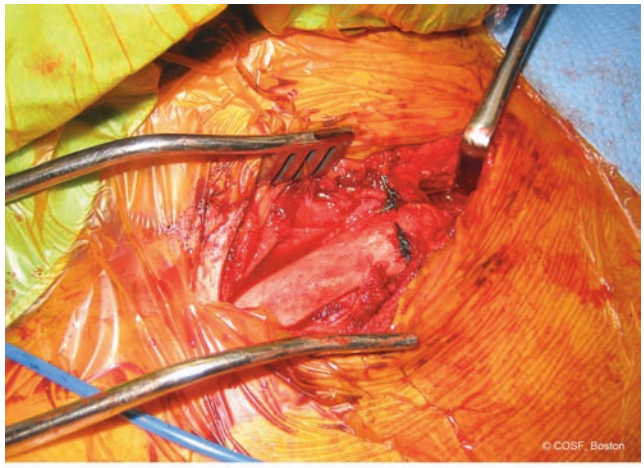

G

FIGURE 24-6 *(continued)* Surgical reduction and stabilization of the acute posterior SCJ fracture dislocation. **E:** Drill holes are created in the medial clavicle and sternum (or medial clavicular metaphysis and clavicular epiphysis, in cases of physeal fractures). **F:** Heavy nonabsorbable sutures are passed in a figure-of-eight fashion through the drill holes. **G:** The sutures are tied with the joint reduced, completing the stabilization.

the clavicular head only partially seats into the clavicular notch of the manubrium. In cases of physeal fractures, drill holes are created into both the medial clavicular metaphysis and epiphysis, and heavy nonabsorbable sutures are passed in a figure-of-eight fashion to provide stability. In cases of SCJ dislocations, primary repair of the costoclavicular and sternoclavicular ligaments may be performed, followed by bony stabilization with sutures passed through the anterior manubrium and medial clavicle epiphysis using the technique described above. Smooth pins, screws, and Dacron tape are avoided to prevent complications of implant migration and osteolysis.[12–14] Stability is assessed intraoperatively by ranging the ipsilateral shoulder and upper limb. The surrounding periosteal sleeve is reapproximated with heavy absorbable sutures, and the skin and subcutaneous tissues are closed in layers while protecting the cutaneous nerves. Patients are immobilized in sling and swathe postoperatively.

Medial Clavicle Resection Arthroplasty

Medial clavicular resection with ligament reconstruction or soft tissue interposition has been advocated, particularly in the setting of bony changes or joint arthrosis precluding anatomic SCJ reduction[15–19] (Figure 24-7). This scenario is seen in long-standing post-traumatic instability, sometimes in recurrent atraumatic instability, as well as in rare situations of inflammatory arthritis, prior septic arthritis, or systemic conditions such as neurofibromatosis or osteochondromatosis. Via a curvilinear incision centered on the SCJ, the skin and joint capsule are incised. Approximately 1 cm of the prominent medial clavicle is resected obliquely, preserving the inferior ligamentous attachments. The intra-articular disk is identified, and while preserving its attachment to the sternum, the superior end is passed into the intramedullary canal of the clavicle and subsequently secured via sutures tied

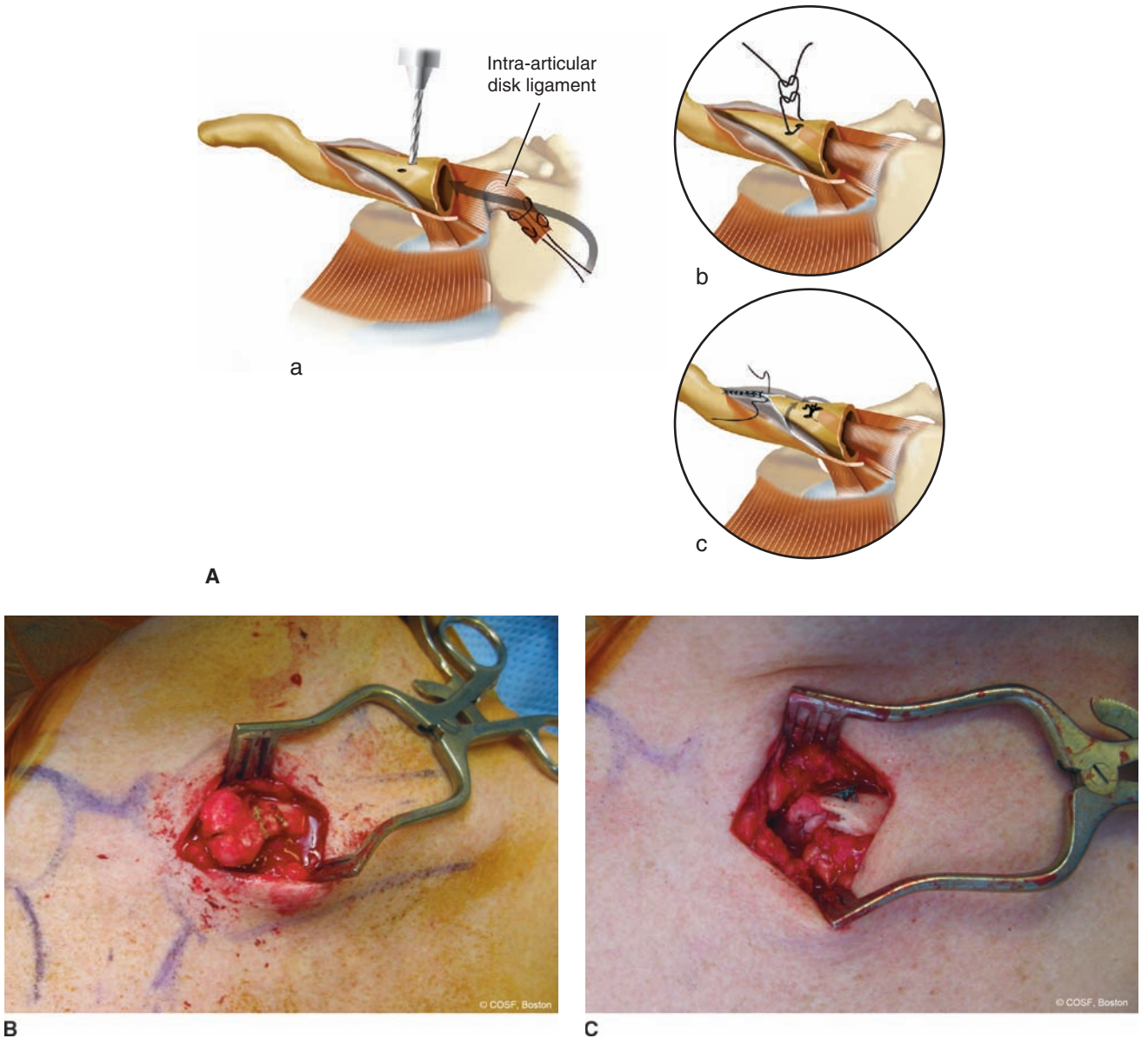

FIGURE 24-7 Medial clavicular resection arthroplasty. **A:** Schematic diagram depicting the technique of medial clavicular resection arthroplasty. **B:** Intraoperative photograph of a patient with symptomatic recurrent anterior SCJ instability associated with a deformed and irreducible clavicular head. **C:** After clavicular head resection and intramedullary passage of the intra-articular disk ligament, the resection arthroplasty is complete.

over drill holes. Stability is supplemented by sutures passed from the preserved costoclavicular ligament to the clavicle. Motion is checked to be certain there is no impingement or instability and that sufficient bone has been resected. The capsule and subcutaneous tissues are closed in layers, and sling-and-swathe immobilization is used postoperatively. While some have reported satisfactory results with resection arthroplasty following the principles listed above, others have reported suboptimal outcomes.[16,19,20] For this reason, we consider resection arthroplasty a salvage procedure and attempt ligament repair/reconstruction if possible.

◆ Recurrent Anterior Instability

If you want to increase your success rate, double your failure rate.
—Tom Watson

Symptomatic *chronic anterior instability* is an uncommon problem. Patients will present with pain, "clicking," or "popping" with shoulder motion and limitations with away from body or overhead activities. Nonoperative treatment modalities, including physical therapy, are the treatment of choice and will help the majority of patients. Therapy should

Table 24.1

Treatment options for symptomatic chronic SCJ instability

Medial clavicular resection arthroplasty
Open reduction and SCJ capsulorrhaphy
Open reduction and ligament reconstruction
Subclavius tendon
Intra-articular disk
Figure-of-eight tendon graft
Plate fixation

incorporate biofeedback techniques and emphasize scapulothoracic mechanics to promote scapular retraction and avoid provocative positioning. In cases of failed nonoperative therapy, surgical treatment may be considered (Table 24.1).

A number of techniques have been proposed for anatomic ligament reconstruction in cases of chronic anterior instability. Tenodesis using the subclavius tendon, intra-articular disk ligament reconstruction, and figure-of-eight tendon reconstructions using hamstring tendon autograft or allograft have all been advocated[21,22] (Figure 24-8). Prior biomechanical testing has demonstrated that figure-of-eight tendon graft reconstructions provide the strongest restraints to anterior and posterior loading of the SCJ.

Via a transverse skin incision and following exposure of the SCJ, drill holes may be created in the medial clavicle and manubrium while protecting the adjacent mediastinal structures. Small malleable ribbon or blunt Hohmann retractors are helpful to provide adequate exposure and protect the nearby mediastinal structures. Semitendinosus autograft or allograft (preferred) is then passed through the drill holes in a figure-of-eight fashion, ensuring that the parallel fibers lie on the side of instability and the crossed tendon lies opposite the direction of instability. As with other ligament reconstruction techniques, sutures may be passed first and used to shuttle the tendon graft through the drill holes. After satisfactory joint reduction, the graft limbs may be secured to one another with nonabsorbable sutures, avoiding overtightening of the reconstruction. The deep tissues are closed in layers, and patients are sling-and-swathe immobilized postoperatively.

◆ Reconstruction of Chronic, Painful Posterior Fracture-Dislocation

Patients with chronic posterior SCJ fracture dislocations and pain present the most challenging reconstructions. Surgical reduction and stabilization are recommended to alleviate pain and also to avoid the adverse sequelae of chronic posterior injuries. Technical challenges include scar formation and periosteal bone or fracture callus formation throughout the zone of injury, causing difficulties with surgical exposure, clavicular mobilization, and congruent joint reduction.

Surgery is again performed in the modified beach chair position with wide access to the shoulder girdle, ipsilateral upper extremity, and chest. A transverse incision centered upon the SCJ is utilized and dissection carried down to the joint through the deltotrapezial fascia. Starting first with the more lateral clavicular diaphysis, subperiosteal elevation and

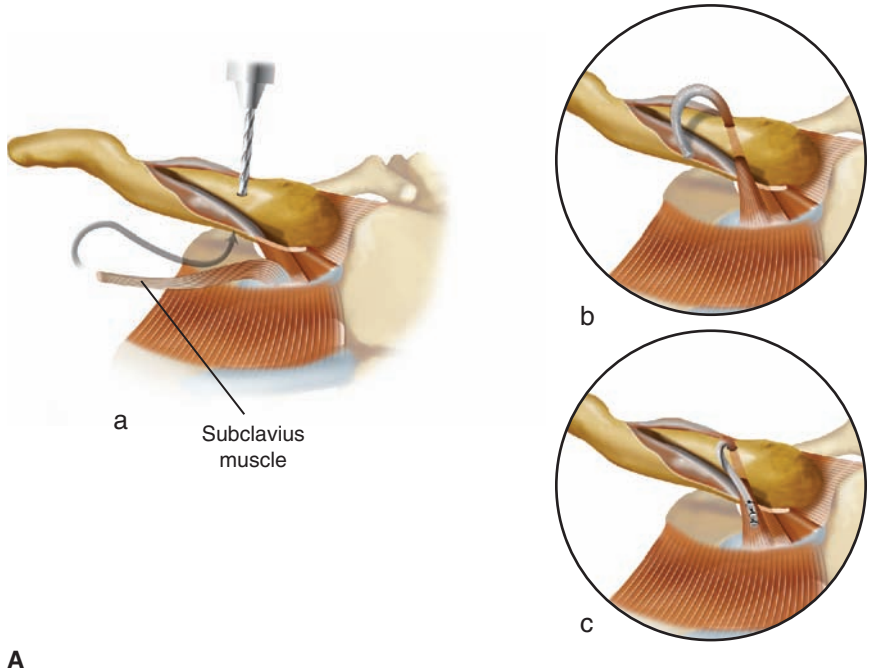

FIGURE 24-8 Ligament reconstruction for chronic SCJ instability. **A:** Diagram of the subclavius tenodesis technique.

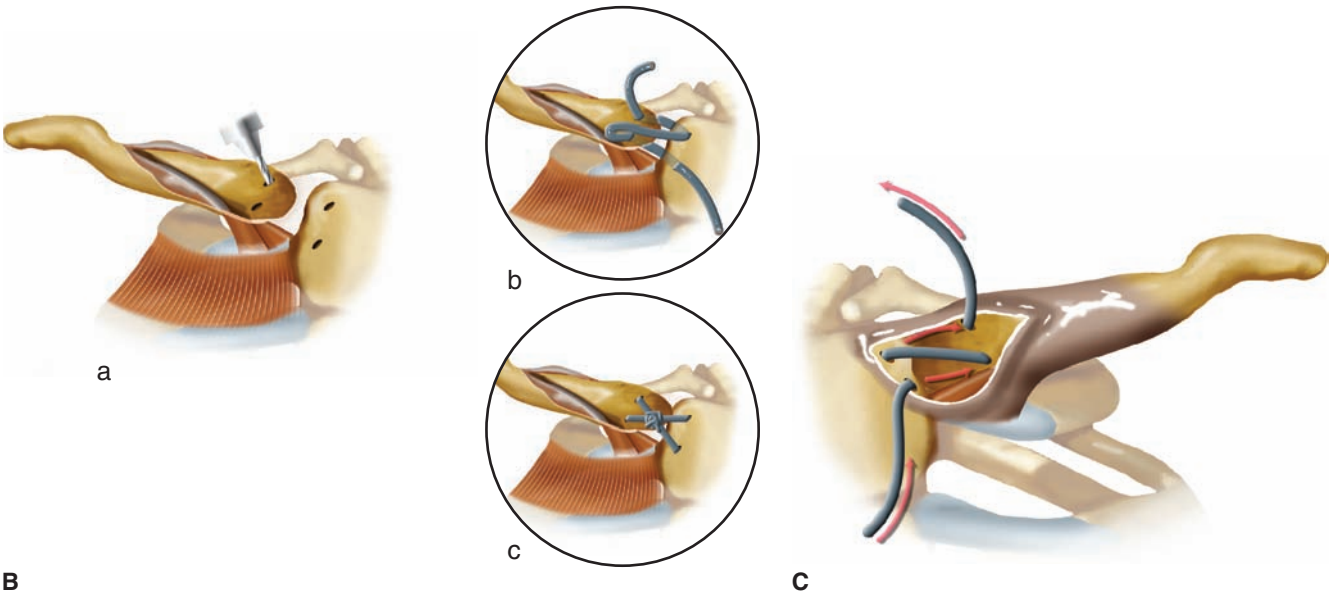

FIGURE 24-8 *(continued)* **B:** Diagram of ligament reconstruction using tendon graft passed in a figure-of-eight fashion. **C:** Illustration of graft passage during reconstruction of chronic posterior SCJ instability.

dissection are performed in a lateral-to-medial direction until the posteriorly displaced clavicular head is identified. In cases of displaced physeal fractures, careful bony resection is performed of the fracture callus and bony prominences along the posterior aspect of the clavicle, with judicious retraction and protection of the adjacent soft tissues. Use of malleable ribbon retractors, small, blunt Hohmann retractors, or small, curved Bennett retractors can be very useful. Following medial clavicular mobilization, if the joint is reducible, repair or reconstruction using the above-stated techniques is performed. Stability is confirmed on the table with shoulder range of motion and direct lateral blows to the shoulder girdle. The SCJ capsule and periosteum are anatomically closed in layers and the limb immobilized in sling and swathe.

POSTOPERATIVE

Postoperatively, patients are immobilized with sling and swathe, and postoperative CT scans may be performed to confirm anatomic reduction. The shoulder is immobilized for 4 to 6 weeks, followed by range-of-motion exercises. Strengthening is initiated at 3 months. Contact sports are restricted for 6 months postoperatively.

ANTICIPATED RESULTS

Better to master one mountain than a thousand foothills.
—William A. Ward

Following open reduction and stabilization of acute posterior traumatic SCJ dislocations, SCJ stability and full return to activities may be anticipated. Our experiences are described in small retrospective case series that are representative of our overall, larger clinical experience.[5,10] In a previously published series of 13 patients treated with open reduction and suture fixation for acute posterior SCJ fracture dislocations, all patients had restoration of SCJ stability and shoulder motion with full return to activities.[5] Rockwood scores were perfect at mean 22-month follow-up, and no respiratory or vascular complications were seen.

Anticipated results of ligament reconstruction for chronic recurrent instability are favorable as well. In a published report of 15 patients treated with either resection arthroplasty or ligament reconstruction for chronic SCJ instability, >85% achieved complete SCJ stability, and the majority had complete resolution of pain.[20] Functional outcomes as assessed by the American shoulder and elbow surgeons score and simple shoulder test were near normal, and no complications were reported. However, 13 of the 15 patients had mild persistent limitations with overhead athletic or recreational activities. Although no statistical differences were seen between surgical techniques, a trend for better outcomes was noted with ligament reconstruction.

COMPLICATIONS

When we fail our pride supports us and when we succeed, it betrays us.
—Charles Colton

Despite their proximity to the SCJ, injury to critical neurovascular and mediastinal structures is rare, particularly in acute cases. Meticulous surgical dissection, judicious soft tissue retraction and protection, and the presence of general surgery or thoracic surgery "backup" will help minimize surgical complications. Although the medial

clavicle often abuts the great vessels (e.g., brachiocephalic vein) on preoperative imaging, the risk of hemorrhage due to vascular injury is quite low.[5,10]

Recurrent instability is similarly rare following acute repair or reconstruction of chronic post-traumatic injuries. It is important to remember that only 50% of the clavicular head normally engages the sternal notch. For the inexperienced surgeon, the temptation to "overreduce" the SCJ should be avoided, as this may result in fixation in a posteriorly subluxed position. Consideration should be made for postoperative CT scans to confirm anatomic reduction, particularly early in one's experience with SCJ injuries. Furthermore, passage of figure-of-eight tendon grafts should be performed with the parallel fibers on the "instability side" to minimize the risk of recurrent instability.

CASE OUTCOME

The diagnosis of an acute, posteriorly displaced traumatic SCJ dislocation was made (Figure 24-1). Open reduction and stabilization was performed 1 day after presentation, using the techniques described here (Figure 24-6). The patient achieved a stable reduction, with full shoulder range of motion and strength. He returned to sports participation at 6 months postoperatively.

SUMMARY

Although SCJ injuries are relatively uncommon shoulder girdle injuries, the potential sequelae of posteriorly displaced injuries may be disastrous. Surgical reduction and stabilization is recommended in acute posteriorly displaced injuries, as well as chronic injuries with functionally limiting pain and shoulder impairment refractory to activity modification and physical therapy. With appropriate patient selection and surgical technique, SCJ stability and functional gains may be safely and effectively achieved in the vast majority of patients.

SIDEBAR

Anatomy of the SCJ

The clavicle arises from two primary centers of ossification, which fuse in utero, making the clavicle among the first long bones to become radiographically visible.[23] The medial clavicular epiphysis, however, does not ossify until approximately 18 to 20 years of age, and the medial clavicular physis does not close until 22 to 25 years of age. Awareness of these anatomic points is important in the radiographic evaluation of SCJ injuries. Indeed, many "dislocations" may indeed represent displaced physeal fractures of the medial clavicle in which the medial epiphysis is not radiographically apparent. Furthermore, the medial physis contributes to approximately 80% of the longitudinal growth of the clavicle. Due to the proximity of the SCJ to the medial physis, there may be remodeling potential of bony deformities in young patients with skeletal growth remaining.

The medial clavicle is surrounded by a number of anatomic structures that influence treatment decisions and surgical approaches. The sternocleidomastoid, pectoralis major, and sternohyoid muscles all have their origins or attachments on the medial clavicle. More importantly, however, is the close proximity of the SCJ to the mediastinal structures, including the trachea, esophagus, brachiocephalic veins, aorta, common carotid arteries, and brachial plexus (Figure 24-9). Concern regarding acute or chronic compromise to these structures in part drives orthopaedic decision making.[24]

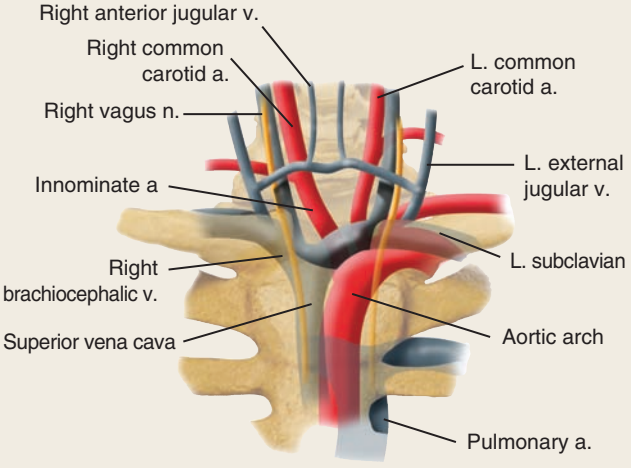

FIGURE 24-9 Proximity of the SCJ to critical mediastinal structures. (From Bucholz RE et al. *Rockwood & Wilkins Fractures in Adults.* 7th ed. Philadelphia, PA: Lippincott Williams & Wilkins, 2010.)

The SCJ is a true diarthrodial joint between the medial clavicle and clavicular notch of the sternum.[23] The joint is saddle shaped, however, as the medial head is concave in the anterior-posterior dimension and convex in the superior inferiorly. Less than 50% of the bulbous clavicular head articulates with the clavicular notch of the sternum, resulting in little bony congruity. As Grant has pointed out in his anatomy writings, "The two [make] an ill fit."[2,25]

(*Continued*)

SIDEBAR *(continued)*

Due to the lack of inherent bony constraint, the SCJ relies upon a number of ligamentous structures to provide both motion and stability (Figure 24-10). The intra-articular disk is a flat, circular fibrocartilaginous structure attached both to the superior-posterior aspect of the clavicular articular surface and inferiorly to the costocartilaginous junction of the first rib. Unlike its counterpart in the acromioclavicular joint, the intra-articular disk is complete in most individuals, perhaps explaining the observation that degenerative arthritis of the SCJ is rarely seen. There are both anterior and posterior SCJ ligaments, which are broad and reinforce the thickened anterior and posterior SCJ capsule. The interclavicular ligament connects the medial ends of both clavicles, running along the superior border of the sternal manubrium. Finally, the costoclavicular ligament arises from the inferior aspect of the medial clavicle and attaches to the superior costal cartilage of the adjacent rib.

Prior biomechanical studies have documented significant motion in the SCJ with shoulder activities.[4] Indeed, the SCJ contributes to 35 degrees of forward flexion, 35 degrees of flexion and extension, and 45 degrees of rotation around its longitudinal axis. Most SCJ motion occurs between the articular disk and the clavicle. Prior cadaveric studies have demonstrated that the posterior capsule and posterior SCJ ligaments provide the greatest restraint to anterior translation of the clavicle, whereas the posterior capsule alone confers restraint to posterior translation.[22,26] The interclavicular and costoclavicular ligaments provide relatively little stability with SCJ motion.

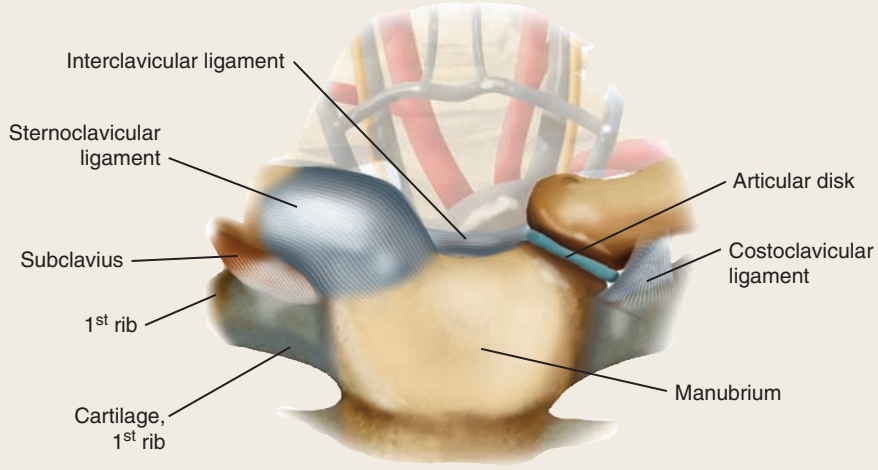

FIGURE 24-10 Diagram of the ligamentous stabilizers of the SCJ.

COACH'S CORNER

Beware the Atraumatic Unstable SCJ!

Great care should be taken to avoid surgical reconstruction in cases of atraumatic SCJ instability in adolescents and young adults, particularly in patients with collagen disorders or excessive ligamentous laxity.[4] While these patients may complain of marked pain and functional disability and demonstrate striking SCJ instability on physical examination, caution may be taken prior to any attempted surgical treatment. Indeed, in a previous report of 37 patients with atraumatic SCJ instability, 29 patients treated nonoperatively went on to symptomatic improvement and unrestricted activities. Patients who underwent surgery commonly had persistent pain, instability, and required multiple procedures, including total claviculectomy! These results highlight the importance of careful history, physical examination, and patient selection.

In patients with recurrent, anterior, atraumatic instability, we recommend rigorous physical therapy, with emphasis on periscapular strengthening to correct the scapular protraction and scapulothoracic dyskinesis that often is seen in ligamentously lax patients with atraumatic SCJ instability. Biofeedback and other modalities are extremely helpful in these situations to educate and guide the patient regarding posture, shoulder girdle dynamics, and methods that may be employed to promote SCJ stability. Surgical stabilization is indeed a last resort in these cases, and patients/families must be counseled regarding the risk of recurrent/persistent pain and instability after attempted reconstruction.

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CHAPTER

25

Clavicle Fractures

CASE PRESENTATION

A 16-year-old female presents for management of an isolated right clavicle fracture 3 days after a collision with an opponent in a soccer game (Figure 25-1). She has been treated in a sling and swathe for immobilization since her initial evaluation in an emergency care setting. The fracture is closed, but there is mild tenting of the skin superior and anterior to the mid-diaphysis of the clavicle by a palpable fracture fragment. Capillary refill is intact over that fragment, and the skin is not blanched. The distal neurovascular status is intact to the ipsilateral arm and hand.

CLINICAL QUESTIONS

- What are the mechanisms of injury for neonatal, pediatric, and adolescent clavicle fractures?
- What are the associated injuries with a clavicle fracture?
- What is the expected outcome from nonoperative treatment of a clavicle fracture?
- Is there a difference in outcome between sling and figure-of-eight immobilization treatment for clavicle fractures?
- What are the indications for operative treatment of a clavicle fracture?
- Is there a difference in results between nonoperative and operative methods?
- Is there a difference in outcome and/or complication rates from internal fixation with K-wires, intramedullary elastic nails, intramedullary screws, or plate and screw fixation?
- What are the complications from clavicle fractures and the various methods of treatment?
- How are nonunions of the clavicle treated?

THE FUNDAMENTALS

Etiology and Epidemiology

The clavicle is an S-shaped bone that articulates medially with the sternum and laterally with the acromial extension of the scapula. The clavicle serves as the origin for the pectoralis major and deltoid muscles along with the insertion of the sternocleidomastoid and trapezius muscles. The sternoclavicular joint (SCJ) and acromioclavicular joint (ACJ) ligaments insert proximally and distally on the clavicle, respectively. The motions of the clavicle include protraction and retraction, and rotation and elevation during shoulder abduction. The brachial plexus, subclavian vessels, and apex of the lung lie beneath the clavicle and are at risk for injury with a displaced clavicle fracture. The clavicle is predominately subcutaneous and susceptible to injury with a direct blow (less common) or lateral compression trauma (most frequent).

Clavicle fractures are common in children and adolescents. Birth fractures occur in 1% to 2% of all vaginal deliveries, most often with large-for-gestational-age infants and during extraction and difficult deliveries.[1–3] Childhood injuries resulting from a fall include those involving bicycles, playground equipment, and sports. Adolescent injuries usually involve contact sports. Motor vehicle accidents account for many of the clavicle fractures associated with polytrauma.[4] Rare stress fractures of the clavicle have occurred in rowers, gymnasts, and other athletes involved in repetitive, high-intensity training sports.[5]

Clinical Evaluation

Clavicle fractures are almost always associated with pain. In the neonates, their discomfort can be mild, especially with stable fractures, and thus misinterpreted as hygiene

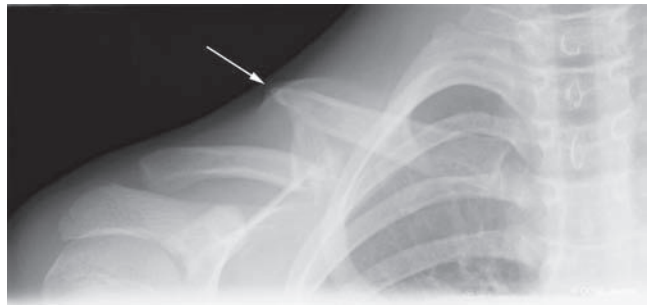


FIGURE 25-1 Preoperative radiograph of segmental right clavicle fracture with pending skin compromise (*arrow*).

or hunger complaints. At times, this will result in a delay of proper diagnosis until there is palpable callus at 5 to 21 days. The most common associated diagnosis with a neonatal clavicle fracture is a brachial plexus injury. The flail limb in these children can be either a pseudoparalysis from an unstable fracture or a combination nerve and skeletal injury. If limited motion persists when the fracture heals or obvious signs of a severe nerve injury are seen immediately after birth (Horner syndrome, flail hand, elevated hemidiaphragm), appropriate care for a brachial plexus palsy is warranted (see Chapter 20).

In an infant and young child, the differential diagnosis includes nontraumatic disorders such as infantile cortical hyperostosis, congenital pseudarthrosis (see Chapter 18), cleidocranial dysplasia, and short clavicle syndrome. In older children and adolescents, the differential includes neurofibromatosis and clavicular pseudarthrosis, Friedrich disease, hypertrophic osteitis, chronic multifocal periostitis and osteomyelitis, and SAPHO syndrome (synovitis, acne, pustulosis, hyperostosis, osteitis).[6]

Pediatric and adolescent fractures are classified by location and fracture pattern. Simply, the fractures are (1) medial fractures and SCJ dislocations (see Chapter 24), (2) diaphyseal, and (3) lateral (distal) fractures and ACJ joint dislocations. The most common injury is in the middle third (75% to 85%) (sternocleidomastoid muscle insertion to coracoclavicular ligament insertion) followed by distal third (10% to 20%). The fractures can be subclassified as two-part, segmental, or comminuted; open or closed; and nondisplaced or displaced. The more complex the fracture pattern, the more risk of associated injuries, nonunion or malunion, and need for operative intervention.

Lateral or distal clavicle fracture dislocations at the ACJ in children and adolescents were classified by Dameron and Rockwood as a modification of the adult ACJ separation classification system. Defining the injuries to the periosteum, acromioclavicular (AC), and coracoclavicular ligaments and assessing the direction of clavicular displacement determines the classification type. The coracoclavicular ligaments remain attached to the periosteum, and the clavicle bone remains intact but displaces out of the periosteal sleeve. Type I is nondisplaced; type II is a partial tear of the AC ligaments and lateral periosteum with some instability of the clavicle; in type III the clavicle is displaced superiorly (25% to 100% width of clavicle) with complete tear of AC ligaments and superolateral periosteum; with type IV the clavicle displaces posteriorly and gets entrapped in the trapezius muscle; type V is completely displaced (>100%) superiorly into the subcutaneous tissues; and type VI is displaced inferiorly beneath the coracoid. Distal clavicle fractures are further divided into nondisplaced or minimally displaced (type I); fractures medial to coracoclavicular ligament (type II); and intra-articular fractures (type III). Displaced intra-articular fractures are problematic.

More severe injuries can include a floating shoulder with damage to the clavicle and the scapula.[7–9] This situation involves disruption of the superior shoulder suspensory complex and potentially an unstable shoulder girdle. Operative treatment of both fractures, one fracture, or neither has been advocated. Stabilization of unstable, displaced fractures is appropriate. Floating shoulder injuries are rare in children but should not be missed due to concern about associated injuries to the chest and intrathoracic organs. Similarly, there are reports of associated C1–C2 rotatory displacement with clavicle fractures. Finally pathologic fractures, such as postirradiation treatment, can occur and require a different and often more aggressive treatment protocol for successful healing.[10]

Surgical Indications

They want some clarity. We just don't have answers for them.
—Ted Ludwig

The mainstay for treatment of midshaft and lateral clavicle fractures is immobilization and biologic healing in situ. Nonoperative treatment is indicated in the majority of middle and distal clavicle fractures. However, like many other pediatric and adolescent fractures, clavicle fracture treatment in the young, especially the athletic adolescent, is influenced by operative techniques and internal fixation outcomes in the adult.[11–15]

The indications for open reduction internal fixation (ORIF) of clavicle fractures in children are changing as we write. Clear indications for surgery include (1) open fractures, (2) displaced fractures with skin compromise (Figure 25-2) or neurovascular impairment, and (3), for most surgeons including us, type III, IV, and V lateral clavicle fracture dislocations. Evolving indications in many centers (including ours) for ORIF now include (1) displaced segmental and comminuted diaphyseal fractures in the adolescent (Figure 25-1), (2) polytrauma patients with displaced fractures, and (3) (less often) diaphyseal fractures with >2 cm of overlap in the older adolescent. The adult patients with the greatest initial fracture displacement had the most long-term complaints in terms of overhead strength and endurance.[13,16,17] Polytrauma patients with displaced clavicle fractures had lower outcome scores.[18] The risk of nonunion is higher when a lack of cortical contact and/or comminution exists between fracture fragments.[19]

All of the reasons noted above make ORIF of certain clavicular fractures in specific clinical situations and pediatric patients appropriate.

SURGICAL PROCEDURES

Nonoperative Treatment

Nonoperative treatment of a nondisplaced or minimally displaced (<1 to 2 cm) fracture is indicated and will result in a 95% to 98% union rate and positive outcome[20,21]

FIGURE 25-2 **A:** Tenting of the skin by a displaced, segmental diaphyseal clavicle fracture. This requires ORIF to prevent skin breakdown and an open wound. **B:** Closer inspection (*circle*) denotes the ischemic changes of the skin with blanching.

(Figure 25-3). Comparative results indicate that both a sling and a figure-of-eight dressing are equivalent. There is even some evidence that follow-up care is not necessary in these children, though we tend to follow them until full healing of bone and soft tissues is apparent.[22]

Radiographic healing occurs over the course of 4 to 12 weeks depending on the fracture pattern, age, and overall health of the patient. Palpable callus is present early (7 to 14 days) and coincides with decreased pain and self-protection. Restoration of motion and strength occurs readily in these stable fractures. Protection against refracture (~2%) is important until there is full bony healing, motion, and strength.

Types I, II, and III lateral clavicle fractures can be treated closed. The torn periosteum will heal (Figure 25-4), and even the mild-to-moderate displaced fractures will remodel. There are times where a distal "double barrel" clavicle will appear before the old superior clavicle resorbs as the new inferior clavicle forms in the periosteal sleeve. This can even occur in type V clavicle fractures if the patient is young enough and the family and surgeon can wait long enough. As with diaphyseal fractures, short-term immobilization for up to 3 to 4 weeks is followed by restoration of motion and strength before return to full activities.

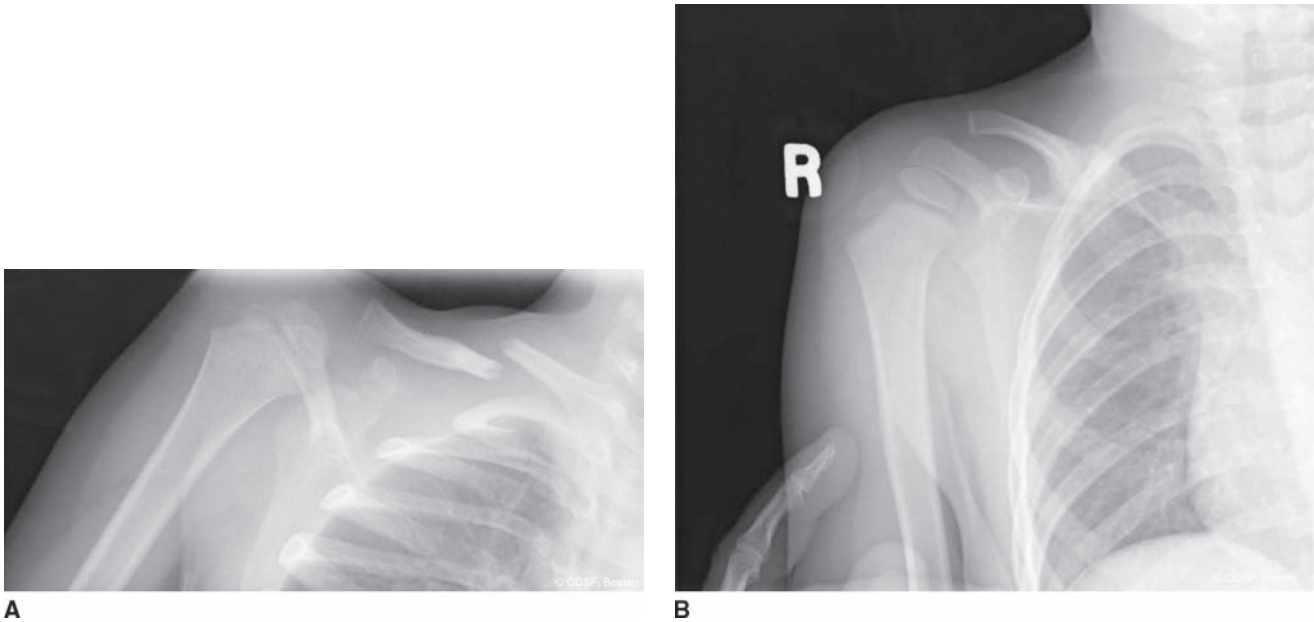


FIGURE 25-3 **A:** Moderately displaced fracture treated with sling immobilization. **B:** Healed fracture with radiographic evidence of palpable callus on clinical exam.

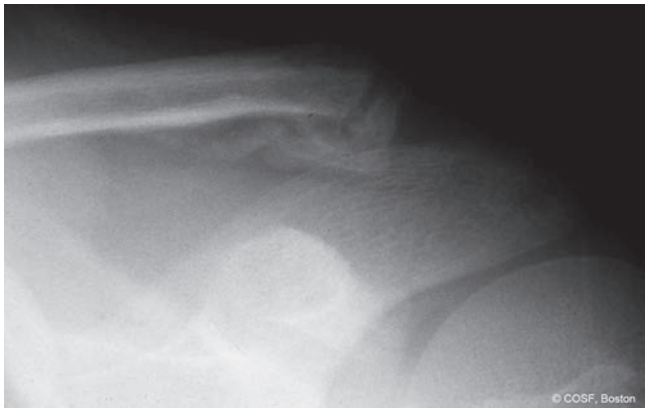


FIGURE 25-4 Lateral clavicle fragment, type II, with abundant periosteal healing. The displacement will remodel with time.

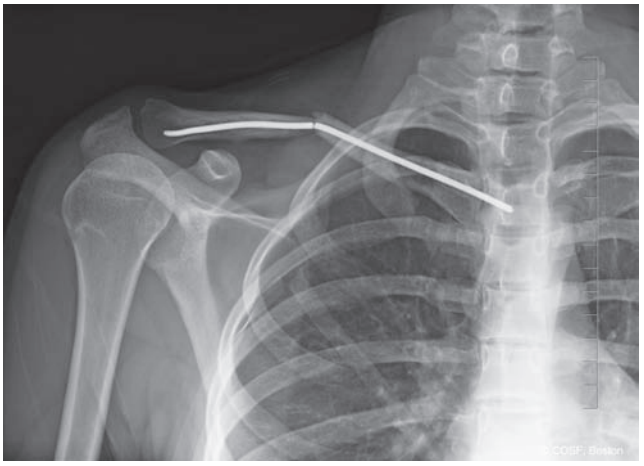


FIGURE 25-5 Broken elastic nail placed at another institution as treatment for a diaphyseal clavicle fracture.

Exostosis Excision

Of the displaced fractures treated nonoperatively, some will heal with a symptomatic malunion. There will be a palpable exostosis, and the patients will complain of pain with direct contact (backpacks, sporting equipment). There may be loss of endurance and strength with overhead activities. Surgical treatment is either by corrective osteotomy or by exostosis excision. For the patients in whom there is normal strength, motion, and endurance but pain with direct pressure, exostosis excision is indicated.[23]

A modified beach chair position is utilized with prepping and draping of the involved arm and entire shoulder girdle to the SCJ. An incision in the skin lines is made directly over the clavicular malunion. Dissection is carried down to the exostosis while identifying and protecting the cutaneous nerves as they cross the clavicle from superior to inferior. The nerves descend deep into the platysma layer and often course with more easily identified veins. Cutting these nerves will cause a symptomatic neuroma. Subperiosteal dissection is performed, and the exostosis is isolated. With a rongeur and osteotomes, the exostosis is excised and the bone contoured to smooth surfaces. Rasping of the bone may be necessary. Bone wax is applied, and the wound is closed in layers, including periosteum, platysma, subcutaneous, and skin layers. Since we are trading a symptomatic bump for a scar, the aesthetics of the closure matter. Sling protection and restriction of activities are utilized until the risk of refracture is minimal.

ORIF Displaced Diaphyseal Clavicle Fractures

Plate and Screw Fixation

The will to win is important, but the will to prepare is vital.
—Joe Paterno

An ORIF approach to segmental, comminuted, open and markedly displaced fractures is more commonplace now than an orthopaedic generation ago. Fixation methods of diaphyseal fractures include plate and screws (locked and nonlocked, standard and precontoured),[24–26] elastic nails,[27–29] intramedullary screws,[30] threaded wires, and suture repair, among others. Although smooth wires have been used, concern about migration to areas of serious anatomic consideration makes most surgeons stay away from that technique. Although we use elastic nails for many pediatric fractures, we advocate for the use of plate and screw fixation with ORIF of operative clavicle fractures. We like to see and gently manipulate the segmental pieces into place while protecting the surrounding nerves, blood vessels, and vital organs. The fixation is stronger[31] (Figure 25-5), and early rehabilitation is safer in our hands with stable plate and screw fixation. That does not mean that the other methods cannot work, as the evidence clearly shows they can. Healing and complication rates appear comparable, though there is no prospective analysis for each method against each fracture type. Hardware irritation and removal rates and ease of extraction may differ among these methods.

The options with plates include nonlocked versus locked; precontoured clavicle versus bending of standard double-stacked semitubular, dynamic compression, or pelvic reconstruction plates; and superior versus anterior-inferior plate placement. The advantages of anterior-inferior plates are theoretically a reduced risk of neurovascular injury with drilling and screw fixation and less of a likelihood of symptomatic hardware requiring implant removal. Superior plate position has better load to failure bending and torsional failure stiffness than anterior-inferior plates. Laterally, subperiosteal anterior plates may displace the periosteal attachment of the coracoclavicular ligaments. Locked plates are stiffer.[32,33] Precontoured plates fit best on the medial 60% of the clavicle and fit adult men better than young people and women.[34] Precontoured plates often lead to symptomatic hardware in young people, especially athletic women. The risk of refracture with clavicular implant

removal leads us to a bias away from precontoured plates in many circumstances in adolescents unless the fit is perfect or the plate can be bent appropriately. Right now, we tend to bend standard plates (pelvic reconstruction most often) for best fit and place the plate superiorly.

Surgery is carried out in a modified beach chair position. The entire shoulder girdle from opposite the SCJ through the ipsilateral arm is prepped and draped to allow for free arm movement during fracture reduction and fixation. Exposure is through an incision in the skin lines. The platysma, fascia, and periosteum are split in line with the clavicle. Care is taken to identify and protect the cutaneous nerves as they cross the clavicle to avoid a symptomatic neuroma (Figure 25-6B). Subperiosteal dissection of the clavicle is begun on either side of the fracture and carefully brought to the midline. Soft tissue attachments to malrotated, segmental fracture fragments are maintained. Vertical segmental pieces may project toward and/or lie adjacent to the brachial plexus, subclavian vessels, and apex of the ipsilateral lung. These vertical fracture fragments often have an obvious or subtle coronal fracture line that increases the difficulty of fracture fixation. Careful dissection here is imperative. Fracture reduction is carried out while maintaining periosteal attachments to prevent devascularization of the bony fragments. Anatomic length and contour of the clavicle are restored. Temporary fixation with smooth wires may be necessary. The contoured (pre- or bent) plate is applied with proximal and distal screw fixation to maintain length and alignment. The plate chosen should fit the local anatomy (Figure 25-6C). Interfragmentary screw, or even suture, fixation of the segmental pieces is performed as necessary. Completion of screw fixation is performed while protecting the neighboring neurovascular structures with appropriate retractors and exposure. Rigid fixation is achieved with anatomic restoration of the clavicle. The periosteum, fascia, platysma, subcutaneous, and skin layers are closed. A simple dressing (Telfa and Tegaderm [Covidien, Mansfield, MA

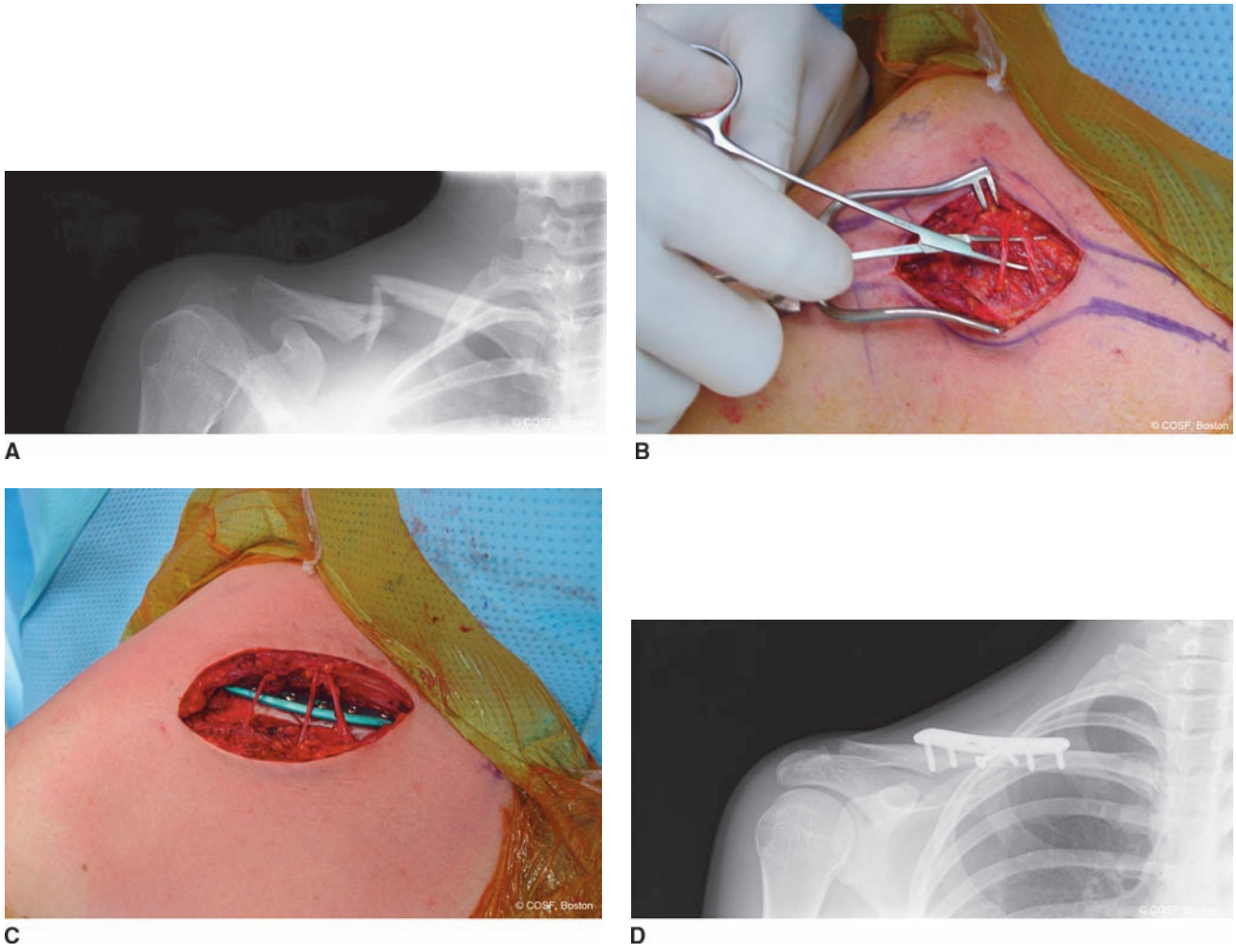


FIGURE 25-6 **A:** Preoperative segmental fracture. **B:** Operative exposure for ORIF clavicle fracture with isolation and preservation of the supraclavicular cutaneous nerves. **C:** ORIF of a displaced diaphyseal clavicle fracture with a precontoured clavicle plate. Note the preserved cutaneous nerves. **D:** Postoperative radiographs. Note the precontoured plate is not a perfect fit for this adolescent female. An interfragmentary compression screw was also used for stabilization of the segmental fracture fragment.

and 3M, St. Paul, MN, respectively]) is applied over the wound after local anesthesia injection. Either a sling or sling and swathe is used depending on the personality of the patient, fracture pattern, and fixation methods.

◆ ORIF Displaced Distal Clavicle Fractures

When you're riding, only the race in which you're riding is important.
—Willie Shoemaker

Most type IV, V, and VI lateral clavicle fractures require ORIF. The type V and VI fractures are evident on plain radiographs. The type V is evident on exam from across the room. The markedly displaced type IV fracture can be missed on radiographs if attention is focused only on the AP view and/or the lateral view is inadequate. In the type IV fracture dislocation, the clavicle displaces posteriorly out of the periosteal sleeve and becomes entrapped in the trapezius muscle. The AP x-ray will look as if the clavicle is on the same plane as the acromion. Closer inspection will reveal a wider than expected gap between the clavicle (Figure 25-7) and the acromion for a minimally displaced fracture such as a type II or III pediatric AC injury (Figure 25-8). A lateral view will show the displacement but often is not adequately obtained such that the overlapping bony structures (ribs, acromion, coracoid, clavicle) and lung can confuse the reader. Physical exam for the type IV injury is very helpful,

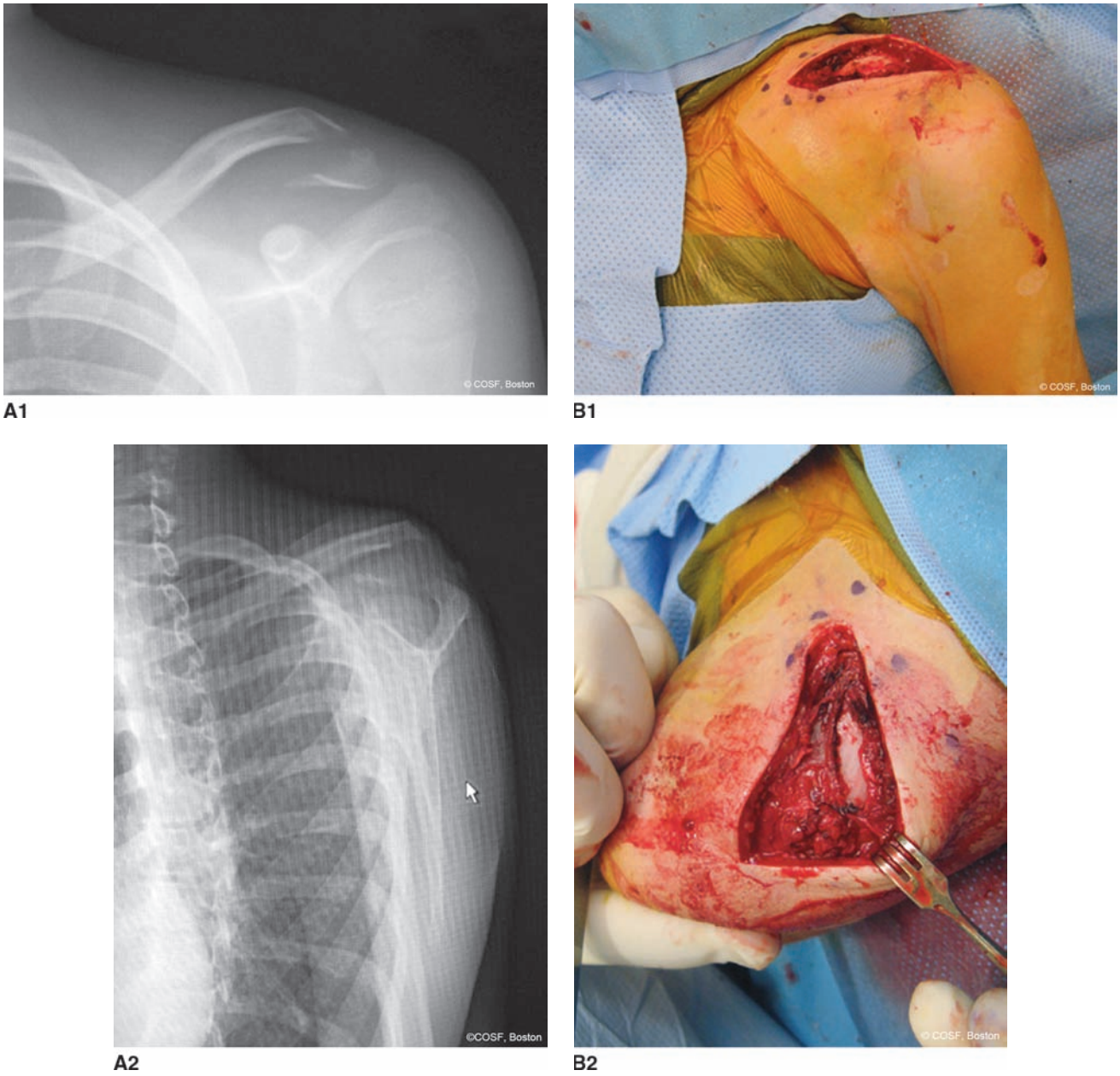


FIGURE 25-7 **A1,A2:** Preoperative radiographs of displaced lateral clavicle fracture (type IV pediatric AC separation). **B1,B2:** Operative exposure and suture repair during ORIF.

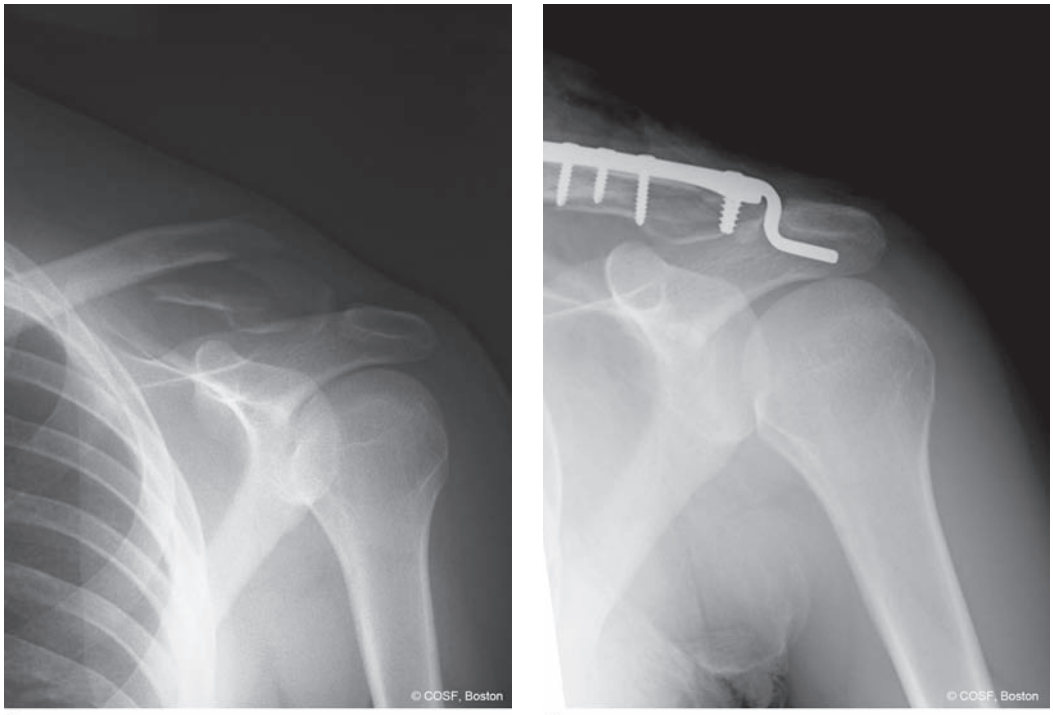


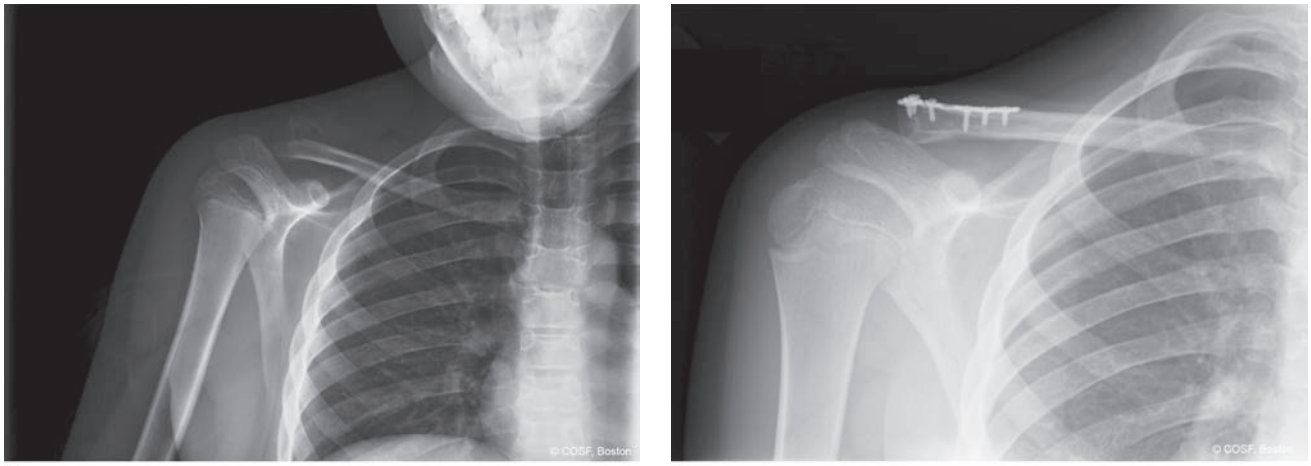
FIGURE 25-8 **A:** Preoperative radiographs of displaced intra-articular lateral clavicle fracture. The displaced medial clavicle of this type IV pediatric AC injury was entrapped in the trapezius muscle. **B:** Radiograph after ORIF with a hook plate. Implant removal is planned.

as the displaced clavicle is palpable in the suprascapular region. Often this is what alerts us to the need for operative intervention.

Intra-articular fractures (type III distal clavicle fracture) require closer inspection of radiographs and, at times, CT scans. Surgical planning of fixation methods is dependent on an understanding of fragment number, size, and orientation. Displaced intra-articular fractures clearly require ORIF.

Surgical techniques for fixation vary depending on the age of the patient, fracture pattern, status of the periosteum, and size of the bone.[35] Suture repair[36] (Figure 25-7), transacromial K-wire,[37] plates including special lateral clavicle hook plates (Clavicle Hook Plate, Synthes, Inc., West Chester, PA),[38–41] and the fixation of the clavicle to the coracoid with a screw or loop suture by either open or arthroscopic technique have been successfully used in pediatric and adult ACJ injuries and lateral clavicle fractures.[42] The method we use really depends on the situation. Periosteal repair is a major part of any lateral clavicle fracture ORIF in children and adolescents. Hook plates are reserved for special circumstances and are always removed after 3 to 6 months. However, there are certain fractures where the hook plate is needed to restore anatomic alignment (Figure 25-8B). Small plates and screws may be necessary in some children with displaced intra-articular fractures (Figure 25-9). We avoid the use of K-wires due to the risk of implant breakage or migration except in rare circumstances. If wires are used as part of a tension band technique, larger wires are chosen, more restrictive postoperative immobilization is used, and the wires are removed at 4 to 6 weeks to lessen the risk of serious complications.

Surgery is carried out in a modified beach chair position. The entire shoulder girdle from medial clavicle through the ipsilateral arm is prepped and draped to allow for free arm movement during fracture reduction and fixation. Exposure is through an incision in the skin lines over the distal third of the clavicle and ACJ. Skin and subcutaneous flaps are elevated. In a type V fracture, the superiorly displaced clavicle will be readily apparent. In the type IV fracture, the clavicle needs to be extracted from entrapment in the trapezius. In the type VI fracture, the periosteum is torn more medially, and the clavicle is locked beneath the coracoid and its muscle attachments. The musculocutaneous nerve needs to be protected during exposure and reduction. If necessary the short head of biceps, coracobrachialis, and pectoralis minor muscles need to be elevated from the coracoid during fracture reduction and then repaired back to the coracoid. The torn periosteum is isolated in type IV, V, and VI pediatric AC injuries. The clavicle fracture is reduced with alignment of the distal clavicle to the acromion. Temporary transacromial pinning may be necessary while deciding on the best



A B

FIGURE 25-9 **A:** Radiographs of a 10-year-old male with a superiorly and posteriorly displaced lateral clavicle fracture entrapped in trapezius muscle. ORIF is indicated. **B:** Healed fracture at 2 months after ORIF with small plate and screws used to match fracture and patient size.

repair technique. Repair can be by direct suturing of the periosteum and ligamentous structures directly over the reduced clavicle.

If the fracture is segmental and intra-articular, plate fixation of an appropriate size for the child and fracture fragments is performed. Lower profile plates are preferred, and at times this means use of the modular hand instruments (Synthes, Inc., West Chester, PA) (Figure 25-9). Hook plates are reserved for larger patients with adult-like injury patterns. Implant selection is based on side (right or left) and size (six or eight holes, 15 or 18 mm hook depth) with 3.5 mm cortical or 4.0 mm cancellous screws used (Figure 25-8). Anatomic reduction and fixation of the fracture fragments is followed by soft tissue reconstruction of the periosteum and ligaments. Standard layered aesthetic closure with absorbable suture is performed.

◆ Nonunion ORIF

The rate of nonunion with a diaphyseal clavicle fracture is approximately 3% to 5%. The more displaced the fracture, the higher the risk of nonunion with nonoperative management. Treatment of a symptomatic nonunion involves ORIF, typically with plate and screw fixation. Since clavicular nonunions are usually hypertrophic (Figure 25-10), a donor site bone graft is usually not required. Operative exposure is the same as described for ORIF. The nonunion site is similarly approached from either end with care taken to protect the underlying brachial plexus and subclavian vessels. The hypertrophic bone can be impinging on those neurovascular structures, so careful elevation is imperative. Once the two ends of the clavicle are mobilized, reduction is performed and clamped. Excess bone is removed (with rongeur, osteotome, or saw) and morselized for bone grafting. The plate is bent and contoured to fit the alignment of the reduced clavicle, usually with a pelvic reconstruction plate. As mentioned under the ORIF section, precontoured clavicle plates and locked and nonlocked plates can all be used successfully. The differences are not only in biomechanical properties but also in the likelihood of symptomatic hardware after healing.[43,44] Compression techniques are preferred and, if possible, should include an interfragmentary screw. The morselized bone is densely packed in the nonunion site followed by a standard layered closure from the periosteum to the skin.

◆ Osteotomy for Symptomatic Malunion

Diaphyseal clavicle fractures treated nonoperatively can heal malaligned. Some of these malunions will be symptomatic, including local discomfort with direct pressure,

FIGURE 25-10 Hypertrophic nonunion of displaced clavicle fracture.

thoracic outlet syndrome, and/or overhead decreased strength and endurance. Problems at the ACJ and SCJ can occur with more complex malunions. Surgical treatment is by single-level (usual) or on rare occasions two-level osteotomy.[45–48] An AP chest radiograph that allows for comparative sternal to acromial measurement is useful. In complex situations, preoperative 3-D CT scanning is helpful with planning. Surgical exposure is identical to exposure for open reduction or treatment of a nonunion of the clavicle. Most of the malunions are oblique, which makes restoration of length and anatomic orientation of the clavicle easier. The maximum plane of deformity is identified (Figure 25-11), and the single osteotomy cut is made with an oscillating saw. Local protection from neurovascular injury and thermal necrosis is performed. The clavicle is then elongated with correction of malrotation and malangulation. Reduction clamps are applied. Redundant hypertrophic bone is excised, morselized, and used as bone graft. Plate and screw fixation is performed similar to the fracture and nonunion situations (Figure 25-11). The ultimate difference in outcome between an acute ORIF of a displaced fracture or a late osteotomy of a symptomatic malunion remains unclear. The evidence so far in adults and children indicates there are at most only subtle differences.[14,49]

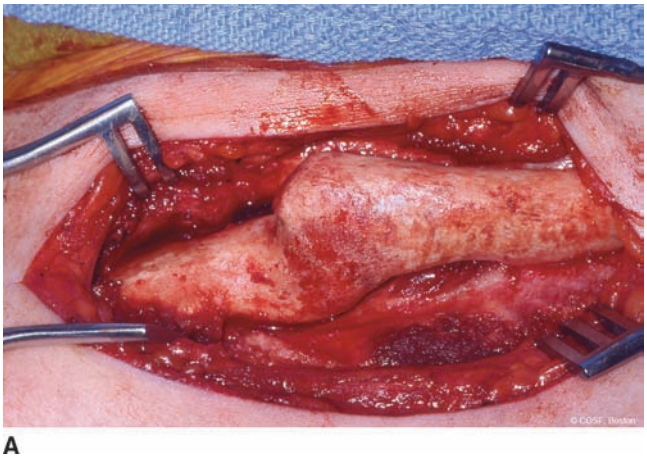
◆◆ Nonunion ORIF with Vascularized Bone or Corticoperiosteal Flap

The principle is competing against yourself. It's about self-improvement, about being better than you were the day before.
—Steve Young

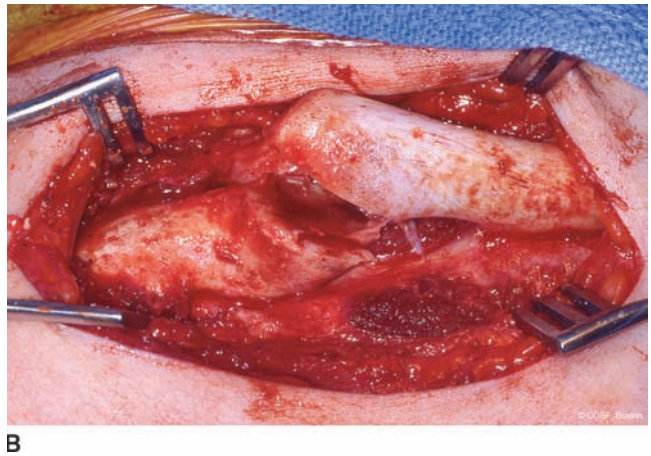
There are some rare nonunions of the clavicle that require vascularized bone to achieve union. Although straight rather than S-shaped, the fibula is an ideal option. There are readily accessible vessels for end-to-end vascular repair, and the bone can be readily contoured for stable fixation. Like nonunions in other locations for which we use the fibula (see Chapter 44), Z-cuts of the recipient clavicle and donor fibula are made to achieve stable fixation[50,51] (Figure 25-12). Other surgeons have used pedicled rib transfers and free corticoperiosteal flaps for complex clavicular nonunions.[52,53] Prolonged postoperative protection is necessary until union and hypertrophy of the bone occurs to prevent fracture.

POSTOPERATIVE

Sling or sling-and-swathe immobilization is carried out until there is sufficient bony healing to prevent fracture



A



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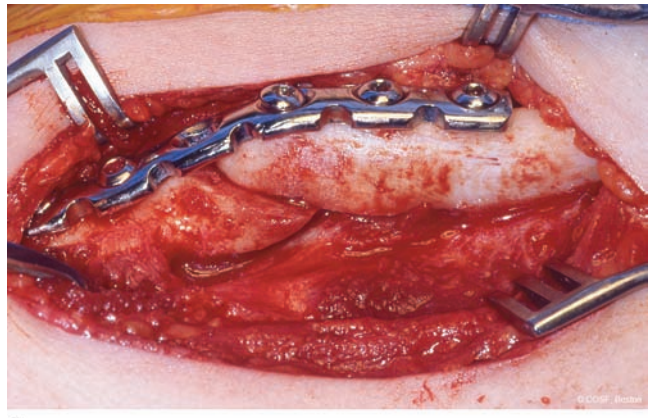

C

FIGURE 25-11 **A:** Intraoperative isolation of the malunion. **B:** The osteotomy has been performed in the plane of maximum deformity. **C:** Reduction and plating.

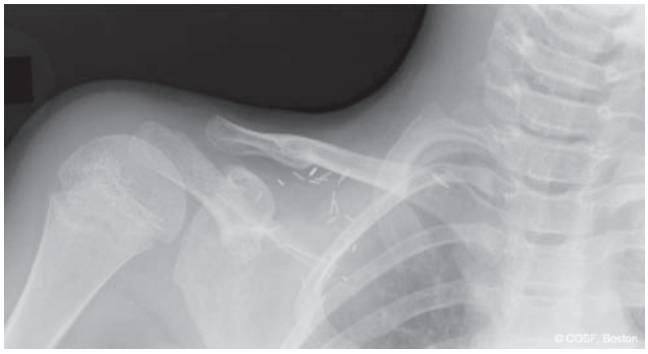

FIGURE 25-12 Healed clavicle from vascularized fibula graft.

and/or hardware displacement. Clavicle fractures, operative reductions, nonunions, and malunion osteotomies can take 6 to 12 weeks to heal. Rehabilitation is begun when the construct is stable and the patient is trustworthy. For most, this is with wound healing at 2 weeks. Hardware removal is dependent on the implant as well as the patient's symptoms. K-wires, though rarely used by us in clavicles, should always be removed quickly to prevent migration complications. Hook plates also always have planned implant removal, usually at 3 to 6 months.

ANTICIPATED RESULTS

The only place where success comes before work is in the dictionary.
—Vidal Sassoon

Clavicle fractures will heal in 95% to 98% of cases. Restoration of motion and strength is anticipated. Malunions do occur in nonoperatively treated fractures. In the young pediatric patient (<10 years), remodeling can occur. In adults with malunions, the evidence of the last decade now shows that loss of endurance and overhead strength is more common (25% to 50% of malunions with >2 cm displacement) than previously described. This has led to a more aggressive operative treatment of displaced, segmental, and comminuted clavicle fractures in both adults and active adolescents. The outcomes from ORIF are excellent in terms of healing and restoration of function. Late osteotomy of a healed, symptomatic malunion achieves near equivalent results to acute ORIF.

COMPLICATIONS

How you respond to the challenge in the second half will determine what you become after the game, whether you are a winner or a loser.
—Lou Holtz

Nonunion occurs rarely.[54] Malunion occurs commonly, though not always symptomatically.[17,47,55] Both malunion and nonunion can cause pain, thoracic outlet syndrome, and brachial plexus irritation.[56–58] The thoracic outlet and brachial plexus conditions usually respond to restoration of clavicular anatomy and healing by operative reconstruction of the nonunion and malunion, respectively. Hardware problems, the most serious of which is pin migration,[59] do occur and respond to hardware removal. Symptomatic cutaneous neuromas can be excised and the proximal end of the nerve buried in muscles and attached to an adjacent nerve in hopes of relieving pain. Refracture is an issue, especially after hardware removal, and needs to be advised about and protected against. Hypertrophied scars and, less commonly, infections (0.5% to 1%) do occur after operative reconstruction of a clavicle fracture.[60] In some extreme situations, the only salvage procedure remaining may be a total claviculectomy.[61]

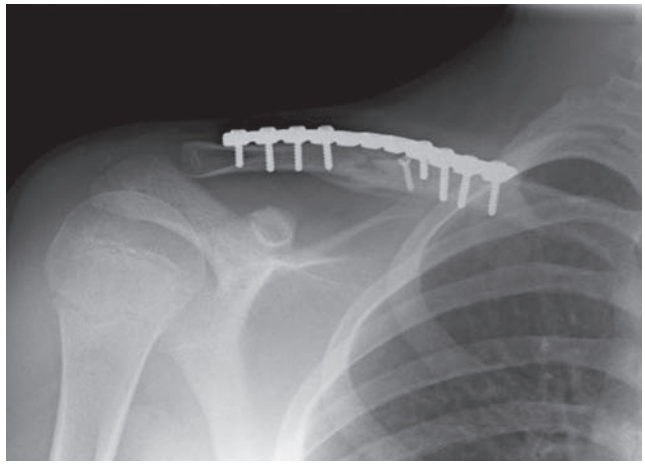

FIGURE 25-13 Postoperative radiograph of healed fracture treated with plate and screw fixation including lag screw of vertical split.

CASE OUTCOME

Due to the segmental nature of this fracture, age of the patient, potential skin compromise, and her planned athletic endeavors (soccer goalie with collegiate scholarship potential), the patient was treated with ORIF of her fracture (Figure 25-13). She achieved bony union by 8 weeks and returned to sports by 3 months. Her hardware is still in place.

SUMMARY

Clavicle fractures are common in children and adolescents. Children under 10 years with diaphyseal or distal clavicle fractures should almost always be treated nonoperatively. Adolescents with (1) segmental, comminuted, or open diaphyseal fractures; (2) neurovascular compromise or polytrauma; (3) type IV, V, or VI pediatric AC injuries; or (4) displaced intra-articular distal clavicle fractures should be treated with ORIF.

COACH'S CORNER

We appear to have gone over the tipping point in terms of operative treatment of clavicle fractures. More and more clavicle fractures in adolescents, and now some young children, are being treated operatively. Once any of us have the skill, we tend to apply that skill in more and more boundary area clinical cases. ("When you are a hammer, all the world looks like a nail.") We all also have a better chance of improving if we practice and perform an activity frequently. Right now, it is unclear where the edge of ORIF versus immobilization of childhood clavicle fractures lies. In the gray zone between clear indications will be some clinical equipoise situations in which costs, complications, and convenience, along with surgical and patient biases, impact the decision. Simply, whatever you choose for your patients, do it well. As one of our partners (who will remain unidentified) says with a smile: "Unindicated surgery done well is better than indicated surgery done poorly." However, we hope we all strive for both proper indications and skilled surgical care.

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CHAPTER

26

Proximal Humerus and Humeral Diaphyseal Fractures

CASE PRESENTATION

A 14-year-old male presents for evaluation of left shoulder pain after a fall. On clinical examination, there is swelling, tenderness, mild ecchymosis, and limited range of motion of the shoulder. The affected hand is pink and well perfused with a palpable radial pulse. Median, ulnar, and radial nerve function is intact, though he does complain of decreased sensation to light touch over the lateral deltoid. Radiographs demonstrate a displaced proximal humeral physeal fracture (Figure 26-1).

CLINICAL QUESTIONS

- How do fractures of the proximal humerus and humeral shaft present in skeletally immature patients?
- What are the radiographic views used to assess proximal humerus and humeral shaft fractures?
- How are proximal humerus and humeral shaft fractures classified?
- What is the remodeling potential of proximal humerus fractures?
- How much deformity may be accepted in the nonoperative care of humeral shaft fractures?
- What are the indications for surgical treatment of proximal humerus fractures? Of humeral shaft fractures?
- What are the surgical approaches and methods of fixation for proximal humerus and humeral shaft fractures?
- What are the treatment principles for humeral shaft fractures associated with radial nerve palsy?
- What are the anticipated results of treatment?
- What are the potential complications of surgical care?

THE FUNDAMENTALS

Fractures of the proximal humerus and humeral diaphysis are common injuries in children and adolescents.[1] Due to the compensatory motion of the glenohumeral joint and tremendous remodeling potential imparted by the proximal humeral physis, the majority of these injuries can be treated nonoperatively with good clinical outcomes.[2–6] However, in older children with less growth remaining, severely displaced fractures may require operative treatment to restore anatomic alignment and maximize shoulder motion.[7–9] In these situations, a number of surgical techniques may be employed to achieve bony healing, improve skeletal alignment, and minimize potential complications.

Etiology and Epidemiology

Proximal humerus fractures are relatively common in children and adolescents, with an estimated incidence of 1 to 4:1,000 fractures per year.[10,11] The pattern of injury is associated with age, with Salter-Harris type I fractures predominating in children <5 years old, metaphyseal fractures in children 5 to 11 years old, and Salter-Harris type II fractures in patients >11 years of age. The primary mechanisms of injury are direct blows to the shoulder or indirect forces resulting from a fall onto an outstretched hand. In addition to these traumatic causes, proximal humerus fractures may be seen in the setting of traumatic birth injuries or pathologic lesions of the humerus (see Chapters 20 and 50).

Humeral diaphyseal fractures are less common, accounting for 2% to 5% of childhood fractures.[12] The estimated incidence is approximately 1 to 3:10,000 per year.[11,13] A bimodal distribution has been observed, with the majority of humeral shaft fractures seen in children younger than 3 and older than 12 years of age.[14] Humeral diaphyseal fractures may occur during birth, particularly in cases of macrosomia and breech presentation. In older patients, shaft fractures are due to direct trauma, indirect forces sustained during falls, penetrating injuries, or motor vehicle collisions.

Nonaccidental trauma should be considered as a part of the differential diagnosis for very young patients presenting with proximal humeral or diaphyseal fractures. Indeed, humerus fractures are thought to represent over 60% of newly diagnosed injuries and 12% of all fractures in cases of child abuse.[15,16]

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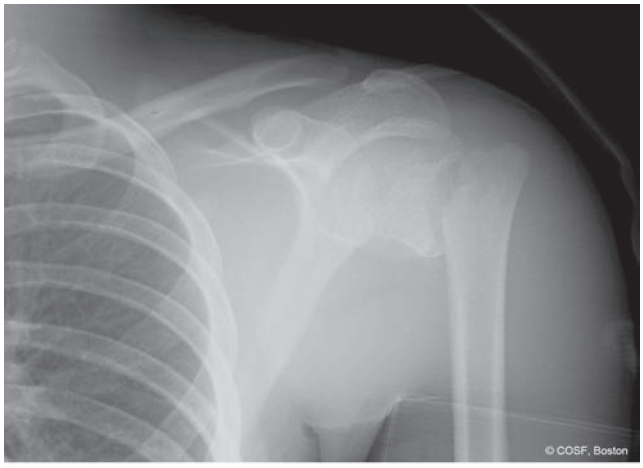

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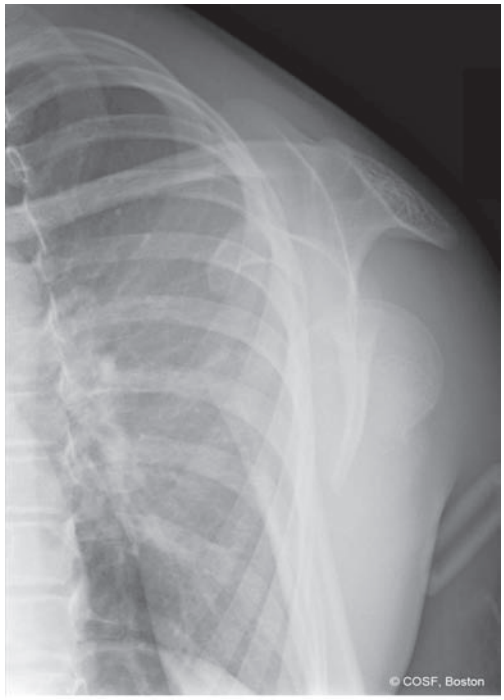

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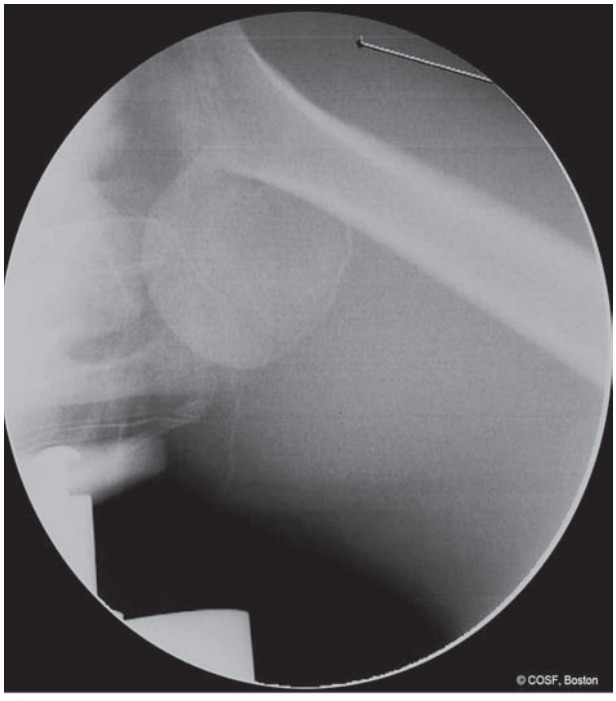

C

FIGURE 26-1 **A:** Anteroposterior radiograph of the left shoulder demonstrates a displaced proximal humeral physeal fracture with translation and varus angulation. **B:** Transthoracic "Y" view. **C:** Axillary view obtained intraoperatively highlights the translation and apex anterior angulation of the injury.

Clinical Evaluation

Take off the blinders. You have to see opportunity before you can seize it.
—Greg Hickman

Patients typically present with pain, swelling, ecchymosis, and limited shoulder and elbow motion. The affected extremity is usually held in adduction and internal rotation, with fullness or deformity about the injury site. A comprehensive physical examination should rule out concomitant neurovascular injury. Deltoid function and sensibility along the lateral aspect of the shoulder should be checked in cases of proximal humerus fractures to rule out concomitant axillary nerve injury. Careful assessment of radial nerve function (first dorsal web sensation, wrist extensor, and thumb and digital extensor motor function)

is imperative in cases of humeral shaft fractures to assess for radial nerve palsy.

Plain radiographs will confirm the diagnosis. Recommended for evaluation are anteroposterior (AP) lateral (scapular Y view), and axillary views of the proximal humerus. While axillary views are sometimes difficult to obtain, they are necessary to quantify displacement and angulation, which is often apex anterior (Figure 26-1C). In situations where an axillary view cannot be obtained, an apical oblique view of the shoulder (AP radiograph with 45 degrees of caudal tilt) may be useful. Pathologic fractures in the setting of unicameral bone cysts, aneurysmal bone cysts, or other benign and malignant conditions commonly occur in the proximal humerus. Radiographs should be carefully evaluated for underlying bony abnormalities, and further diagnostic workup should be considered prior to any surgical intervention in cases of diagnostic unknowns.

Understanding of the normal appearance of the secondary centers of ossification in the proximal humerus is imperative for accurate diagnosis. The proximal humeral epiphysis becomes radiographically apparent at 6 months of age; for this reason, infantile proximal humerus fractures require other imaging modalities (e.g., ultrasound, magnetic resonance imaging (MRI)) for adequate visualization. The greater and lesser tuberosities appear by 3 and 5 years of age, respectively. The tuberosities coalesce between 5 and 7 years and fuse with the humeral epiphysis at 7 to 13 years of age. Unlike adults, pediatric proximal humerus fractures rarely require computed tomography (CT) scans to identify fracture pattern and guide treatment.

Proximal humerus fractures are characterized according to their anatomic location and displacement. Physeal fractures are typically classified according to the Salter-Harris classification.[17] In addition, Neer and Horwitz[18] have proposed a classification based on the amount of radiographic displacement (Table 26-1).

Radiographic evaluation of humeral diaphyseal injuries is straightforward and based upon AP and lateral views of the entire humerus. The shoulder and elbow joints should be visualized to confirm appropriate joint alignment and rule out the rare associated floating elbow or fracture dislocation. Humeral shaft fractures are similarly classified according to their anatomic location, displacement, and angulation.

Surgical Indications

The time is always right to do what is right.
—Martin Luther King, Jr.

As the proximal physis contributes approximately 80% of the longitudinal growth of the humerus, there is great remodeling potential of displaced proximal humerus fractures in skeletally immature patients. For this reason, the majority of proximal humerus fractures may be successfully treated nonoperatively. Surgical treatment is typically considered in older patients with fracture displacement or angulation beyond what might be expected to spontaneously correct with continued skeletal growth (Neer and Horwitz grade 3 and 4 injuries) or in those patients with concomitant musculoskeletal or neurovascular injury.

Traditional guidelines have been proposed regarding what constitutes "acceptable" proximal humeral deformity amenable to nonoperative care[6,14,18] (Table 26-2). In cases of unacceptable displacement in an older child or adolescent, closed reduction (CR) and/or surgical stabilization of the proximal humerus fracture may provide the best long-term outcome. Current indications for surgical treatment with internal or percutaneous skeletal fixation include open fractures, fractures associated with vascular compromise, fractures in the multiple-trauma patient, displaced intra-articular fractures, and unstable or unacceptable fracture displacement in an older child or adolescent.[7] In the older child, if the proximal aspect of the greater tuberosity impinges on the acromion with attempted elevation, and the child is too skeletally mature to remodel, then closed reduction percutaneous pinning (CRPP) or intramedullary fixation is performed. It is our preference to use percutaneous pins for displaced physeal fractures and intramedullary fixation for metaphyseal injuries.

Table 26.1

Classification of pediatric proximal humerus fractures

Neer and Horwitz Grade	Fracture Displacement
I	<5 mm displacement
II	1/3 shaft diameter
III	2/3 shaft diameter
IV	>2/3 shaft diameter

From Neer CS II, Horwitz BS. Fractures of the proximal humeral epiphysial plate. *Clin Orthop Relat Res*. 1965;41:24–31.

Table 26.2

Guidelines for "acceptable" alignment of proximal humerus fractures in children and adolescents

Patient Age (y)	Angulation (degrees)	Displacement (%)
<5	70	100
5–12	40–70	50–100
>12	<40	<50

From Sherk HH, Probst C. Fractures of the proximal humeral epiphysis. *Orthop Clin North Am*. 1975;6:401–413, Beaty JH. Fractures of the proximal humerus and shaft in children. *Instr Course Lect*. 1992;41:369–372, and Neer CS II, Horwitz BS. Fractures of the proximal humeral epiphysial plate. *Clin Orthop Relat Res*. 1965;41:24–31.

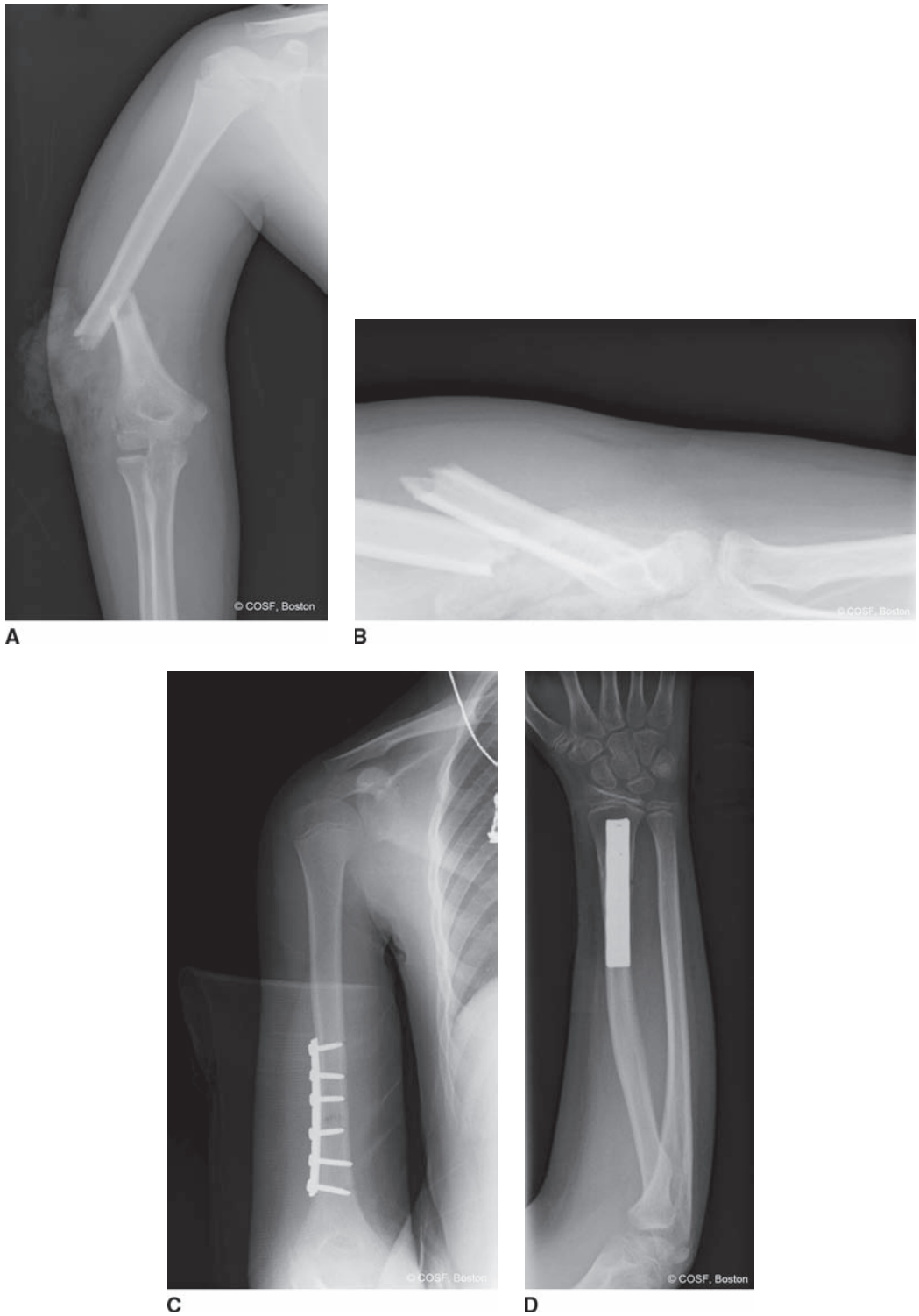

FIGURE 26-2 Open humeral shaft fracture associated with a floating elbow injury in a 10-year-old female after a motor vehicle collision. **A:** AP radiograph of the humerus depicting an open humeral diaphysis fracture. **B:** Lateral radiograph. **C:** Postoperative radiograph of the right humerus after ORIF through the traumatic lateral wound. **D:** Radiograph of the forearm fracture after open plating of the radius, sparing the distal physis.

Similar considerations dictate humeral shaft fracture care. Due to the remodeling potential as well as the compensatory motion of the glenohumeral and scapulothoracic joints, considerable deformity is functionally and aesthetically acceptable. Indeed, up to 30 degrees of angulation, 2 cm of bayonet apposition, and 20 degrees of internal rotation are deemed acceptable. Surgical treatment is indicated in cases of excessive deformity, open fractures, fractures with associated vascular injury, floating elbow injuries, and the multiple-trauma patient (Figure 26-2).

SURGICAL PROCEDURES

A host of surgical techniques are available for reduction and stabilization of proximal humerus and shaft fractures. All are effective, and all should be in the quiver of the pediatric hand and upper extremity surgeon. The decision regarding which method of exposure, reduction, and fixation is dependent upon an array of individual patient factors, including skeletal maturity, injury pattern, and associated bony or soft tissue injuries. In general, the simplest and least invasive technique that can achieve the desired result should be selected.

Fracture reduction with percutaneous or internal fixation offers a number of theoretical advantages. First, bony fixation maintains fracture reduction, decreasing the risk of late displacement that may occur with immobilization alone. In addition, anatomic fracture reduction lessens the risk of shoulder impingement and loss of function. Furthermore, the fracture stability provided by skeletal fixation lessens pain and allows for a more expedient return to activities of daily living. Finally, in cases of severely displaced physeal fractures, anatomic reduction theoretically reduces the risk of post-traumatic growth disturbance.

Disadvantages include all the attendant risks of surgical intervention. In particular, there is a risk of a pin tract infection and/or iatrogenic axillary nerve injury with percutaneous pinning techniques. Finally, in cases where intramedullary fixation is utilized or where pins are cut beneath the skin, a second anesthetic is required for implant removal.

Nonoperative Care

Nonoperative care is appropriate and effective for the majority of proximal humerus and humeral diaphyseal fractures. For proximal humerus fractures, simple sling immobilization is sufficient, with the expectation for bony healing in 4 to 6 weeks. In cases of diaphyseal humerus fractures with acceptable alignment, initial sling or coaptation splint immobilization followed by Sarmiento fracture bracing is effective[19] (Figure 26-3).

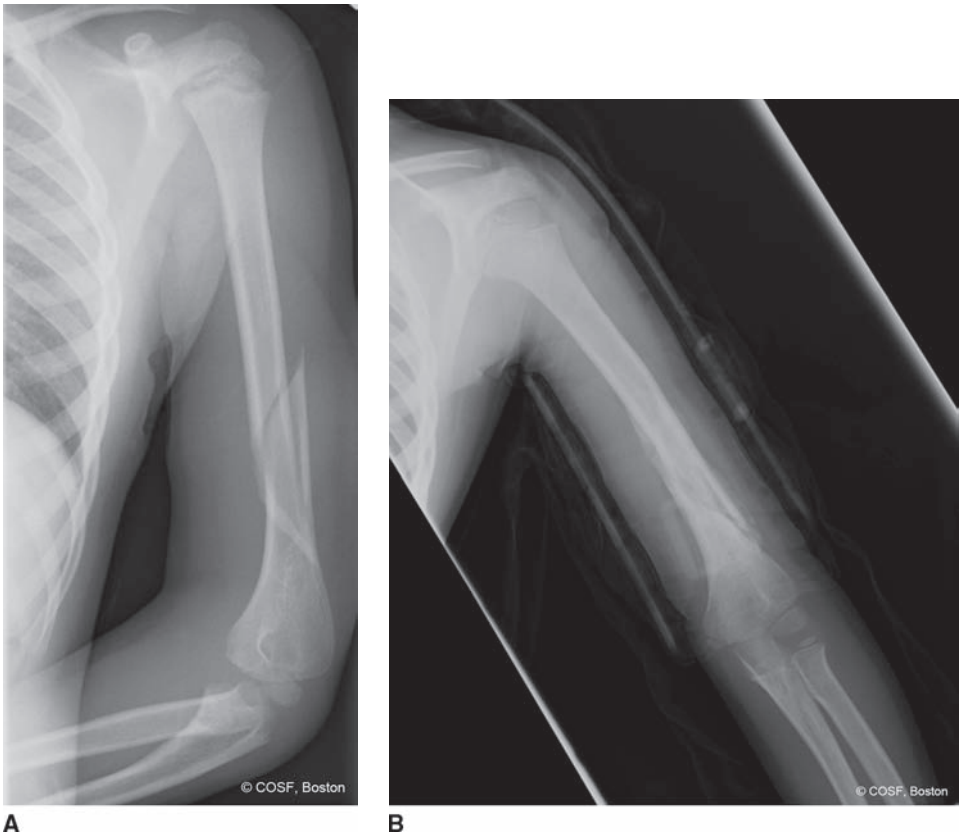

FIGURE 26-3 Nonoperative treatment of humeral shaft fracture. **A:** Injury AP radiograph of a 6-year-old male with an oblique distal third humeral diaphyseal fracture. **B:** AP radiograph after 1 month of Sarmiento fracture bracing. The alignment is well preserved, and early fracture healing is noted.

Closed Reduction and Pinning of Proximal Humerus Fracture

You must not only aim right, but draw the bow with all your might.
—Henry David Thoreau

CRPP is commonly utilized in the treatment of displaced proximal humerus fractures in older children and adolescents. CR maneuvers must counteract the typical deforming forces imparted on the fracture fragments to be successful. In proximal fractures, the humeral head fragment typically abducts, flexes, and externally rotates, due to the action of the rotator cuff muscles. Conversely, the diaphyseal fracture fragment is displaced proximally by the deltoid and adducted and internally rotated by the pectoralis major. While successful CR may be achieved in many cases, up to 50% of patients will demonstrate a loss of reduction with immobilization alone.[8,18] For this reason, percutaneous pinning is added to maintain alignment during the healing process.

The patient is placed supine on a radiolucent table or in the modified beach chair position (Figure 26-4).

A

B

C

FIGURE 26-4 CRPP of displaced proximal humerus fractures. **A:** Modified beach chair positioning allows for fluoroscopic AP and axillary views of the proximal humerus. **B:** Intraoperative image depicting reduction and placement of two smooth K-wires. **C:** Intraoperative axillary view.

We prefer the modified beach chair position, as it allows full shoulder motion and facilitates intraoperative fluoroscopy in the AP and axillary projections. Due to the deforming muscle forces, CR is generally facilitated by general anesthesia with muscle paralysis. The entire shoulder and ipsilateral upper extremity is prepped and draped to facilitate fracture manipulation and fixation. Longitudinal traction followed by flexion, abduction, and external rotation of the humeral diaphysis is applied, reversing the deformity and reducing the distal fragment to the proximal fragment. Alternatively, shoulder abduction followed by forward flexion to 90 degrees followed by external rotation may be utilized to achieve reduction. Intraoperative fluoroscopy in orthogonal planes is used to assess the adequacy of fracture reduction. In situations where an adequate CR cannot be achieved, usually due to soft tissue interposition (biceps tendon, periosteum), open reduction is required. The standard deltopectoral approach is used to expose the fracture site, clear any interposed soft tissue, and restore anatomic alignment. Direct visualization as well as intraoperative fluoroscopy is utilized to confirm reduction.

Once reduction is achieved, percutaneous skeletal fixation using smooth 0.0625" or 5/64" K-wires is performed. Stab incisions are made laterally at the level of the deltoid insertion through the dermis only. While this starting position necessitates a steeper angle for pin placement, this inferior starting position lessens the risk of iatrogenic axillary nerve injury.[20] In adults, the starting point should be >8 cm below the acromion to avoid injuries to the axillary nerve. Blunt dissection is performed down to the level of the lateral cortex of the humeral diaphysis. Two K-wires are then passed from distal-lateral to proximal-medial, traversing the fracture site. A larger drill hole in the lateral cortex often makes exact positioning of the K-wires in the head easier. The risk is penetrating the joint cartilage or neighboring neurovascular structures. Exact placement of stable K-wires in the humeral head by CRPP can be harder than you would think. Pins should be placed parallel or slightly divergent to one another to confer rotational stability, and, again, care is taken not to violate the articular surface of the humeral head.

In cases of marked fracture instability, reduction may be lost when the arm is brought down into the adducted and internally rotated position. In these situations, it may be necessary to place the K-wires with the shoulder abducted, flexed, and externally rotated. As this is technically difficult, the K-wires may be started in the distal lateral humeral diaphysis, stopping short of the fracture site; fracture reduction may then be performed and the preplaced wires passed across the fracture into the proximal humeral segment. Alternatively, a "greater tuberosity pin" may be placed first and used as a joystick to reduce the proximal fracture fragment and provide provisional stability.

Intraoperative fluoroscopy is performed to confirm appropriate pin placement and fracture alignment; ranging the shoulder under live fluoroscopy will demonstrate fracture stability. If additional fixation is required, a third K-wire may be passed proximal-lateral to distal-medial from the greater tuberosity to the distal medial humeral cortex.

After the K-wires have been placed and fracture stability confirmed, the pins may be bent and cut outside the skin or cut beneath the skin. A bulky sterile bandage is applied, followed by a sling and swathe. In larger adolescents, more noncompliant patients, and/or more unstable fractures, an abduction brace or pillow can be used to impart additional stability and protection.

Intramedullary Rodding of Proximal Humerus Fracture

Intramedullary fixation using flexible titanium or stainless steel nails has also been utilized to stabilize proximal humerus as well as humeral diaphyseal fractures.[9,21–23] This technique is familiar to pediatric orthopaedists, and the principles echo those used in forearm and femur fracture fixation.

Again, under general anesthesia in the supine or beach chair position, closed fracture reduction is performed (Figure 26-5). Following bony realignment, preparation is made for intramedullary nail insertion. A longitudinal incision is made along the lateral column of the distal humerus at the level of the superior aspect of the olecranon fossa. Blunt soft tissue dissection is performed through the subcutaneous tissues down to the level of the distal humerus. With adequate soft tissue protection, a 3.2 or 4.5 mm drill bit is used to create a cortical window in the lateral column; care is taken to create this starting hole obliquely from distal-lateral to proximal-medial to facilitate subsequent nail passage. Appropriately sized flexible titanium nails (typically 2.5 to 4 mm in diameter) are then prebent; if both nails are to be passed via a lateral entry point, one nail is bent in the shape of a gentle "C" and the other in the shape of a lazy "S" to allow for some divergence of the nail ends in the proximal fracture fragment. Nails are then passed through the lateral column entry site, up the intramedullary canal of the humerus, across the fracture site, and into the proximal fracture fragment. Typically, the nails must be impacted into the proximal humerus with care to avoid distraction at the fracture site. Translation or angulation at the fracture site may be corrected with nail rotation once the proximal fragment is engaged. Intraoperative fluoroscopy is utilized to confirm nail placement, fracture alignment, and stability. Nails are then cut beneath the skin with the distal ends prominent to allow for subsequent removal. Wound(s) are then closed, the dressing applied, and the upper extremity placed in sling-and-swathe immobilization.

Several variations of intramedullary nail fixation for pediatric proximal humerus fractures have been used with success. Although there have been reports of

successful healing and maintenance of reduction with the use of a single nail, it is our preference to use two nails.[9] Furthermore, while the technique of dual nail placement via lateral column entry is described here, nails may be safely and effectively placed via medial column, medial epicondyle, or posterior humeral entry sites. In cases of posterior nail insertion, a small posterior triceps-splitting approach is used to expose the humeral cortex just superior to the olecranon fossa. Our preference is to use the lateral column entry site to avoid complications of stiffness, nail migration, and ulnar nerve injury seen with posterior and medial entry respectively.

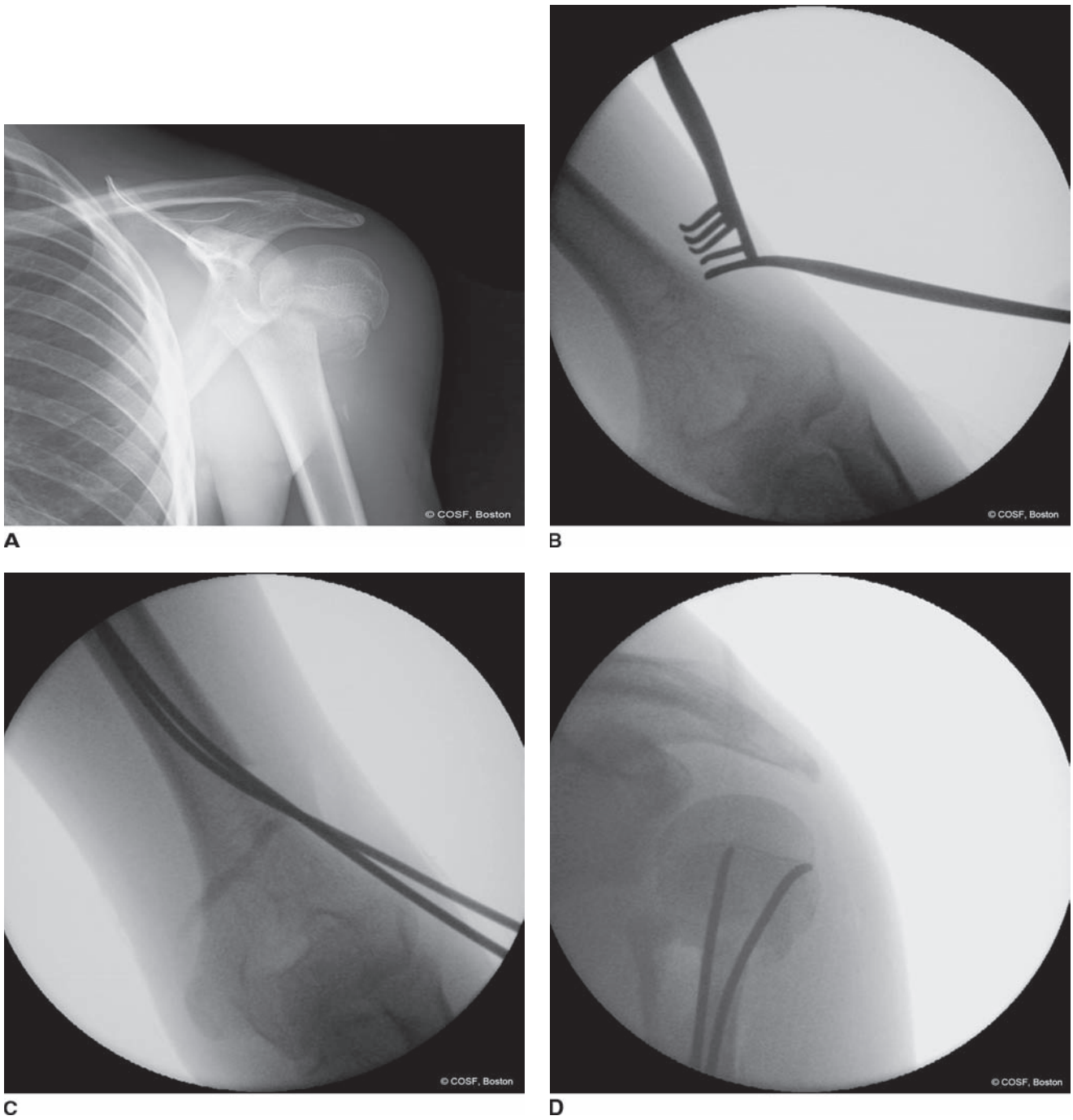

FIGURE 26-5 Intramedullary fixation of proximal humerus fractures. **A:** AP radiograph depicting a displaced proximal humerus fracture. **B:** Intraoperative fluoroscopic image depicting preparation of the nail entry site along the lateral column of the distal humerus. **C, D:** Precontoured flexible titanium nails are then passed into the intramedullary canal of the humerus, engaging the humeral head fragment across the fracture site.

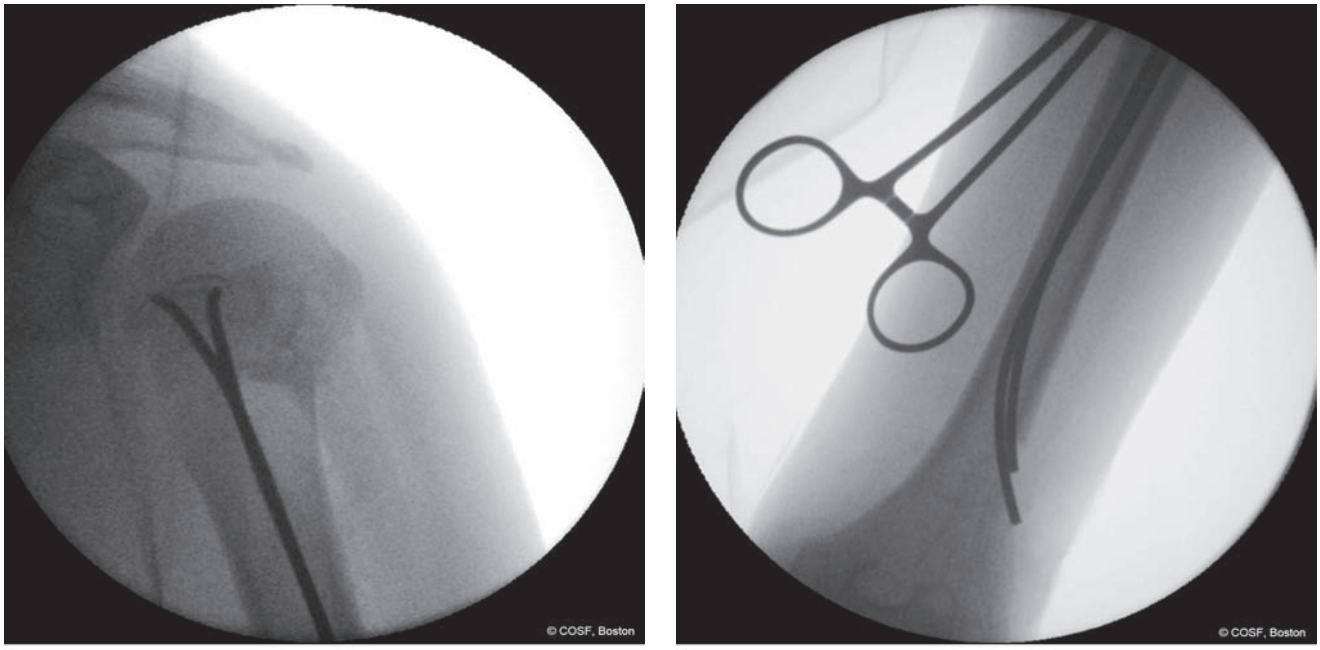

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FIGURE 26-5 *(continued)* **E:** Rotation of the implants may be used to correct residual translation and angulation. **F:** Nails are cut beneath the skin and allowed to recoil against the lateral column, avoiding soft tissue irritation while providing access for subsequent removal.

Open Reduction and Internal Fixation of Humerus Shaft Fracture

Formal open reduction and internal fixation (ORIF) using compression plating techniques is used in specific circumstances. Typical indications include open fractures, associated vascular injury, delayed union or nonunion, and cases in which radial nerve exploration is warranted (see Coach's Corner).

The affected extremity is prepped and draped with the patient in the supine position. General anesthesia is used, though paralytic anesthetic agents may be avoided when radial nerve function is to be assessed intraoperatively. Choice of incision and surgical approach is dependent upon associated soft tissue considerations. In cases of vascular compromise, an extensile medial approach is used to allow bony access as well as exposure of the brachial artery and vein. In cases of radial nerve palsy, a modified posterolateral approach is our preference.[24–26]

A longitudinal lateral incision is made and wide skin flaps are developed (Figure 26-6). The triceps fascia is incised just posterior to the palpable lateral intermuscular septum. From distal to proximal, the triceps is swept posteriorly and medially away from the lateral intermuscular septum. At the junction of the distal one-third and proximal two-thirds of the humerus, the posterior antebrachial cutaneous nerve will be encountered, and this may be traced proximally to the radial nerve. Alternatively, the radial nerve may be found as it crosses the lateral intermuscular septum from the posterior to anterior compartment in the abrupt transition from triceps muscle to perineural fat. While adult cadaveric studies have quantified the distances from the lateral epicondyle to the radial nerve, such measurements are not easily translated to the young, skeletally immature patient. As a general reference, however, the radial nerve does lie directly posterior to the humeral diaphysis at the level of the deltoid insertion, after which it passes laterally and distally toward the lateral intermuscular septum.[26]

After the radial nerve has been successfully identified and circumferentially freed, subperiosteal exposure of the humeral diaphysis may be liberally obtained. Fracture reduction and plate fixation may then be performed following traditional orthopaedic principles. Great care is taken in obtaining adequate proximal exposure and liberation of the radial nerve to avoid iatrogenic nerve injury during plate placement. In younger patients in whom fracture healing potential is more robust and more restrictive postoperative immobilization is planned, four cortices of fixation proximal and distal to the fracture may be sufficient. The wound is closed in layers and the limb immobilized in a simple sling, extended long-arm cast, or rarely an upper extremity spica cast.

Valgus Closing Wedge Osteotomy for Humerus Varus

Humerus varus refers to increased varus angulation of the proximal humerus. Radiographically, humerus varus

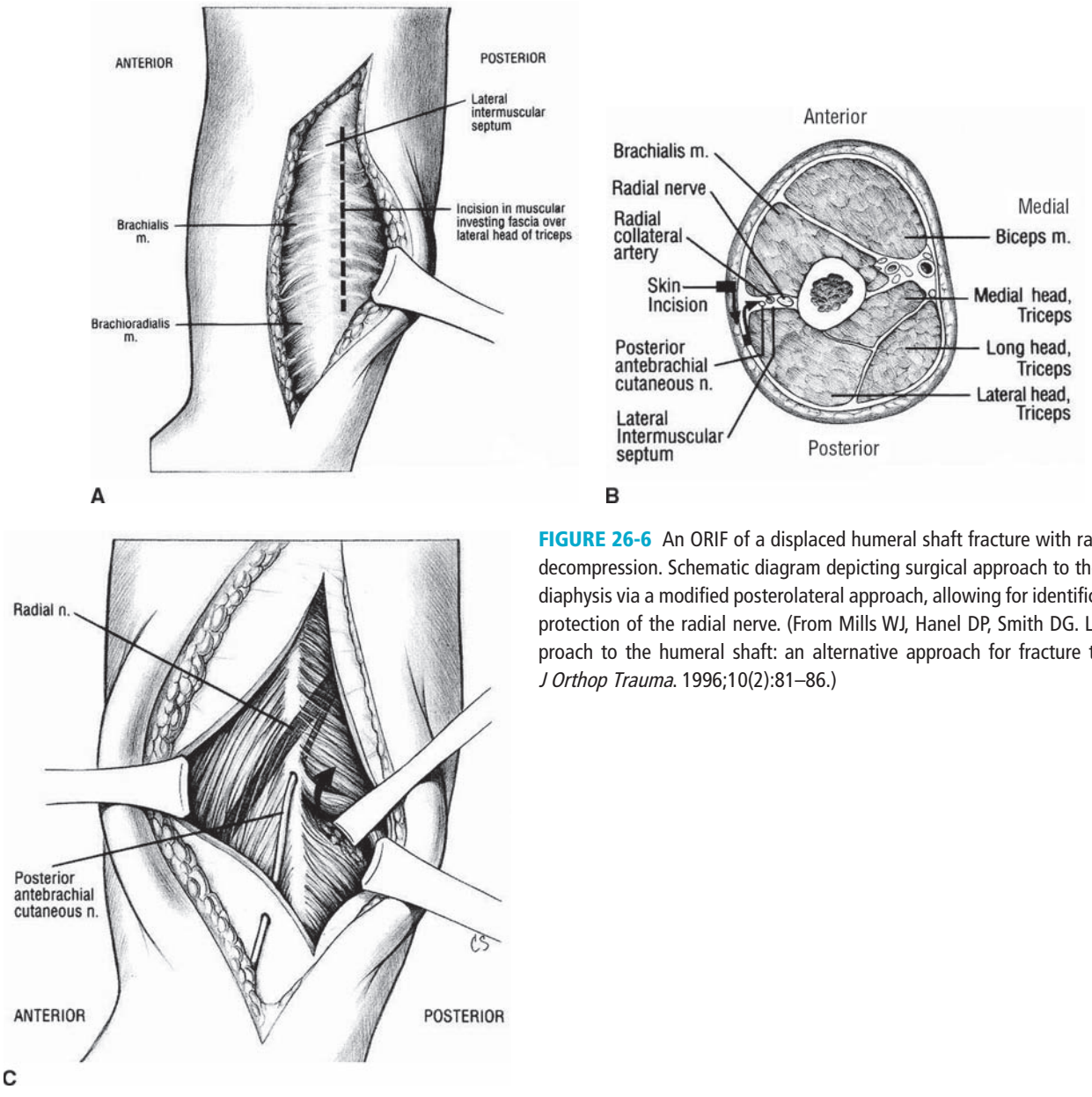

FIGURE 26-6 An ORIF of a displaced humeral shaft fracture with radial nerve decompression. Schematic diagram depicting surgical approach to the humeral diaphysis via a modified posterolateral approach, allowing for identification and protection of the radial nerve. (From Mills WJ, Hanel DP, Smith DG. Lateral approach to the humeral shaft: an alternative approach for fracture treatment. *J Orthop Trauma*. 1996;10(2):81–86.)

is defined by a neck-shaft angle of <140 degrees, a greater tuberosity elevated above the superior margin of the humeral head as seen on an AP view, and a reduced distance between the articular surface of the humerus and lateral humeral cortex.[27] Humerus varus may lead to pain and limitations in forward flexion and lateral abduction of the shoulder as the greater tuberosity impinges against the acromion.

Humerus varus may result from fracture malunion as well as partial growth arrest after prior proximal humerus physeal fracture, osteomyelitis or septic arthritis of the shoulder, or curettage and grafting of proximal humeral cysts.[28–32] In cases of established or progressive humerus varus associated with pain and functional limitations, valgus closing wedge osteotomy is a safe and reliable means of deformity correction and functional improvement.[33,34]

Patients are placed in the modified beach chair position (Figure 26-7). Care is taken to ascertain that appropriate intraoperative fluoroscopic imaging of the proximal humerus can be performed. Preliminary fluoroscopic views are obtained with K-wires placed on the skin to simulate the planned osteotomy and the skin marked defining the anticipated closing wedge saw and/or osteotome cuts. The superior cut will come right off the acromion parallel to the humeral head joint surface; the lateral cut will be perpendicular to the lateral shaft, so the two cuts meet at the medial cortex in the growth arrest. The proximal humerus is exposed via a deltopectoral approach with care taken not to further disrupt the proximal humeral physis. The pectoralis major and deltoid insertions are reflected in a subperiosteal fashion to allow for subsequent

reapproximation. Two parallel 2 mm K-wires are introduced into the lateral cortex of the humeral shaft at the site of the deltoid insertion and directed proximally toward the humeral head perpendicular to the planned osteotomy site for preliminary fixation of the distal fragment. Ideally, K-wires are positioned to cross perpendicular to the planned osteotomy site.

Tension band fixation is prepared using heavy nonabsorbable suture (no. 1 Ethibond, Ethicon, Inc., Somerville, NJ, or no. 2 Fiberwire, Arthrex, Inc, Naples, FL) passed in

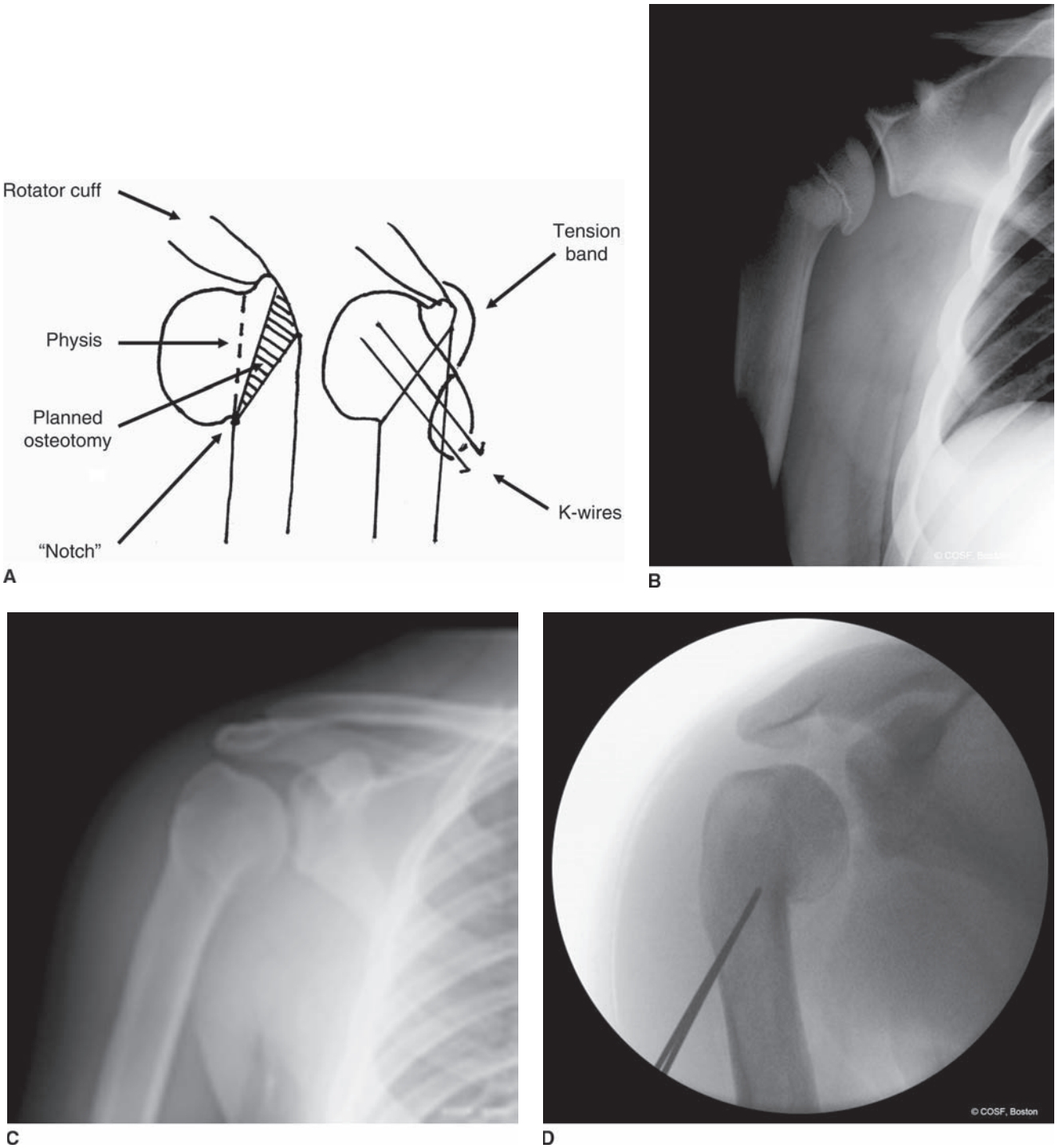

FIGURE 26-7 Valgus closing wedge osteotomy for humerus varus. **A:** Schematic diagram depicting technique of valgus closing wedge osteotomy. **B:** Injury AP radiograph of a 14-year-old right hand–dominant male who sustained a proximal humeral physeal fracture. **C:** AP radiograph 2 years later, demonstrating humerus varus. **D:** Intraoperative fluoroscopic images demonstrating preset K-wires in the distal humerus.

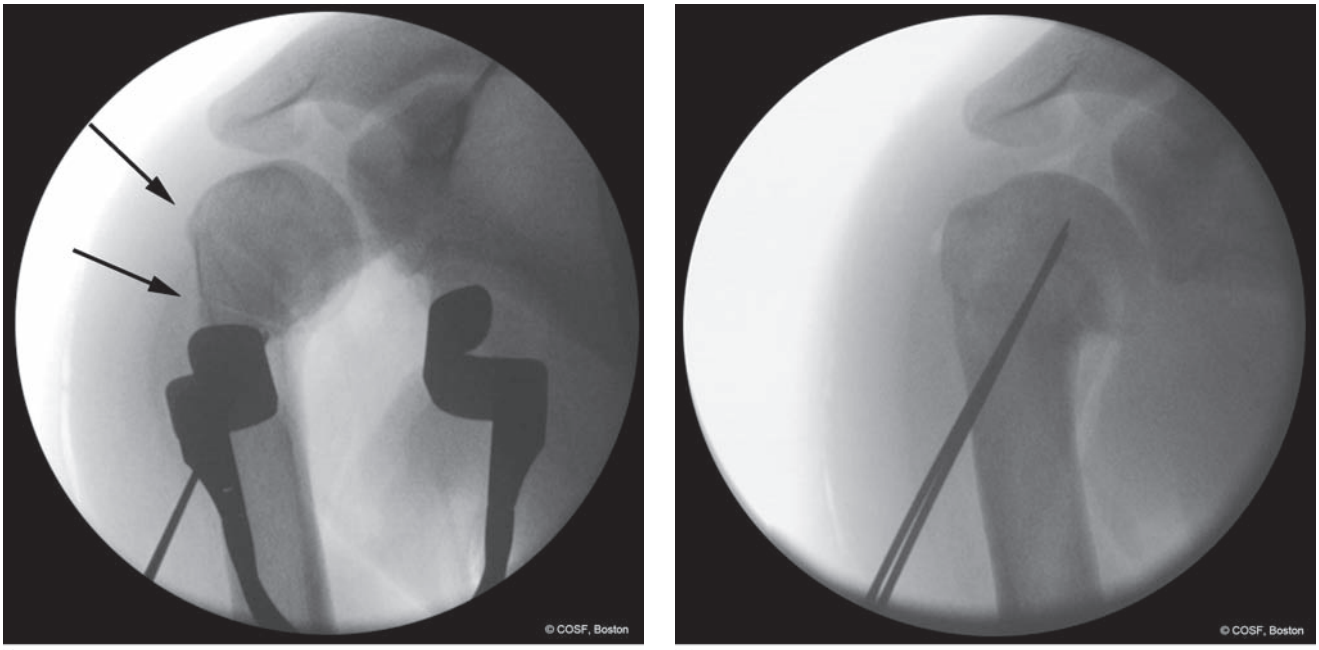

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FIGURE 26-7 *(continued)* **E:** Cuts have been made in the proximal humerus. **F:** Intraoperative images after completion of the closing wedge osteotomy and K-wire fixation.

a figure-of-eight fashion between the insertion of the rotator cuff at the greater tuberosity and K-wires at the humeral shaft. Under direct vision, an oblique closing wedge osteotomy is performed. Angled guides similar to those used for intertrochanteric osteotomies of the hip may be used during surgery to help achieve the desired angular correction as determined from the preoperative radiographs. Furthermore, smaller smooth K-wires may be passed along the planned trajectory of the lateral closing wedge osteotomy to serve as cutting guides and confirm adequacy of deformity correction. The osteotomy is made just distal to the physeal plate in the region of the metaphyseal deformity. Osteotomy cuts are made to converge at the radiographic "notch," corresponding to the point of medial physeal arrest. To avoid iatrogenic injury to the ascending branch of the anterior humeral circumflex artery and thus minimize the risk of humeral head osteonecrosis, the osteotomy is created laterally, and care is taken to preserve the far medial humeral cortex. The medial humeral cortex and periosteum are left intact during the osteotomy, also allowing it to serve as a hinge during closure of the osteotomy, providing additional rotational control at the osteotomy site, and protecting the medial neurovascular structures. At this stage, closure of the osteotomy is performed, followed by immediate passage of the smooth K-wires into the humeral head. Fluoroscopic visualization is used to ascertain appropriate K-wire placement and avoid intraarticular penetration. The tension band sutures are then tightened across the osteotomy site, providing compression and stability at the osteotomy site.

After surgery, older compliant patients are placed in a sling and swathe and may begin gentle pendulum exercises immediately. Very young children and those likely to be noncompliant with activity modification are placed in a shoulder spica cast followed by abduction splint.

◆ Shoulder Fracture Dislocation

Closed Reduction, CRPP, ORIF

Fracture dislocations of the shoulder are uncommon in children and adolescents. Treatment is dependent upon the direction of dislocation and associated fracture pattern. Most commonly, patients sustain an anterior glenohumeral dislocation with associated greater tuberosity fracture (Figure 26-8). In these situations, CR under conscious sedation or general anesthesia is performed, followed by reassessment of the fracture. Typically, the greater tuberosity fracture reduces with joint reduction; in cases where >5 mm of displacement persists, open reduction and pin or screw fixation through a limited deltoid-splitting approach is recommended.[35] In patients with associated physeal or metaphyseal fractures, closed glenohumeral reduction may not be feasible, and formal open reduction and fracture fixation is required (Figure 26-9). A deltopectoral approach is used to access both the joint and proximal humerus fracture. Following reduction, stable internal fixation may be achieved using plate-and-screw constructs.

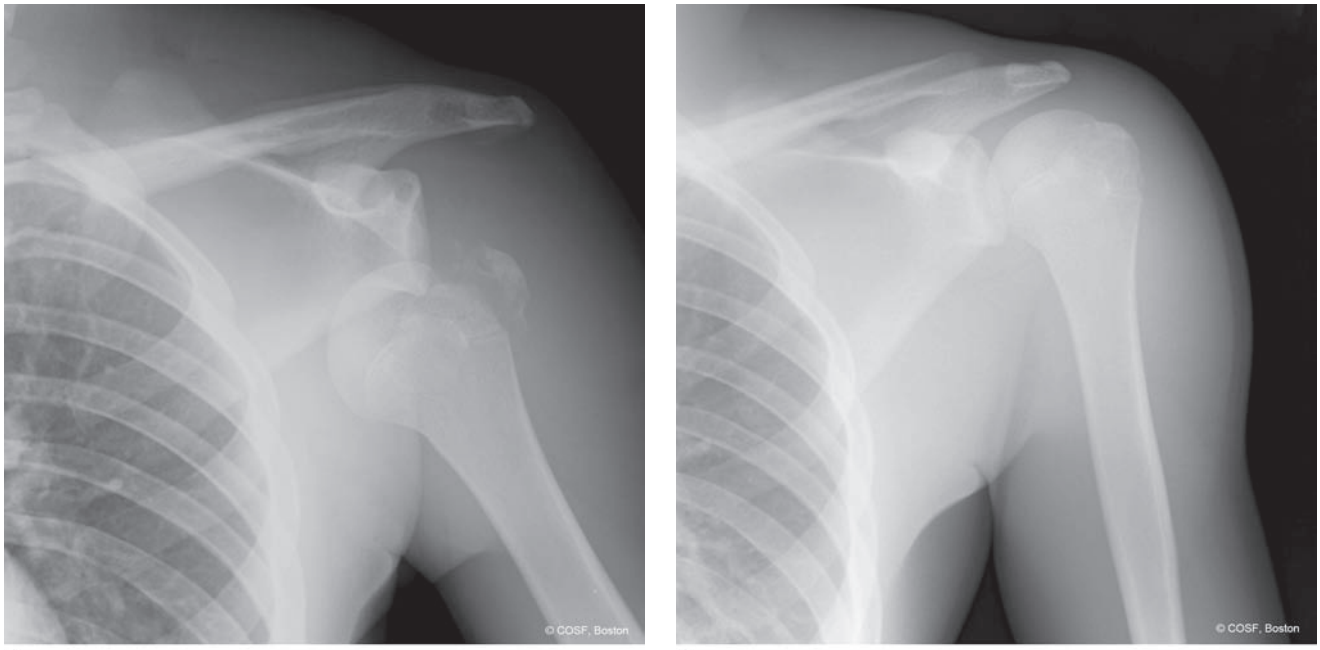

FIGURE 26-8 Glenohumeral joint dislocation with associated greater tuberosity fracture. **A:** Injury radiographs of a 16-year-old male with a fracture dislocation of the left shoulder. **B:** After CR, the greater tuberosity lies in anatomic position.

◆◆ Avascular Limb with Open Humerus Fracture

Rarely, patients with proximal or diaphyseal humerus fractures may present with true limb ischemia.[36–39] Typically associated with valgus proximal humerus fractures or open humeral diaphyseal fractures, these avascular limbs constitute a surgical emergency. Treatment involves irrigation and debridement of open fractures, closed or open fracture reduction with stable internal fixation using percutaneous pinning or plate-and-screw constructs, followed by revascularization. Due to the extensive zone of

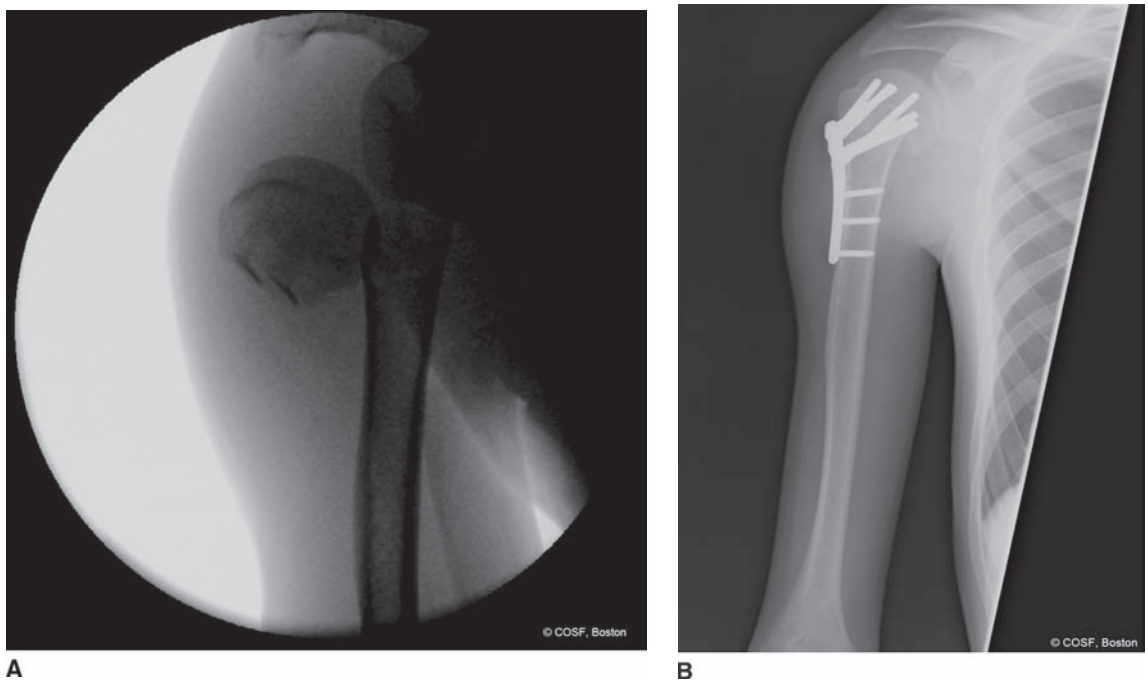

FIGURE 26-9 An ORIF of a right shoulder fracture dislocation. **A:** AP injury radiograph. **B:** Postoperative radiograph demonstrating glenohumeral reduction and rigid fixation of the proximal humerus fracture.

injury seen in these typically high-energy fractures, interpositional vein grafting is commonly needed for vascular reconstitution.

POSTOPERATIVE

Following CR and percutaneous pin or intramedullary nail fixation, patients are sling-and-swathe immobilized for 4 weeks postoperatively. If pins have been left outside the skin, strict immobilization is encouraged to avoid pin migration and pin tract infections. After confirmation of clinical and radiographic healing, percutaneous pins may be removed and the shoulder mobilized. This is typically performed at 4 to 6 weeks postoperatively, though patients treated with intramedullary fixation may begin motion exercises earlier with the implants in place if they are properly trimmed and allowed to recoil against the flare of the lateral column of the distal humerus. Physical therapy for range of motion and strengthening exercises may be initiated following percutaneous pin removal. Return to sports is allowed when shoulder motion and strength return, typically 3 to 6 months postoperatively.

Similar postoperative care is instituted after open reduction and plate fixation. Sling immobilization typically suffices, and early, gentle range of motion of the forearm, wrist, and hand is encouraged. Further shoulder and elbow motion is begun earlier, and unrestricted motion and strengthening are achieved after radiographic evidence of healing. Return to unrestricted activities is anticipated after 3 to 6 months.

After valgus closing wedge osteotomy, sling or cast immobilization is discontinued by the fourth to sixth postoperative week, when radiographic healing is seen across the osteotomy site. After confirmation of radiographic healing, K-wires are removed as a day surgical procedure in the young or in the office under local anesthesia in older patients. A transition abduction brace may be necessary, especially in the young. Active range of motion is begun, with strengthening exercises initiated after complete clinical and radiographic healing, typically 6 to 8 weeks postoperatively.

ANTICIPATED RESULTS

However beautiful the strategy, you should occasionally look at the results.
—Winston Churchill

The published results of percutaneous K-wire or intramedullary flexible nail fixation for displaced proximal humerus fractures demonstrate that these methods provide a safe and effective means of maintaining fracture reduction and ultimately shoulder function in appropriate patients. It is important to remember, however, that surgical treatment is generally reserved for severely displaced injuries in adolescents; there is no controversy regarding the efficacy of sling immobilization for displaced fractures in young children or nondisplaced or minimally displaced injuries in patients of all ages.

Kohler and Trillaud[40] have previously reported the clinical and radiographic outcomes of 52 patients at a mean of 5 years following proximal humerus fractures. Clinical results were "good" or "very good" in all cases, with little correlation to longer term radiographic parameters. Dobbs et al. published their series of 29 patients treated for Neer and Horwitz grade III and IV fractures, of which 25 were treated with closed versus open reduction and pin or screw fixation. The majority of patients were >15 years of age. Postoperatively, all patients improved to a grade I or II deformity, and there were no surgical complications. At a mean follow-up of 4 years, normal or near-normal motion and strength were seen in all patients.

Chee et al.[9] presented their series of 14 patients, mean age 13 years, treated with single intramedullary flexible nail fixation for displaced proximal humerus fractures. All patients had full range of shoulder motion at final follow-up, supporting the authors' assertion that intramedullary fixation is effective in select patients.

Similarly good results may be expected after corrective osteotomy of humerus varus.[33,34]

COMPLICATIONS

Despite the successful results of surgical treatment, complications may occur. Pin migration, pin tract infections, and wound drainage may be seen in cases of percutaneous pin fixation when the pins are bent and cut outside the skin. While this facilitates implant removal and obviates the need for a second anesthetic, cutting wires beneath the level of the skin may avoid these common minor complications. Axillary nerve injury with proximal humerus percutaneous pinning and radial nerve injury with humeral shaft fractures are clear risks. Elbow stiffness may be seen following flexible intramedullary nail placement, particularly when a posterior entry point is utilized; lateral and/or medial column entry may minimize this risk. There is a theoretical risk of iatrogenic humerus fracture with intramedullary nail placement, though this complication may be avoided using the techniques described here. Finally, proximal humeral growth disturbance is a theoretical concern any time implants are placed across the physis; the use of appropriately sized smooth K-wires and timely implant removal may serve to minimize this risk. Minor growth differences do occur with proximal humeral physeal fractures but rarely enough to impair function or require treatment.

CASE OUTCOME

Given the patient's age and fracture displacement, surgical reduction and percutaneous pin fixation was performed, with an excellent radiographic and clinical result (Figure 26-4).

SUMMARY

While the majority of proximal humerus fractures in children and adolescents are effectively treated by simple immobilization, fracture reduction and stabilization using percutaneous K-wire or intramedullary nail fixation is useful, particularly in the older adolescent with a severely displaced injury. With proper patient selection, meticulous surgical technique, and appropriate aftercare, shoulder motion and function may be safely and effectively restored.

COACH'S CORNER

Radial Nerve Palsy and Humeral Shaft Fractures

Due to its course around the posterior aspect of the humeral diaphysis and through the lateral intermuscular septum from the posterior to anterior compartments, the radial nerve is commonly injured in association with humeral diaphyseal fractures.[41] It is clear that the majority of these nerve palsies—when present at the time of injury—are due to neurapraxic mechanisms and will demonstrate spontaneous recovery over the ensuing weeks to months.[41–58] For this reason, observation with serial examinations is recommended, with treatment predicated by standard fracture care.

There are specific situations, however, in which radial nerve exploration—and decompression, repair, or secondary reconstructions—is warranted. First, radial nerve palsy associated with open fractures of the humeral diaphysis should be treated with urgent irrigation and debridement, fracture reduction and stabilization, and radial nerve exploration. There is abundant evidence that the radial nerve is more likely to be lacerated or interposed between fracture fragments in open fractures. Second, radial nerve exploration should be strongly considered when radial nerve function is initially intact but is lost following closed manipulation or surgical treatment (Figure 26-10). Although the temptation exists to observe expectantly, the burden of proof lies with the treating upper limb surgeon to ascertain that the radial nerve is in continuity and not incarcerated within the fracture or impaired by an implant. Furthermore, radial nerve exploration and possible reconstruction should be considered in closed injuries with failure of anticipated recovery in a timely fashion. Although complete neurologic recovery may not be seen for 6 months, in cases of neurapraxic injury, there should be signs of gradual recovery over time: an advancing Tinel sign, recovery of wrist extensor function by 3 months, and gradual improving elbow motion. Failure of these signs should raise concern for an axonotmetic or neurotmetic injury requiring surgical treatment. This is particularly concerning if persistent radial nerve palsy is seen in association with a round lucency at the fracture site, which may represent the nerve entrapped and surrounded by fracture callus.[59]

Finally, though electrodiagnostic studies (electromyography [EMG] and nerve conduction velocities [NCV]) have been advocated to document recovery and assess the extent of injury, caution should be taken when using and interpreting these modalities. Electrodiagnostic evidence of nerve continuity does *not* necessarily correlate with clinically meaningful motor function recovery, and EMG/NCV studies should be used as an adjunct—not false assurance—in the care of peripheral nerve injuries.

In cases of humerus fractures and radial nerve palsy in which neurologic recovery does not proceed as anticipated, we advocate exploration at 3 to 6 months postinjury. Treatment is predicated by the injury pattern, though direct neurorrhaphy or sural nerve grafting may be needed to restore radial nerve function.[59–62] Partial median to posterior interosseous nerve transfers and late tendon transfers are other options (see Chapter 37).

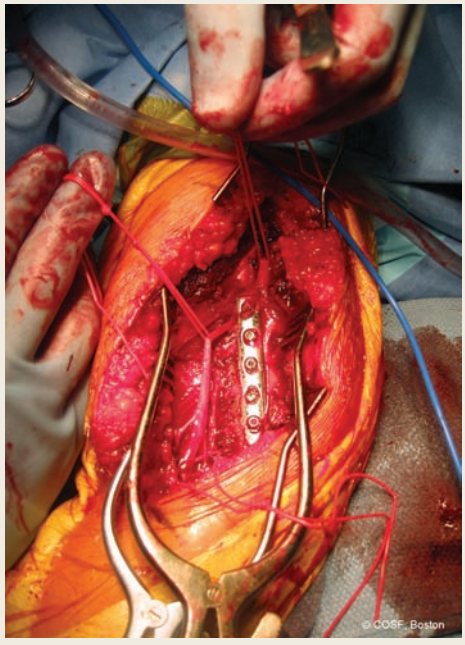

FIGURE 26-10 Intraoperative photograph of an adolescent with a radial nerve palsy following plate fixation of a left humeral diaphysis fracture treated at an outside institution. The radial nerve (identified by the elastic loops) is seen passing below the superior aspect of the plate.

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CHAPTER

27

Distal Humerus Fractures

CASE PRESENTATION

A 5-year-old male falls from the monkey bars at the playground and suffers a supracondylar humerus fracture of his nondominant elbow. No other injuries occurred with the fall. In the emergency room, he is noted to have a pale hand with no radial or ulnar pulse. Testing of his median nerve reveals absent light touch sensibility and no thenar intrinsic opposition or flexor pollicis longus (FPL) motor function. His radiographs reveal a completely displaced fracture (Figure 27-1).

CLINICAL QUESTIONS

- What is the incidence of supracondylar humerus fractures?
- How are these fractures classified?
- What is the incidence of associated neurovascular injuries?
- When is closed reduction or cast immobilization alone indicated?
- What are the indications for closed reduction percutaneous pinning (CRPP)?
- How frequently is open reduction internal fixation (ORIF) performed?
- Are there indications for traction treatment?
- Is an overnight delay for surgery safe?
- Is it best to use lateral entry or crossed medial and lateral pins?
- What is the significance of a pink pulseless hand?
- When is exploration of the brachial artery indicated?
- What is the risk of permanent neurologic injury?
- When is surgical treatment of an injured nerve indicated?
- What are the risk factors for a Volkmann ischemic contracture?
- When is an osteotomy of a malunion indicated?
- What is the best treatment for a T-condylar humerus fracture?
- What are the diagnostic signs of a nonaccidental physeal fracture?

THE FUNDAMENTALS

Etiology and Epidemiology

Supracondylar humerus fractures are most often due to a fall from a height. It is usually the nondominant, outstretched arm (and therefore, typically the left arm since only 8% to 15% of the world's population is left-hand dominant) that hits the ground first and hardest.[1,2] Fortunately, most supracondylar fractures are isolated injuries. Children with ligamentous laxity and hyperextension at the elbow have a higher predilection for a supracondylar rather than a forearm fracture with a fall.[3] The peak age is 5 to 6 years, which is also a time when children have more ligamentous laxity and resultant elbow hyperextension.[4,5] The anatomic mechanism of injury is that the olecranon abuts the olecranon fossa, and the anterior capsule simultaneously provides anterior tension. This combination of traumatic forces propagates an extension fracture through the thin supracondylar bone of the distal humerus. Only about 1% of these injuries are open fractures, but near open fractures with entrapment of the brachialis muscle, periosteum, neurovascular structures, and skin and subcutaneous tissue in the fracture site are more common. On average, there is about an 8% risk of nerve injury. However, the more severely displaced the fracture, the higher the risk of neurovascular compromise. Displaced fractures have, on average, a 20% to 40% risk of neurovascular injury. Supracondylar fractures are the most common and riskiest fractures about the elbow in a child.

Floating elbow injuries with simultaneous supracondylar humerus and forearm fractures are an even higher energy trauma and, therefore, are at more risk for compartment syndrome. Metaphyseal-diaphyseal fractures are more often due to a direct blow and are harder to align by percutaneous pinning techniques. Nonaccidental trauma, including a difficult delivery at birth, can result in a distal humeral physeal separation. A high index of suspicion is necessary for acute diagnosis and treatment of transphyseal injuries, especially when the secondary centers of ossification have yet to appear. T-condylar humerus fractures are usually due to high-velocity sports injuries in the adolescent and require adult-type treatment for best results.

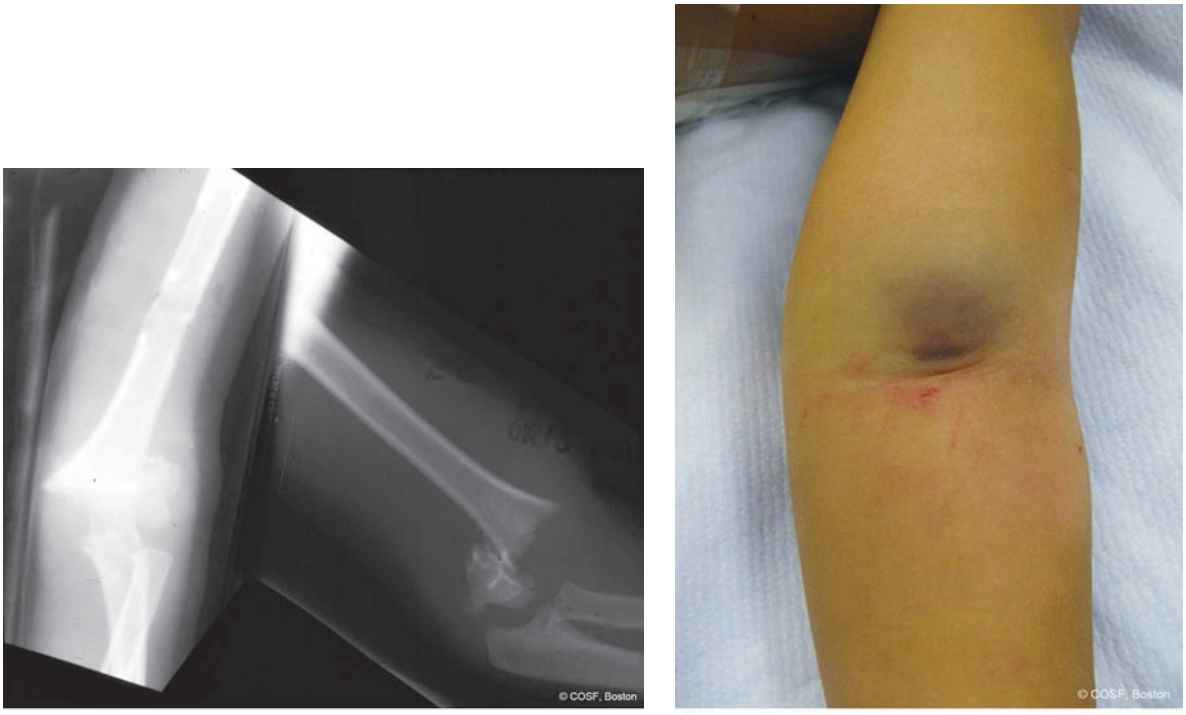

FIGURE 27-1 **A:** Radiographs of a markedly displaced supracondylar humerus fracture. The medial metaphyseal spike of the proximal fragment is tenting the skin (**B**), and presumably the neurovascular bundle (NVB) is draped over this displaced bone and compressed.

Clinical Evaluation

Physical Exam

A careful exam in the acute care setting is mandatory with supracondylar fractures. The presentation can range from minimal swelling and tenderness to marked deformity (Figure 27-2). With the nondisplaced, stable injuries, the child will not move or use the limb. The differential diagnosis includes, among others, infection (septic arthritis, osteomyelitis), inflammatory arthritis (Lyme, juvenile rheumatoid arthritis), nursemaid's or pulled elbow, and an occult fracture elsewhere in the upper limb. Palpation of the entire limb from clavicle to fingers is required. Monitoring of body temperature, generalized physical exam for skin rashes or joint effusions, and appropriate laboratory testing for infection or inflammatory arthritis may be indicated. A posterior fat pad sign on the lateral radiograph is suggestive of a nondisplaced elbow fracture.[6] These stable fractures are in a sense not a problem, as they will heal well without complications. You just do not want to miss a minimally displaced fracture with medial comminution that could drift into varus; an acute infection that needs surgical and antibiotic treatment; an inflammatory or systemic condition that you are treating instead as a localized trauma; or a nonaccidental trauma that puts a child at greater risk without social and medical intervention.

FIGURE 27-2 Intraoperative photograph in splint of a displaced type III supracondylar humerus fracture with marked deformity and anterior ecchymosis. The distal capillary refill is intact.

The displaced fractures are obvious by the deformity at presentation but need a very careful and critical exam for neurovascular compromise and associated injuries. Inspect the anterior cubital fossa for an open fracture, especially when the skin is tented and ecchymotic. Look for skin puckering that indicates the metaphyseal spike of the proximal fragment has entrapped the subcutaneous tissues. A pucker sign means more disruption of the brachialis muscle, soft tissues, and risk of neurovascular entrapment. A precise, step-by-step exam of the three

major nerves (median, radial, and ulnar) in the upper limb and vascularity of the hand (palpable pulses, capillary refill, and color of the hand) is imperative in all displaced fractures. The *median nerve* motor function is tested by isolating extrinsic (FPL and index finger flexor digitorum profundus [FDP II]) and intrinsic (thenar opposition) muscles; the *ulnar nerve* extrinsics by flexor digitorum profundus small finger (FDP V) and intrinsics by first dorsal interosseous (index finger abduction with metacarpophalangeal [MCP] joint flexion) muscle testing; and the *radial nerve* extrinsics by extensor pollicis longus (EPL) (thumb retropulsion and interphalangeal [IP] joint extension), extensor digitorum communis (EDC) (finger MCP joint extension), and/or wrist extension assessment. Of note, isolated nerve injuries to the anterior interosseous branch of the median nerve (FPL, FDP II) are the most common motor impairment with pediatric supracondylar humerus fractures due to this nerve's location right next to the displaced fracture.[7] The direction of fracture displacement usually coincides with the nerve injury and matches the local anatomy: median nerve injury from posterolateral fractures; radial nerve injury from posteromedial fractures; and ulnar nerve injury from flexion displacement.[8] Multiple nerve injuries are common. Sensibility is tested by light touch in all children and two-point discrimination in children >5 years of age. Do not test sensibility by painful pin prick. The median nerve distribution for sensibility is thumb and index finger pulp; ulnar nerve is small finger pulp; radial nerve is dorsal first web space. Accurate preoperative documentation is critical to postoperative decision making. If you cannot tell the status of a nerve by motor and sensibility testing, be truthful in the chart and note that. Later, if the nerve is not functioning, an inaccurate exam or record can impair you or your consultants in making the best decisions about observation versus intervention.

Assessing the vascularity to the hand is critical in defining the extent of soft tissue injury, risk of compartment syndrome, and operative urgency. Start with the color of the hand. Pale is a major problem; pink is obviously good. Up to 20% of supracondylar fractures will have vascular impairment upon presentation. Feel for a pulse and be certain it is not your own. Check the capillary refill, which is normally <3 seconds, and feel the fullness of the pulp. The patient can have a pink hand with normal capillary refill, full pulp, and still have no pulse, thus, the pink pulseless hand (see Sidebar 1). If the median nerve is out in a pink pulseless hand, this is still a surgical emergency. No one will disagree that a pale pulseless hand is a surgical emergency. Also, always look for at risk signs and symptoms for a developing compartment syndrome that will lead you to the operating room more emergently. They include marked swelling, skin puckering, absent pulse and nerve impairment, no bony contact of fracture fragments, and an increasing analgesia requirement that does not relieve the pain, among others.

Radiographic Classification

For evaluation of an acute elbow injury, anteroposterior (AP) and lateral radiographs are standard. Unfortunately, you usually get at least one if not two oblique views instead. Requesting views of the elbow rather than of the distal humerus compounds the problem since all elbow injuries present with an elbow flexion posture. This leads to overlap of the proximal forearm and distal humerus on the AP x-ray view of the elbow, but AP and lateral views of the distal humerus will reveal clear images of the fracture.

Distal humeral varus-valgus alignment is assessed by Baumann angle of the humeral-capitellar line on the AP view (Figure 27-3).[9–12] On the lateral view, the anterior humeral line through the anterior half of the capitellum and the lateral humeral-capitellar angle (usually 40 degrees) defines flexion-extension deformity (Figure 27-4).[13] Since the capitellar secondary center of ossification is the first to appear at 1 to 2 years, the alignment of the distal humerus in most pediatric traumatic injuries can be evaluated by humeral capitellar measurements. The medial epicondylar epiphyseal angle is used by some to assess fracture malalignment and adequacy of reduction in the child old enough to have the medial epicondylar secondary center of ossification.[14] An anterior fat pad sign is often normal, but a posterior fat pad sign is frequently

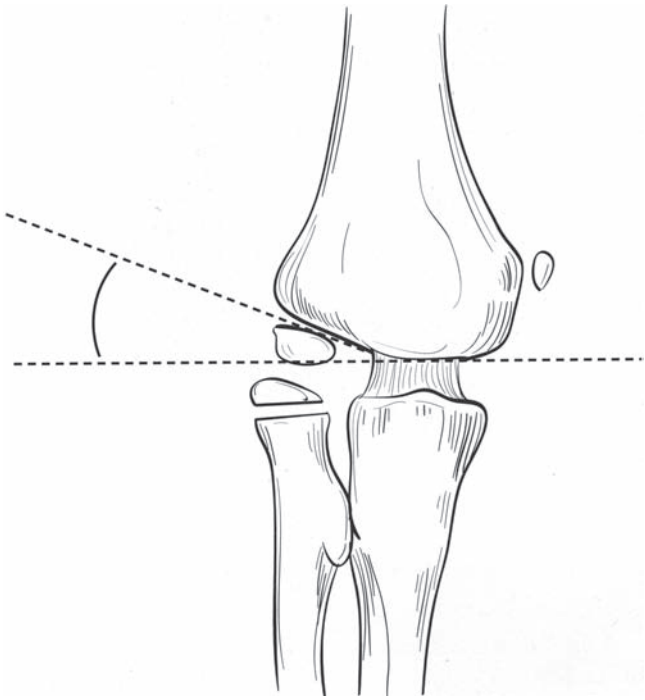

FIGURE 27-3 Baumann angle is illustrated as it would be measured on an AP radiograph of the distal humerus with lines drawn perpendicular to the long axis of the humerus and through the physeal line of the capitellum (From Bucholz RW, Court-Brown CM, Heckman JD, Tornetta P. *Rockwood & Green's Fractures in Adults*. 7th ed: Philadelphia, PA: Lippincott Williams & Wilkins; 2010, with permission.)

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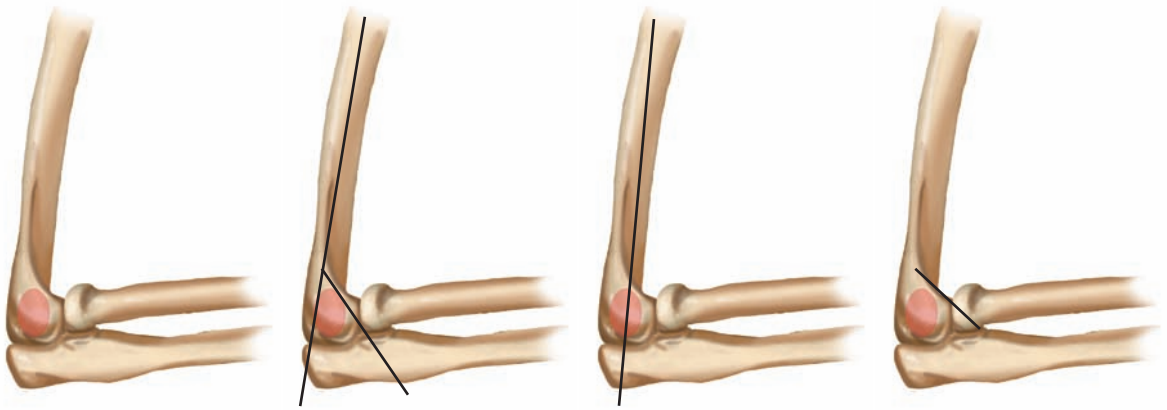

FIGURE 27-4 Illustrations of lateral radiographs of the distal humerus to indicate after the anterior humeral line passing through the capitellar ossification center and the teardrop of the elbow between coronoid and anterior distal humerus.

indicative of an occult elbow fracture (Figure 27-5). The use of CT scans is generally reserved for T-condylar humerus fractures, while MRI scans are employed when there is a diagnostic dilemma or complex fracture dislocation to reveal injuries to the physeal and/or articular cartilage. Ultrasounds are helpful in nonaccidental trauma before the secondary centers of ossification appear.[15–17]

Supracondylar and transphyseal fractures are classified by direction and degree of displacement. Up to 98% of fractures are displaced in extension. The extension fractures are further defined as posteromedial (varus) or posterolateral (valgus). Flexion deformity occurs rarely. Both extension and flexion fractures have three-dimensional deformity and thus also malrotation.[18] The Gartland classification and its modifications define the degree of displacement: type I nondisplaced, type II displaced but hinged with cortical contact, and type III displaced with no cortical contact.[19–21] The modified Gartland classification really helps determine the type of treatment (immobilization alone, closed reduction and immobilization, and reduction and pinning), timing of surgical intervention (emergent, urgent in the morning, or in the next few days), and risk of neurovascular impairment (the higher the class type, the greater the risk). Beware of the "tweeners": Type "1.5" may collapse and be a risk for deformity in a cast (Figure 27-6), type "2.5" is more at risk for instability and neurovascular compromise, and type "3.5" may be unstable in all directions (Skaggs type IV).

Intra-articular humerus fractures are defined by column (medial, lateral, or both) and degree of comminution. The AO classification is used most often (Figure 27-7). T-condylar fractures in the adolescent are usually AO C1 and C2 injuries. Metaphyseal-diaphyseal fractures are separate entities and need to be recognized as such for proper treatment and fixation decisions (Figure 27-8).[22] Floating elbow injuries include simultaneous fractures above and below the elbow joint. More proximal open fractures may require external fixation.

FIGURE 27-5 Lateral radiograph revealing both an anterior and posterior fat pad sign. This patient had a mild supracondylar humerus fracture treated closed.

Surgical Indications

The strong take from the weak, but the smart take from the strong.
—Pete Carril

All displaced supracondylar, transphyseal, metaphyseal-diaphyseal, and T-condylar fractures require reduction and stabilization (Figure 27-9). Almost all, if not all, of these injuries are treated with operative fixation, either percutaneous or open. The major differences in treatment have to do not with whether to perform surgery but rather when and how. Open fractures, pending compartment syndromes, and avascular limbs are emergencies. There is now sufficient evidence to know that overnight delay in surgery is acceptable as long as there is not vascular compromise, worsening peripheral neurologic status, and the wait is not too long (see Coach's Corner).[23–30]

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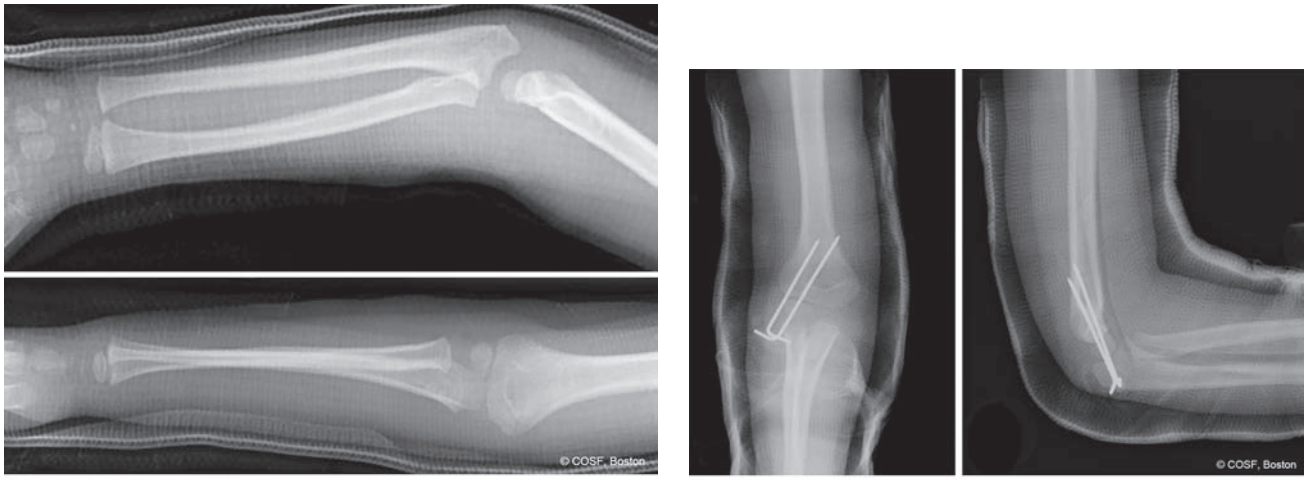


FIGURE 27-6 **A:** Preoperative radiographs revealing minimal extension and varus deformity. Our concern with these "tweener" injuries is long-term deformity, especially in the cubitus rectus children. **B:** CRPP was performed as noted by the radiographs.

SURGICAL PROCEDURES

You can discover more about a person in an hour of play than in a year of conversation.
—Plato

It is important to understand that: (1) there are many different ways to successfully treat supracondylar humerus fractures, and (2) supracondylar humerus fractures have the highest rate of complications of any pediatric fracture. The standard of treatment now is CRPP for displaced supracondylar and transphyseal fractures. The surgical variance is on how many pins (two, three, or rarely more); entry site (lateral only or medial and lateral); and angle of pin placement (parallel or divergent [preferred], distal to proximal [by far the most common], or proximal to distal). Closed reduction and immobilization (cast, collar, and cuff) and traction treatment can be successful, but both have higher rates of malunion and are used rarely now. The ORIF approach is reserved for an avascular limb and irreducible and open supracondylar fractures but could be performed successfully for many displaced fractures. An ORIF with bicolumn plates and screws is the standard treatment for T-condylar humerus fractures in children and adolescents,[31] but some simpler fractures in younger children can be treated with multiple percutaneous pins and/or screws. Both the choosing and the execution of the treatment really make a difference in the outcome of these injuries.

Immobilization

The nondisplaced, stable fracture will heal regardless of what immobilization is chosen. Sling, collar and cuff, posterior splints, and casts have all been used successfully. There is some limited evidence that the children are more comfortable in a posterior above-elbow splint or bivalved cast. Immobilization also protects against repeat injury that could lead to fracture displacement.[32] It is important not to mistake the fracture with minimal medial comminution for a nondisplaced, stable fracture, as this "tweener type 1.5" fracture is the one that will drift and heal in varus and extension with limited immobilization.[33]

Closed Reduction

Type II and even some type III fractures have been treated successfully with closed reduction and cast, sling, splint, or collar and cuff immobilization.[34–42] If closed reduction and immobilization are chosen, careful follow-up clinically and radiographically is necessary to prevent complications. Supracondylar, and especially transphyseal, fractures heal quickly, and there is limited time for repeat reduction. Successful second reduction or conversion to a CRPP or ORIF technique for an impending malunion has been reported on average at 6 days with a range from 2 to 19 days.[43] For us, all displaced (type II and III) fractures are treated with operative reduction and pin stabilization.[44,45] The CRPP approach lessens the risk of malunion in an extended (<90 degrees) cast and neurovascular compromise in a flexed (>120 degrees) cast.[46]

The reduction technique is the same for closed reduction and immobilization or CRPP. With the patient under anesthesia, gentle longitudinal traction is applied with the arm in approximately 30 degrees of flexion until the soft tissues and bony fragments disengage. The closed reduction can be performed with one of the surgeon's hands controlling the distal fragment and the other hand stabilizing the upper arm and proximal fragment or by the surgeon distracting with both hands on the forearm or distal fragment and the assistant holding the upper arm. If there is brachialis muscle entrapment by the metaphyseal

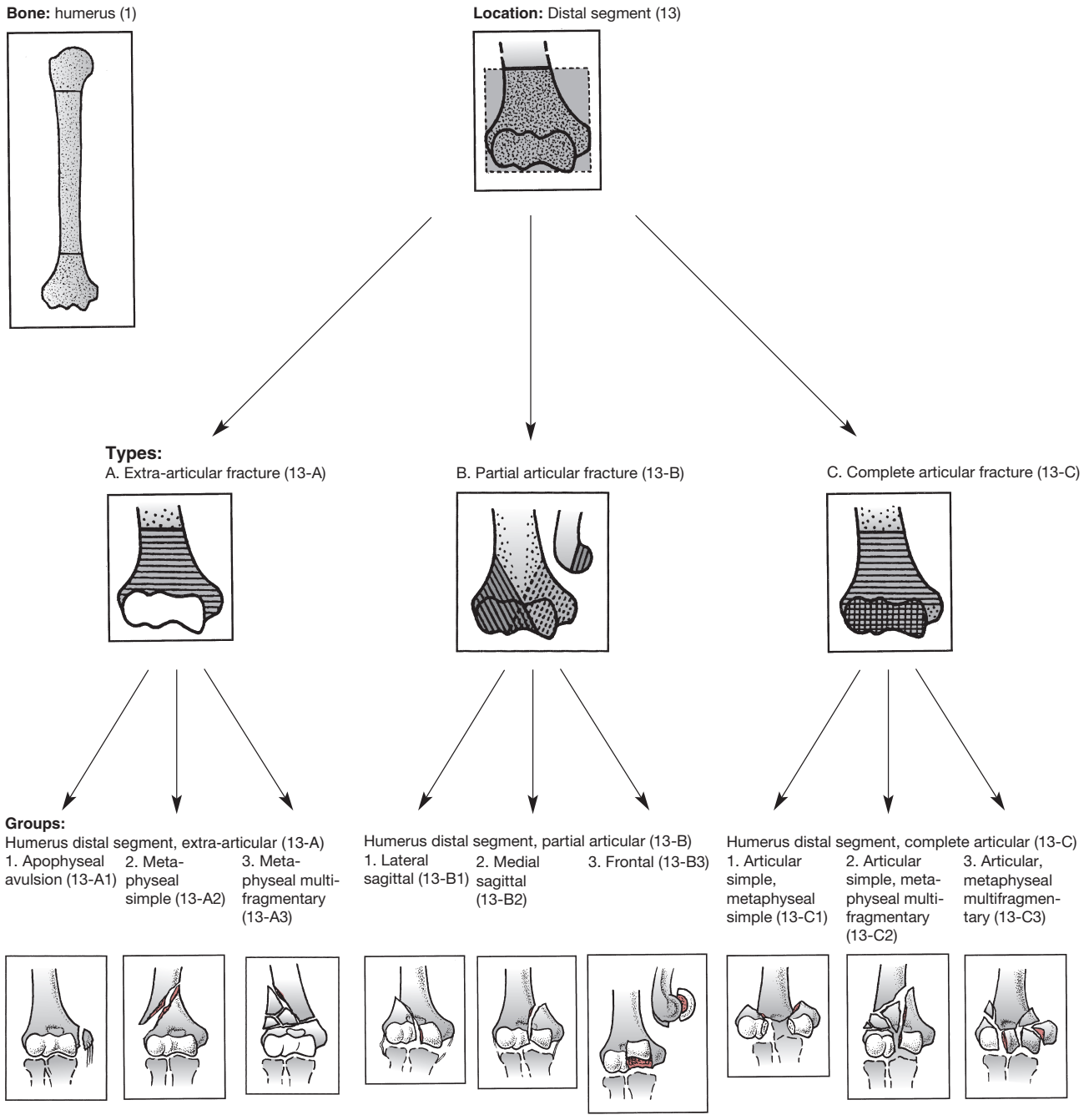
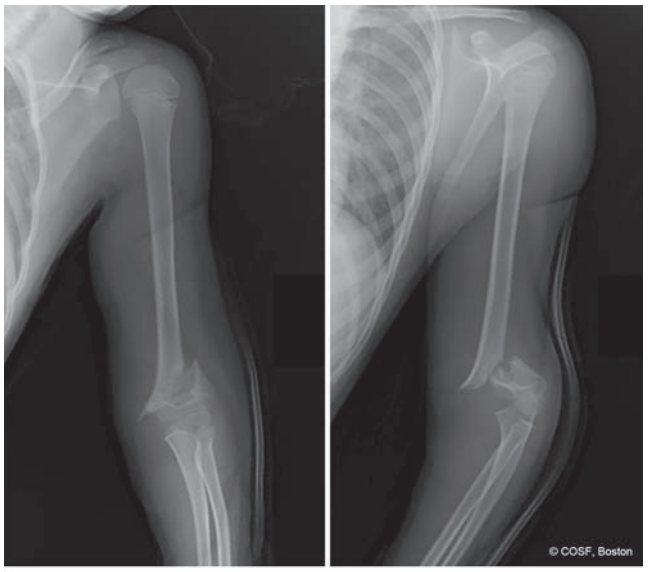
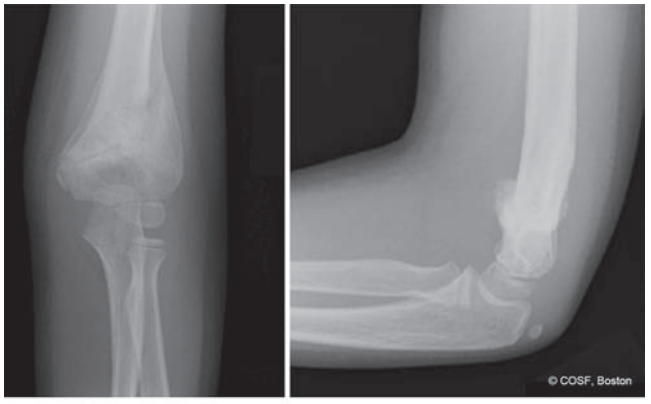


FIGURE 27-7 AO classification of distal humerus intra-articular fractures with C1 (simple articular and simple metaphyseal); C2 (simple articular and multifragmentary metaphyseal); and C3 (multifragmentary articular and metaphyseal). (From Bucholz RW, Court-Brown CM, Heckman JD, Tornetta P. *Rockwood & Green's Fractures in Adults*. 7th ed. Philadelphia, PA: Lippincott Williams & Wilkins; 2010, with permission.)

proximal fragment, the milking maneuver is performed from proximal to distal (Figure 27-10).[47,48] Once the fracture fragments are mobile, valgus-varus malalignment is corrected in 30 to 40 degrees of elbow flexion to prevent neurovascular entrapment. The surgeon's thumb controls one side of the humerus, and the other digits control the other side of the humerus during correction of malalignment (Figure 27-11). Finally, the surgeon's hands are rotated with the thumb over the olecranon apophysis and displaced distal fragment, and the rest of the hand is anterior on the humeral diaphysis to stabilize the proximal fragment (Figure 27-12). An alternative method is to have both of the surgeon's thumbs on the olecranon and the fingers of both hands on the proximal humerus. The extended fragment is then flexed >120 degrees by holding the proximal fragment stable and bringing the olecranon

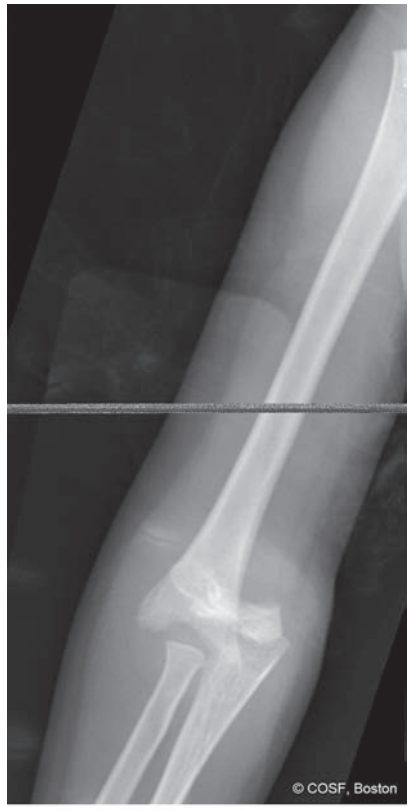


A



B

FIGURE 27-8 **A:** Metaphyseal-diaphyseal fracture with displacement. **B:** Healed fracture after pin removal.



A

B

FIGURE 27-9 Radiographs of markedly displaced supracondylar humerus fracture that will require CRPP or ORIF.

and distal fragment into anatomic position. To correct malrotation and provide periosteal tension band stability, forearm rotation is performed during flexion reduction. For most fractures, this is in pronation. For some posterolateral fractures, this is in supination. (In the more common posteromedially displaced fractures, the lateral periosteum is torn; therefore, additional stability is conferred by pronating the forearm, as this tensions the lateral muscles and soft tissues. Conversely, in posterolateral injuries, the medial periosteum is disrupted, and forearm supination will add stability by tightening the flexor-pronator mass and medial soft tissues.) Proper rotational positioning can be assessed under fluoroscopy. To maintain a stable closed reduction, >120 degrees of flexion is required, which is risky for neurovascular compromise. This is why now all these fractures are pinned.[49–51] If there is a persistent bony block to flexion during reduction, then the fragments have not been disengaged. If there is a "mushy" or "rubbery" feeling, then there is soft tissue interposed, the most worrisome of which could involve the NVB. Confirmation of anatomic reduction is obtained with AP, lateral, and oblique radiographs of the distal humerus. Irreducible fractures, especially those with neurovascular entrapment, require open reduction. The vascularity to the hand is always assessed after closed reduction by feeling for a pulse and checking the color, capillary refill, and fullness of the digital pulps (Figure 27-13).

Closed Reduction Percutaneous Pinning Supracondylar and Transphyseal Fractures

The techniques of CRPP vary in terms of body position (supine [preferred at most centers including ours] or

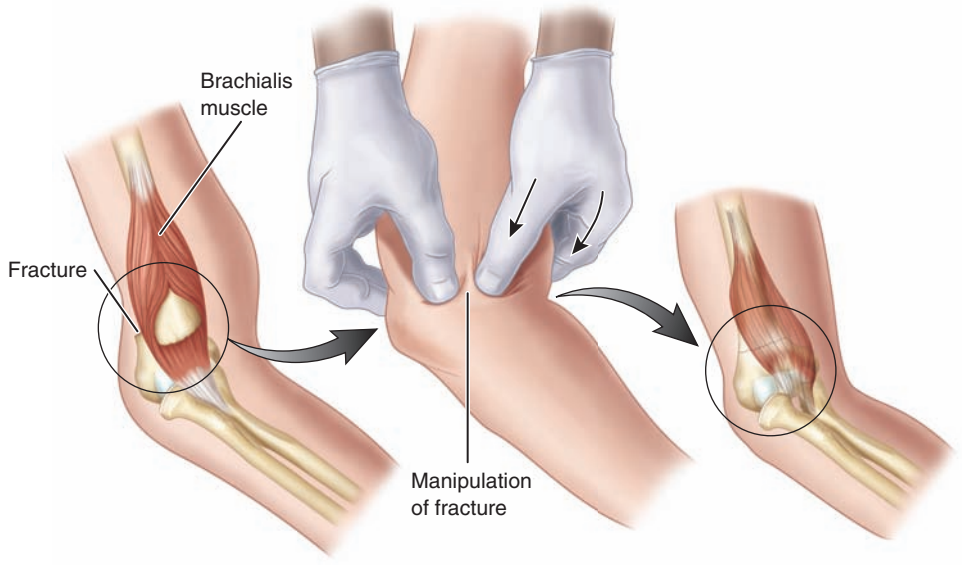
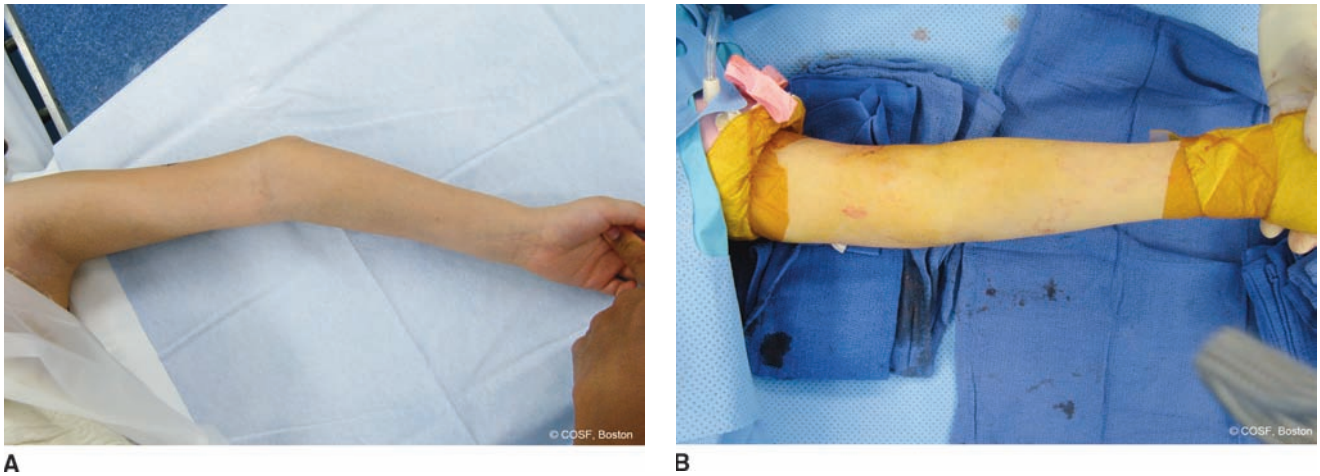


FIGURE 27-10 Milking maneuver noted for reduction of fracture after extraction of brachialis muscle entrapment. (From Beaty JH, Kasser JR. *Rockwood & Wilkins Fractures in Children*. 7th ed. Philadelphia, PA: Lippincott Williams & Wilkins; 2010, with permission.)

prone)[52–54]; divergent lateral entry or medial and lateral entry crossed pins; number of pins placed (two or three); use of arm support (fluoroscopy image intensifier or fluoroscopic arm board); and whether you move the arm through the shoulder (not the fracture site) or rotate the fluoroscopy to obtain a lateral image of the reduction and pinning.

Our method is to perform closed reduction under general anesthesia in the operating room in the supine position after sterile prepping and draping. The fluoroscopy image intensifier is used as the arm support. The forearm, elbow joint in full flexion, and humerus are rotated as a single, stable unit through the shoulder to obtain AP, oblique (optimal views of medial and lateral columns), and lateral fluoroscopic images. Young children have sufficient tension-free shoulder external rotation to 90 degrees or greater to do this safely without loss of fracture reduction. The lateral entry pins are placed obliquely from distal to proximal with one up the lateral column and one across the olecranon fossa (Figure 27-14). The proximal medial humeral cortex needs to be penetrated with each pin for sufficient stability. The medial cortical penetration can be felt by the operating surgeon, heard by the change in pitch of the drill by others in the room, and confirmed by fluoroscopy. The preferred pin size is 5/64″ for children >20 kg and 0.0625″ for children <20 kg. The fracture stability is tested manually with flexion-extension and rotation movements; brief continuous fluoroscopy can be used for confirmation.[55–57] If the fracture is at all unstable or acceptable but not perfect, a third lateral pin or a medial pin is placed (Figure 27-15).[58–61] Biomechanical analysis indicates crossed pins are more stable; clinical evidence



A B

FIGURE 27-11 **A:** Varus deformity noted on intraoperative clinical image before closed reduction. **B:** Anatomic carrying angle restored with closed reduction on fluoroscopic image intensifier.

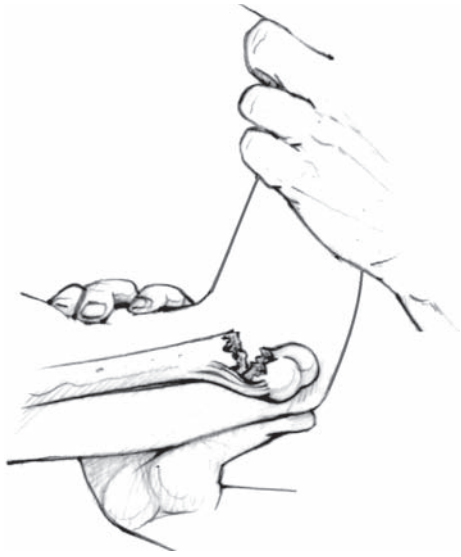


FIGURE 27-12 Reduction maneuver noted to correct extension deformity. The proximal fragment is stabilized with the surgeon's finger, and the thumb is used to reduce the distal fragment by applying pressure over the olecranon with flexion. (From Beaty JH, Kasser JR. *Rockwood & Wilkins Fractures in Children*. 7th ed. Philadelphia, PA: Lippincott Williams & Wilkins; 2010, with permission.)

confirms this trend, but three divergent lateral pins suffice in most cases.[62–64] Divergent lateral pins are more stable than parallel lateral pins.[65]

Although medial pins raise the concern of iatrogenic ulnar nerve injury,[66–68] they can be placed safely through a small incision.[69] Since ulnar nerve instability is common in this age group,[70] the medial pin is placed with <90 degrees of elbow flexion to avoid impingement or injury. The ulnar nerve is identified and protected with a retractor. The pin entry site is more anterior on the medial epicondyle to avoid the posterior position of the ulnar nerve. The pin trajectory is more horizontal to prevent nerve compression.[71] Oscillating technique with the drill is used to prevent soft tissue engagement by the wire that could compress or kink the nerve. Again, confirmation of desired pin placement, fracture alignment, and stability are obtained on the intraoperative fluoroscopic images. The final act when using a medial pin is to check the ulnar nerve, being certain there is no compression, impingement, or kinking of the nerve at rest and with full elbow movement. The wire is bent anterior to lessen the risk of problems.

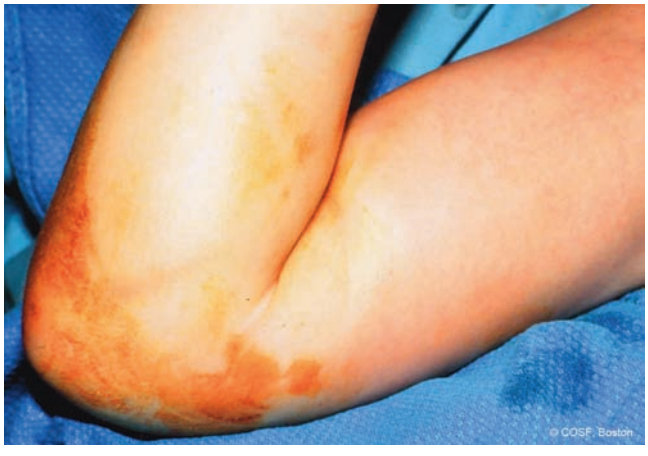


FIGURE 27-13 After closed reduction into full flexion, the limb is avascular beyond the fracture site. After CRPP, this will either be resolved with less elbow flexion (most common) or require ORIF and decompression and/or arterial reconstruction.

Of note, flexion type and multiple-plane, unstable extension fractures can be much harder. To achieve anatomic alignment with CRPP, the fracture fragments often need to be held reduced in space by the surgeon or assistant while the other one gets the first stabilizing lateral entry pin in place. The position is usually with maximum distraction and flexion of 60 to 80 degrees while correcting the varus-valgus malalignment. In flexion-type injuries, axial loading of the forearm may assist in reduction, as the proximal radius and ulna push against the flexed distal humerus. The reduction and pinning are based on the AP plain images only. Be careful not to overirradiate your hands. Once the first pin is across, then the other pin(s) can be placed in the typical fashion noted above. On occasion, two pins are placed appropriately in the distal fragment and used to joystick the fracture reduction before being passed into the proximal fragment.[72] There is a higher incidence of open reduction with flexion injuries. If the ulnar nerve is out preoperatively, decompression is appropriate at the time of open reduction.[73]

Transphyseal fractures are often markedly unstable. The children are often very young, and the diagnosis can be delayed due to the nonaccidental trauma etiology. If you are fortunate enough to make the diagnosis early, CRPP is indicated. In the very young, an intraoperative elbow arthrogram is often necessary to confirm the diagnosis, location of the epiphysis, and articular surface and to guide anatomic reduction (Figure 27-16). Since the periosteum can be disrupted all the way to the shoulder by the force of injury, pin stabilization with two to three lateral pins or crossed pins is mandatory. Placement of these pins is not easy in the small child with a maximally swollen elbow and limited views of the osseous and cartilaginous fracture fragments arthrofluoroscopically.

The metaphyseal-diaphyseal fractures have more obliquity to them and a tendency toward malangulation even after pinning.[22] Some of these fractures need an intramedullary pin or more proximal pin placement to maintain varus-valgus alignment. The radial nerve becomes more at risk the more proximal you place your lateral pins.

If there is a floating elbow injury, pin both the supracondylar and forearm fractures to avoid the risk of a

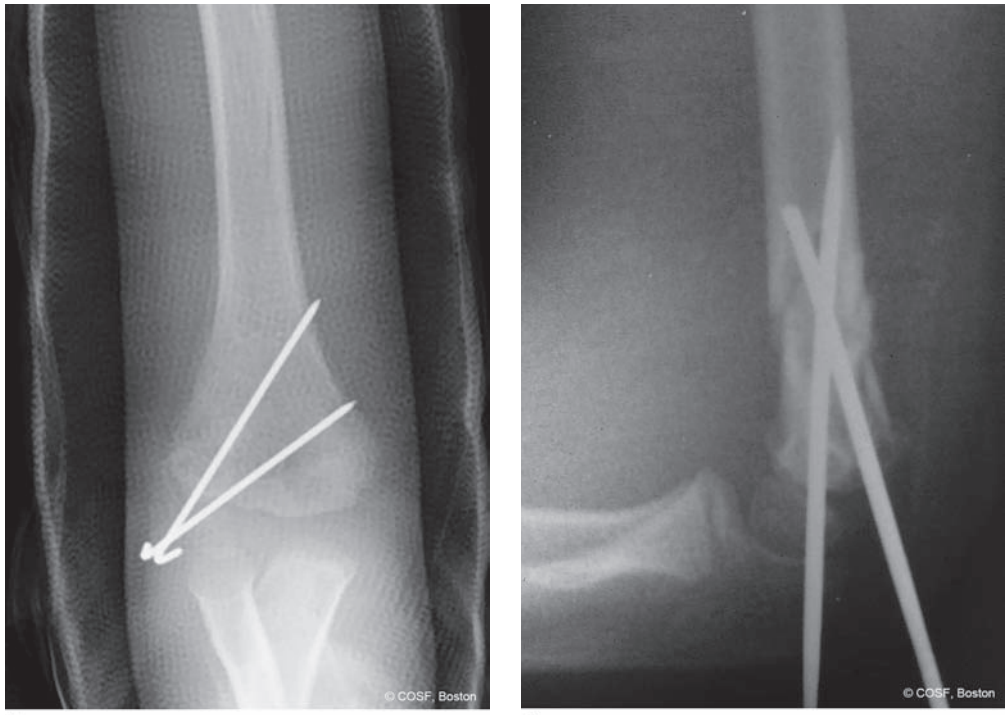


FIGURE 27-14 AP and lateral radiographs of divergent lateral entry fixation.

compartment syndrome in a cast. The most common floating elbow combination in a child is distal radius and supracondylar fractures. The distal radius is pinned first (see Chapter 34) followed by the supracondylar pinning.

FIGURE 27-15 Crossed medial and lateral pin fixation.

The arm is very loosely dressed and immobilized in 30 to 70 degrees of elbow flexion and neutral wrist in an extremely well-padded splint or widely bivalved cast. Pinning both fractures and avoiding compressive immobilization lessen the risk of compartment syndrome in these patients.[74–78]

◆ ORIF of Supracondylar Humerus

The ORIF procedure is indicated for (1) irreducible fractures, (2) open fractures (Figure 27-17), and (3) fractures with an avascular limb after gentle attempt at closed reduction (see Figure 27-13). Open reduction is required about 8% of the time in centers very skilled at CRPP of supracondylar humerus fractures. Anterior, posterior, medial, and lateral methods have been described.[79–85] Our best advice is to approach any pediatric fracture through the already present tear of the periosteum. This method prevents increased destabilization of the fracture by further subperiosteal dissection and allows for direct visualization and extraction of interposed periosteum or soft tissues such as nerves or vessels from the fracture site. The technique exemplifies the Willie Sutton axiom, "Go where the money is." Since 98% of supracondylar humerus fractures are extension type, and most open, irreducible, and neurovascularly impaired fractures are posterolaterally displaced, an anterior approach based medially is best. The incision is made transversely in line with the fracture. It can be extended further across, up, or down as needed (Figure 27-18). The incision is very utilitarian and aesthetic. The soft tissues are often

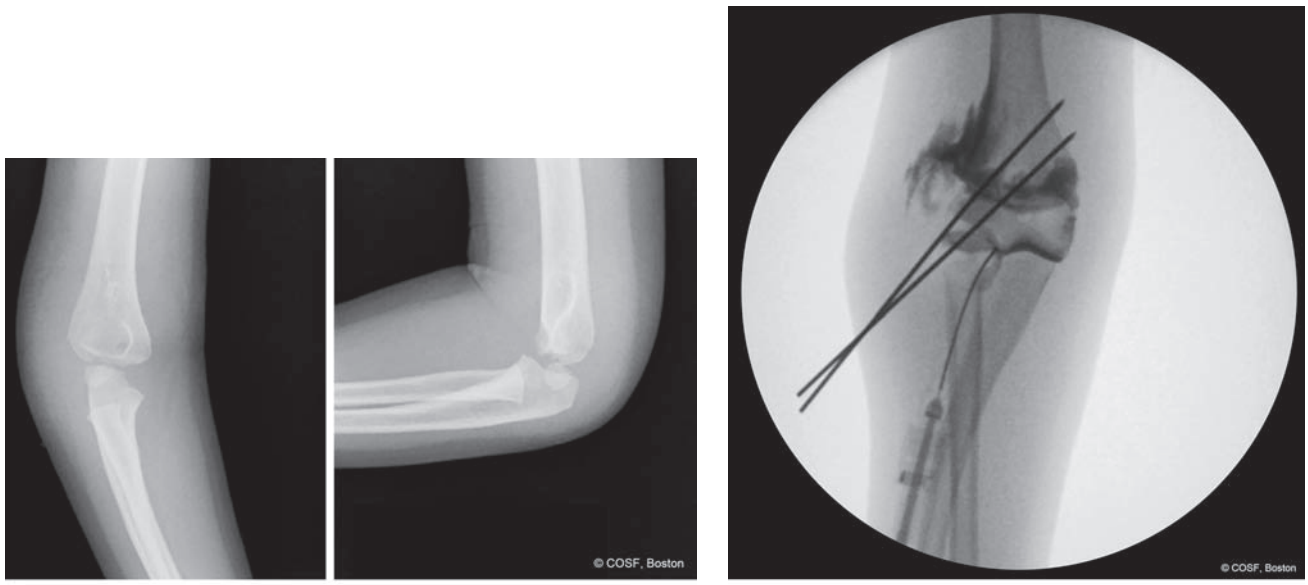


FIGURE 27-16 **A:** Displaced transphyseal fracture radiographs. **B:** Arthrographic-assisted CRPP with divergent lateral pins.

quite disrupted anteriorly, which allows for rapid and safe dissection to the fracture site. The NVB is identified and gently restored to its anatomic location. The entrapped soft tissues are removed with a pickup, elevator, or curved snap (Figure 27-19). The anatomic reduction can be achieved by direct manipulation. The fracture reduction is accomplished by the usual methods, but now your fingers can confirm anatomic alignment. Standard pin placement is performed and stability tested directly. Before closure, the brachial artery is inspected for pulsatile flow. If pulsatile flow is not present, emergent vascular treatment is performed (see next section "Managing the Avascular Limb").

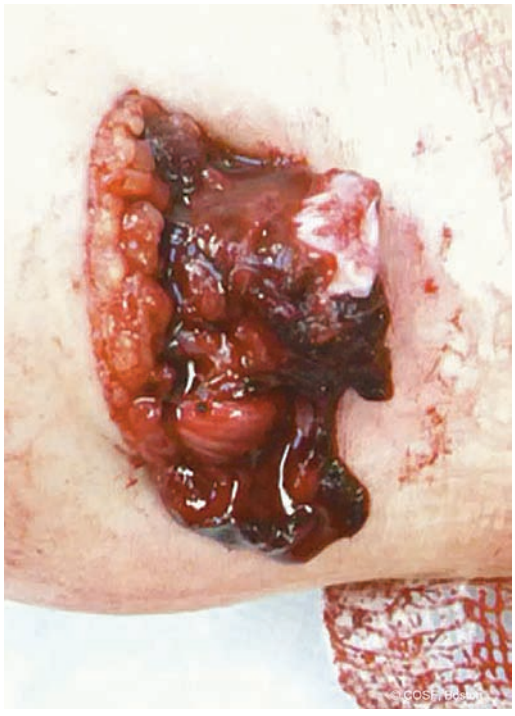
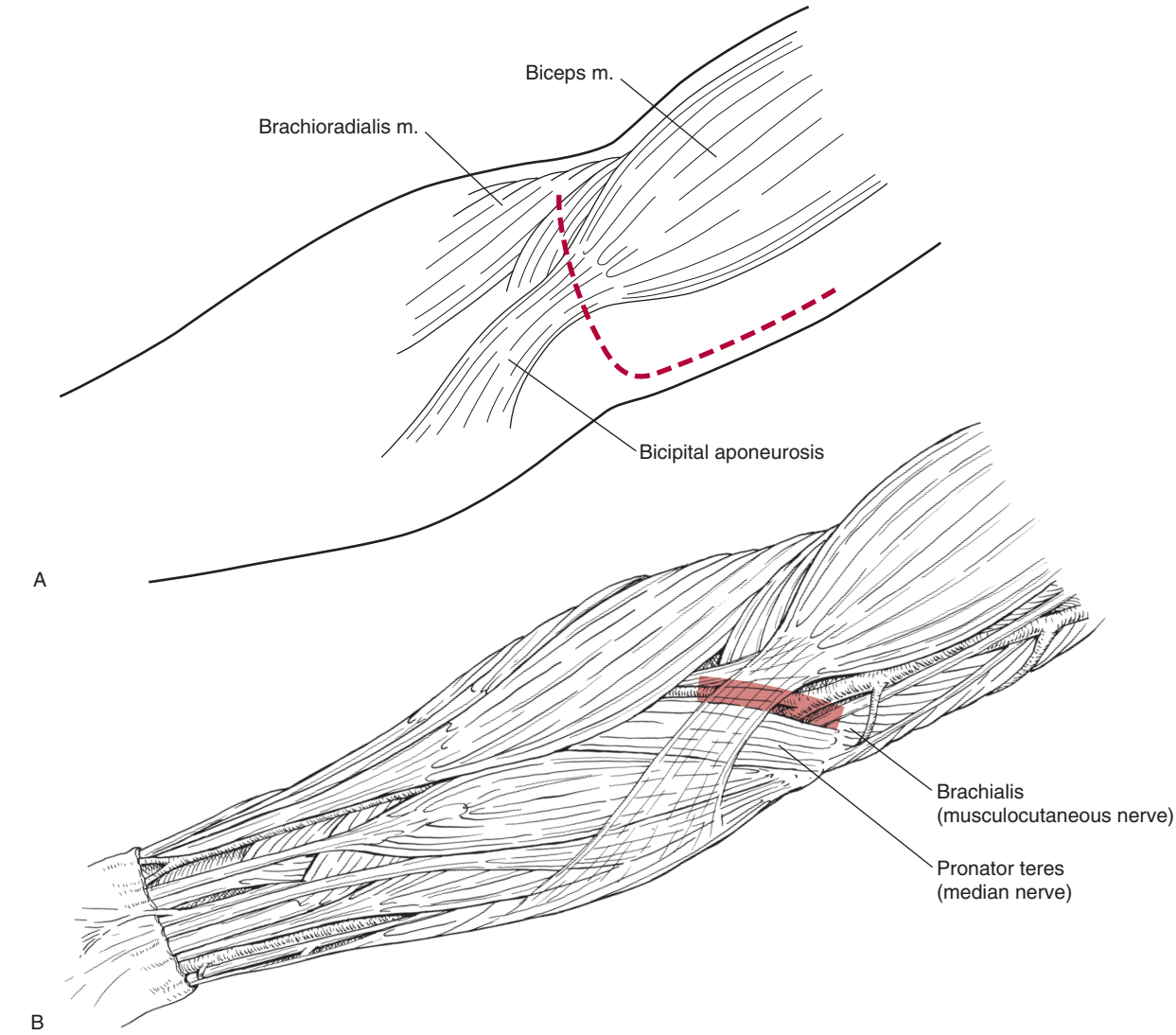


FIGURE 27-17 Open supracondylar humerus fracture. The distal humerus metaphysis is completely protruding through the transverse open wound. Fortunately, the pulse was intact, and the hand was viable.

◆ Managing the Avascular Limb

Being a professional is doing the things you love to do, on the days you don't feel like doing them.
—Julius Erving

First and foremost, the avascular limb needs to go to the operating room no matter when the call to the surgeon comes in. There is no need for arteriography either before or in the operating room as the site of vascular impairment is always at the fracture.[86,87] Gentle closed reduction, as described above, including the milking maneuver for extracting the entrapped brachialis and soft tissues, is the first order of business. Fortunately, closed reduction will restore the blood supply to the hand in 70% to 90% of cases.[8,88–91] If the hand is pink, the capillary refill is normal, and the pulse returns, then all is well now and probably forever. Standard percutaneous pinning is performed. The arm is immobilized in 70 degrees of flexion or less to improve blood flow.[92] If the hand is pink, capillary refill is normal, but the pulse does not return, the so-called pink pulseless hand, then everything is most likely fine but that patient needs to be watched in hospital for 1 to 2 days after pinning (see Sidebar 1). Any hint of the hand not being perfectly pink or the capillary refill not being right, especially when there is a preoperative



B

FIGURE 27-18 **A:** Illustration of transverse incision for ORIF of an open fracture with proximal and distal Z-plasty limbs marked if necessary. **B:** Healed transverse incision.

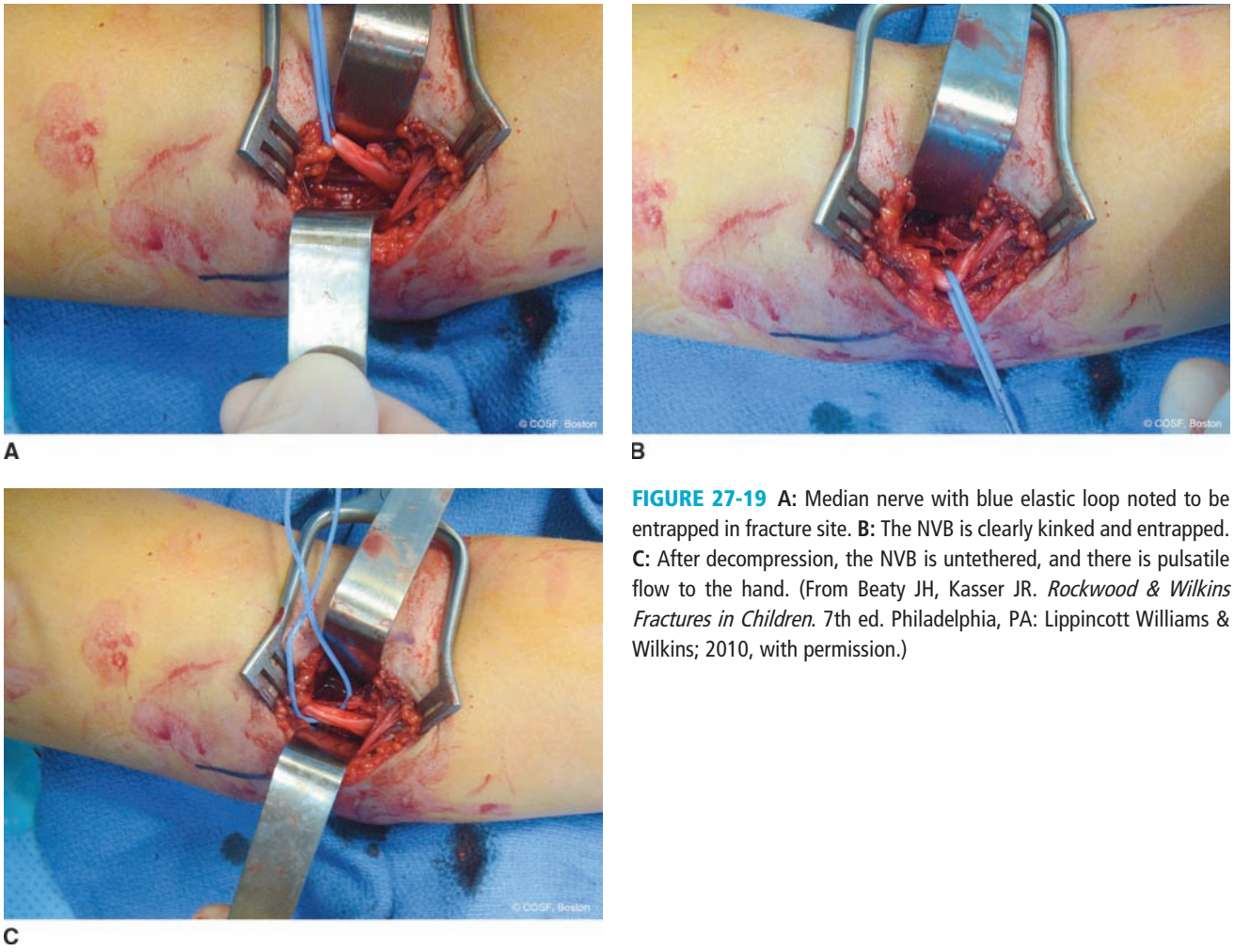


FIGURE 27-19 **A:** Median nerve with blue elastic loop noted to be entrapped in fracture site. **B:** The NVB is clearly kinked and entrapped. **C:** After decompression, the NVB is untethered, and there is pulsatile flow to the hand. (From Beaty JH, Kasser JR. *Rockwood & Wilkins Fractures in Children*. 7th ed. Philadelphia, PA: Lippincott Williams & Wilkins; 2010, with permission.)

median nerve injury, means that patient is at risk for compartment syndrome due to impaired flow (Figure 27-20). An immediate exploration is indicated as the vessel is kinked or compressed. If the hand is still pale, without capillary refill, and without a pulse, then the patient needs an immediate exploration of the brachial artery, as there is kinking, compression, entrapment, or laceration of the artery (Figure 27-21).

Through a transverse, anteromedial incision over the fracture site, or standard extended Henry curvilinear incision, operative exploration of the NVB is performed. The soft tissues are carefully dissected to identify the median nerve and brachial artery. Identifying the NVB proximal to the fracture site and following it distally is safest. Often the NVB is not in the fracture site but merely kinked or compressed by other soft tissues that are entrapped. In these situations, the NVB can be gently released from its entanglement, so vascular flow to the hand can be restored. Then the entrapped periosteum and brachialis can be removed, allowing for an anatomic open reduction and pinning.

However, you have to be ready for this situation to escalate quickly to one that requires a high level of expertise. Vascular surgery with end-to-end microanastomosis or vein grafting may be emergently required. Our partners will place a preemptive call to us when they are going to the operating room with an avascular hand just in case the blood flow is not restored with exploration and open reduction. Papaverine can be used to vasodilate the artery and coax it out of spasm while waiting for your vascular team.[93] Stable anatomic fixation is necessary before proceeding with vascular repair. Some vascular surgeons perform a thrombectomy in this situation. We do not. We always resect the injured segment and directly repair it microscopically end to end without tension, or we replace it with an appropriate-sized vein graft from the arm or leg. Microscopic repair anastomosis is with 8-0 to 9-0 caliber suture, depending on the size of the vessel (Figure 27-21B). Pulsatile flow should be immediately restored after repair (Figure 27-21C). The forearm fascia is always released prophylactically after limb revascularization.[94,95]

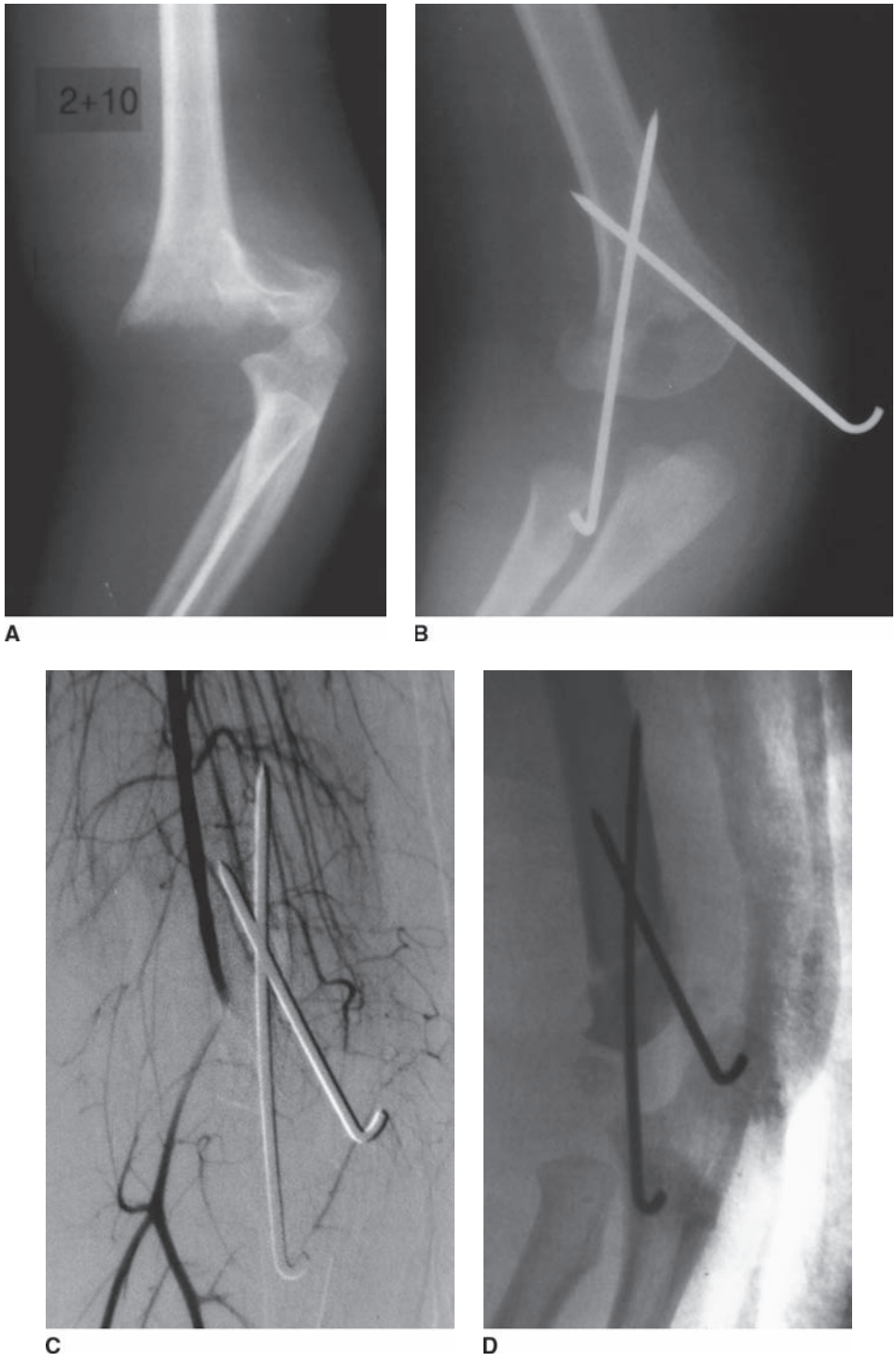


FIGURE 27-20 **A:** Displaced supracondylar humerus fracture. **B:** CRPP was performed, but the child had a dysvascular hand. Note the fracture is not anatomically reduced. **C:** Arteriogram was obtained by original surgeon and vascular compromise at fracture site noted. **D:** After ORIF, vascular decompression, compartment releases, and repeat pinning. (From Beaty JH, Kasser JR. *Rockwood & Wilkins Fractures in Children*. 7th ed. Philadelphia, PA: Lippincott Williams & Wilkins; 2010, with permission.)

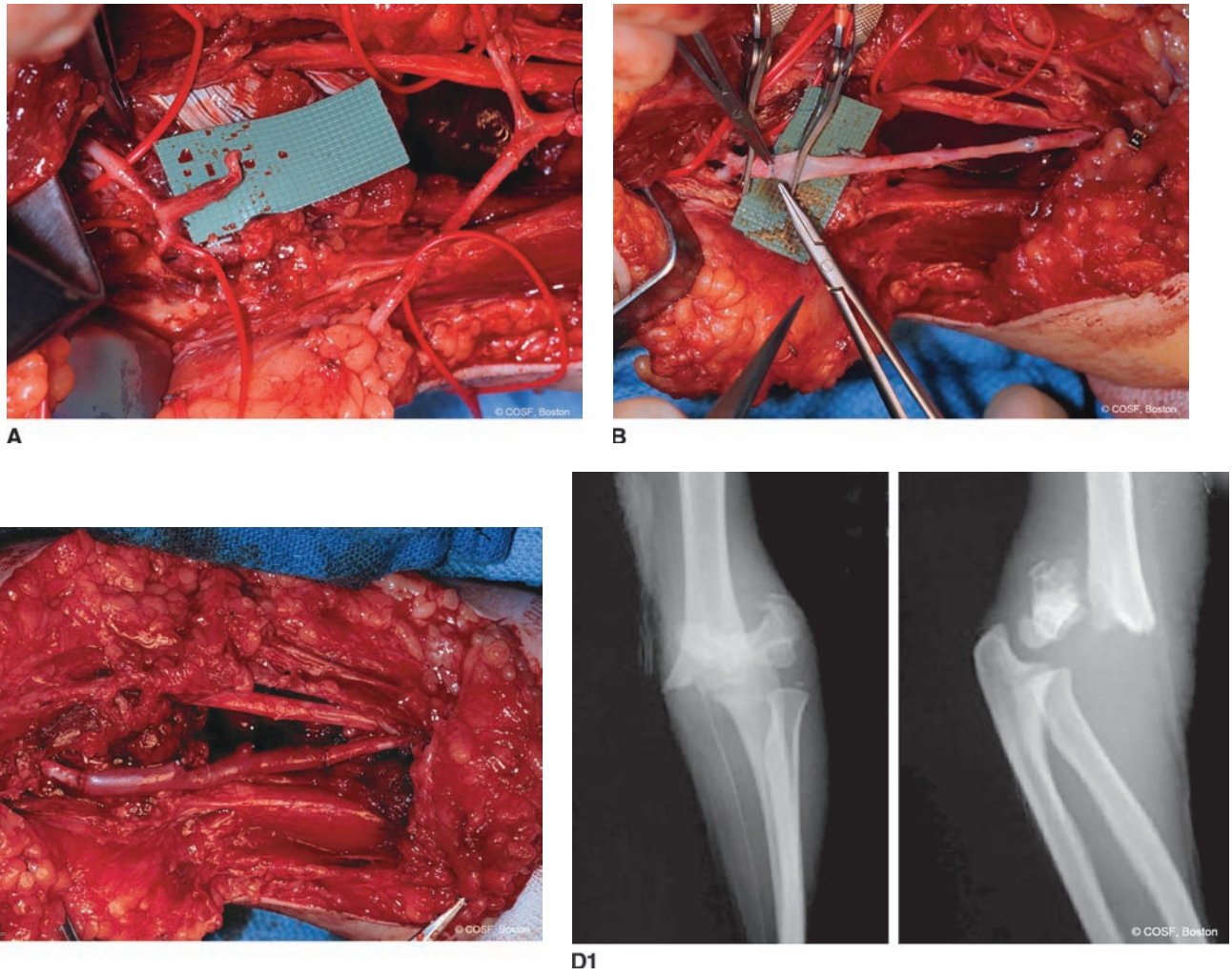


FIGURE 27-21 **A:** Intraoperative photograph of avascular limb with noted disruption of the brachial artery. **B:** Microvascular repair with vein graft being performed. **C:** Pulsatile flow is evident through brachial artery vein graft. Compartments were released after vascular reconstruction. **D:** Preoperative and postoperative radiographs after ORIF.

◆ Open Reduction T-Condylar Humerus

The adolescent with a T-condylar distal humerus fracture should be treated with bicolumn ORIF like an adult.[31,96,97] The surgical decisions to make are (1) the approach (triceps splitting, triceps elevating, paratricipital, or olecranon osteotomy), (2) the type of fixation (single column, bicolumn orthogonal or parallel plating, or rarely three plates), and (3) the body positioning of the patient (side lying, supine, or prone). Since most adolescent fractures are C1 and rarely C2 fractures by the AO classification, a soft tissue approach for T-condylar fractures by either a triceps splitting or triceps reflecting technique is appropriate. If there is anterior comminution, then an olecranon osteotomy may be indicated.

We usually perform the T-condylar reconstruction supine but in a slight "sloppy lateral" position to allow for easier lateral fluoroscopic imaging. A sterile tourniquet is used throughout the surgery. A long curvilinear posterior incision is utilized with the distal extension lateral to the olecranon and then back to the midline onto the proximal ulna. This prevents an irritating direct posterior scar. The skin and subcutaneous flaps are extensively elevated. The ulnar nerve requires careful attention with decompression, mobilization, and protection at this stage and throughout the operation. An elastic loop is placed around the nerve, and the nerve is handled gently for the remainder of the surgical reconstruction. A V-Y triceps-splitting approach is used for the AO C1 fractures. A triceps-splitting approach is used more often with the C2 fractures. An olecranon osteotomy may be used for the rare C3 fracture.

The *triceps-splitting approach* utilizes long, oblique fascia incisions from the lateral and medial epicondyles, respectively, to a more proximal connecting point in the midline. The resultant tongue of fascia is elevated from proximal to distal down to its insertion into the olecranon. The triceps muscle is split in the midline and retracted beyond the medial and lateral columns, respectively. The radial and ulnar nerves are protected behind the retractors. The olecranon fossa is exposed along with the fracture sites. Flexion of the elbow allows for complete visualization and fixation of the articular fragments. The *triceps-reflecting approach (Bryan-Morrey)* partially elevates the triceps insertion off the olecranon. In children and adolescents, this can be achieved with subperiosteal elevation. Care is taken with elevation off the olecranon apophysis because there is risk of buttonholing the insertion and destabilizing the triceps insertion postoperatively. The entire triceps can be reflected either medially or laterally for full view of the fracture sites, olecranon, and articular surfaces similar to the triceps-splitting approach. At the conclusion of the skeletal fixation, the triceps insertion periosteal sleeve is repaired with transosseous sutures or osseous suture anchors. This approach should not be used in open fractures that have penetrated the triceps musculature, as an avascular segment of fascia muscle can be developed. The *olecranon osteotomy* is used by some for all T-condylar fractures but by us only for complex fracture dislocations involving several bones around the elbow or for AO C3 T-condylar fractures. A longitudinal cancellous screw down the olecranon from the tip or apophysis is predrilled and placed. This is removed, and a chevron osteotomy is performed and mobilized for full view of the elbow joint. The osteotomy can alternatively be fixed with parallel K-wires and tension band suture or wires. At the conclusion of the fracture fixation, the olecranon osteotomy is reduced and compression fixation performed with the cancellous screw and washer (Figure 27-22). The tightening of the screw is watched closely and controlled to prevent articular malrotation or malreduction. All three of these approaches are equivalent at long-term follow-up in terms of motion and isokinetic triceps strength testing.[79,98,99]

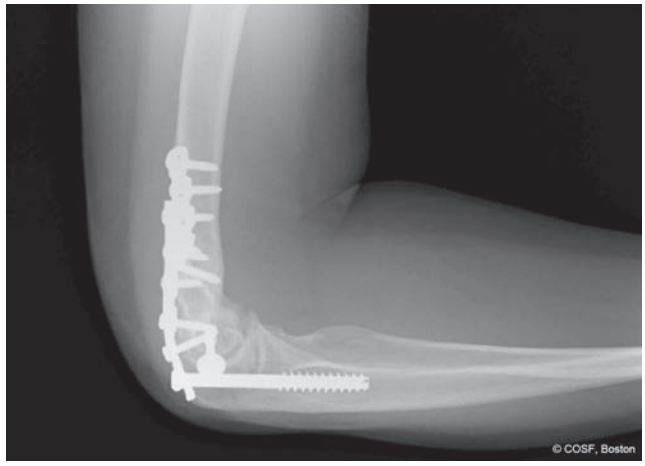


FIGURE 27-22 Postoperative lateral radiograph of ORIF T-condylar distal humerus fracture with olecranon osteotomy.

The principles and steps of the skeletal and joint reconstruction are the same: (1) fix the joint anatomically temporarily, (2) stabilize the anatomic joint fixation to the columns temporarily, (3) be certain there is anatomic alignment by direct visualization and fluoroscopically, (4) replace the temporary cannulated pin fixation with compressive screw fixation across the joint, (5) convert the column fixation to orthogonal plates (medial 3.5 pelvic reconstruction plate and posterolateral 3.5 reconstruction or dynamic compression plate) (Figure 27-23A), and (6) make a decision about the safest place for the ulnar nerve postoperatively with regard to fixation and motion. These steps may sound straightforward, but surgically caring for these fractures is not for everybody. Patience, meticulous attention to detail, and exactness in technique with regard to anatomic articular alignment and rigid fixation allow for early return of motion (Figure 27-23B). You only get one chance to make this right because correcting articular malunion requires a higher level of surgical expertise and often risks a lesser outcome than performing an anatomic, acute surgical repair. In our institution, only certain people take care of this fracture.

There are skeletal reconstruction alternatives including J or Y plates, external fixation, and locking plates.[100,101] Most of these techniques are used in the adult and are not as necessary in the child and adolescent as their fractures are more stable and have less joint comminution. On the other end of the spectrum, there are some pediatric T-condylar fractures in the young that merely hinge at the articular surface. These fractures can be treated with CRPP.[102,103] Standard medial and lateral column fixation, as in a supracondylar fracture, is performed with a third transverse pin holding the articular fragments in proper alignment. A large, external bone-holding compression clamp may be required to reduce the joint before pin

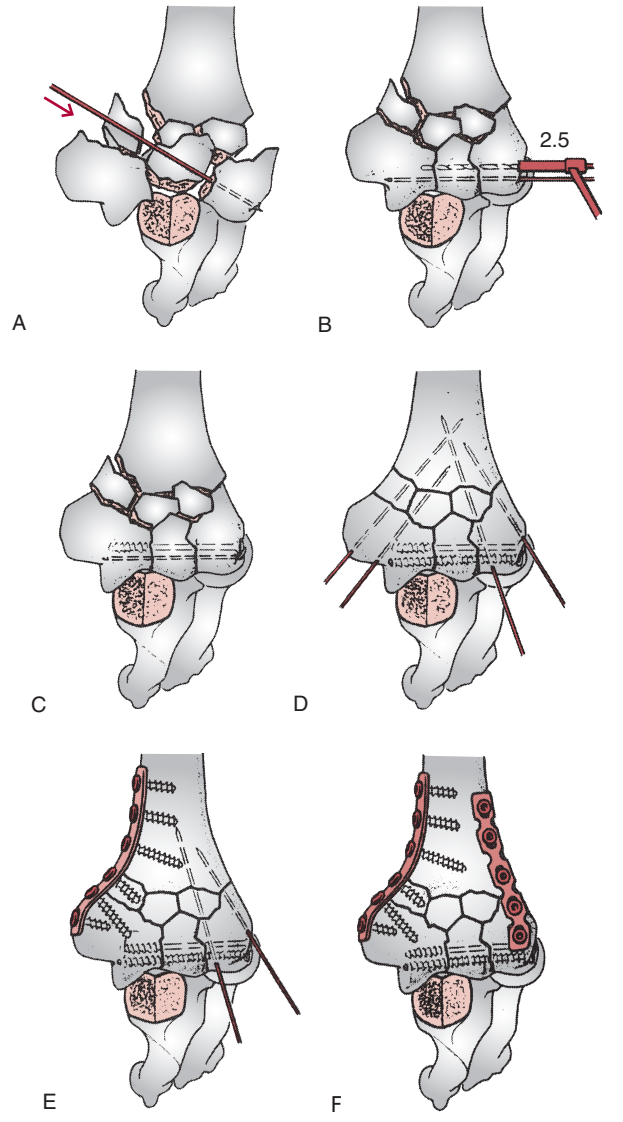


FIGURE 27-23 **A (A-F):** Schematic of sequence of ORIF distal humerus T-condylar fracture. **B:** ORIF with anatomic transarticular screw fixation and bicolumn plates. (A from Heim U, Pfeiffer KM. Internal Fixation of Small Fractures. 3rd ed. Berlin: Springer-Verlag, 1988, with permission.)

placement. Similarly, there are cases where percutaneous transverse compression screw placement and column percutaneous screw fixation are appropriate for rigid reduction and fixation (Figure 27-24). In the adult, this would be a violation of principle, but in some pediatric and young adolescent fractures, it is appropriate, safe, and successful. Outstanding fluoroscopic imaging is required to do these cases percutaneously and avoid the heart-sinking feeling of looking at true AP and lateral postoperative images that reveal a misplaced screw(s) and/or fracture malreduction.

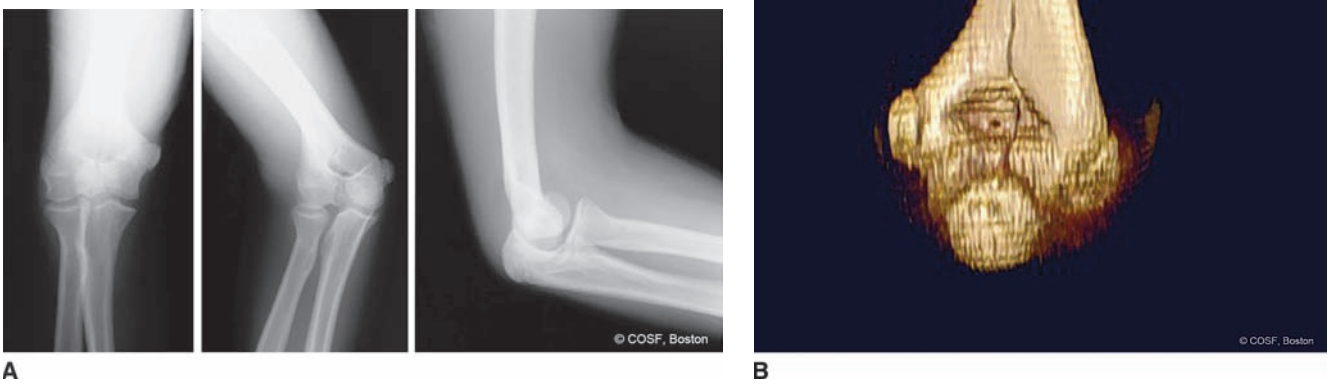
◆ Malunion Osteotomy

Sure, luck means a lot in football. Not having a good quarterback is bad luck.
—Don Shula

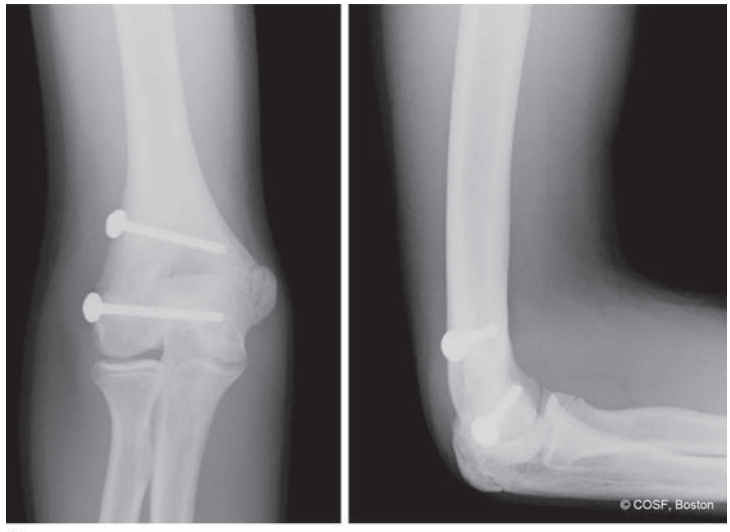
There are many different techniques for corrective osteotomy of a distal humerus supracondylar malunion. These include lateral closing wedge, dome, and triplane osteotomies, among others.[104–107] Osteotomy stabilization with pins, plate and screw constructs, and external fixators has been used.[108–111] There have been reports of unsatisfactory outcomes in up to 33% of patients in some series.[112,113] Using a lateral closing wedge technique,[114] we have not had major complications and have been very satisfied with our results.[115]

Surgery is performed in the supine position with the arm extended to the side on a fluoroscopic hand table. Under tourniquet control, a straight lateral approach to the distal humerus is performed. This may be an extension of previous pin sites from the original fracture care. The incision takes into account the extension and varus deformity. Subperiosteal dissection is performed from above the physis and joint distally to above the olecranon fossa proximally. The subperiosteal dissection ends before the radial nerve is at risk more proximally.

Based on comparative preoperative radiographs and physical exam carrying angle measurements, intraoperative planning and execution of the osteotomy cuts are performed. This is a series of simple but precise steps that allow you to never lose control of the osteotomy and get into trouble (Figure 27-25): (1) place two oblique wires from lateral to medial to outline the saw cuts. The distal wire is just at the superior end of the olecranon fossa to maximum the metaphyseal bone in the osteotomy but prevent violation of the olecranon fossa with the saw cut. The more proximal wire replicates the exact angle of the closing wedge osteotomy (usually 20 to 25 degrees in most operative cases). The two wires should meet just beyond the medial cortex so as to maintain an intact medial cortical and periosteal hinge and not to violate the ulnar nerve; (2) place two smooth wires from the lateral condyle distally up the level of the more distal wire. These pins need to be very vertical so that when the osteotomy wedge is removed,



A B



C

FIGURE 27-24 **A:** Radiographs reveal minimally displaced distal humerus T-condylar fracture, confirmed by CT scan (**B**). **C:** Closed reduction percutaneous screw fixation leads to anatomic healing.

the pins will get secure fixation to the opposite medial cortex; (3) under fluoroscopic guidance, use an oscillating saw to precisely follow the osteotomy guide wires for 90% to 95% of the way from lateral to medial. Be careful not to pronate or supinate, as this will result in a flexion or extension osteotomy. Check by fluoroscopy as you go; (4) with a large rongeur and osteotomes, remove the bone of the closing wedge while leaving the medial cortex intact; (5) close down the osteotomy with full valgus, pronation, and flexion of >120 degrees like a closed reduction of a supracondylar fracture; (6) while maintaining reduction, drive the previously placed pins across the osteotomy site to penetrate the medial cortex with one pin up the lateral column and the other pin across the olecranon fossa; (7) confirm clinically by carrying angle and radiographically by AP, lateral, and oblique fluoroscopic images that the desired correction has been achieved; (8) place morselized cancellous bone graft from the closing wedge at the osteotomy site. Close the periosteal over the osteotomy site; (9) after completion of the closure, dressing, and Webril, univalve the Webril to lessen the risk of excessive postoperative swelling. Place a bivalve cast.

Volkmann Ischemic Contracture Reconstruction

Unfortunately, unrecognized or inadequately treated compartment syndromes still exist and result in ischemic contractures of the forearm. The Holden[116,117] classification is used most often with a type I contracture of the forearm due to an injury proximally (i.e., supracondylar humerus fracture with vascular impairment) and a type II injury by direct trauma at the site (i.e., crush injury forearm). The injuries are further defined by severity: mild, moderate, and severe depending on the extent of muscle necrosis, fibrosis, and sensibility changes. Most Volkmann contractures are the moderate type with involvement of FDP, FPL, pronator teres (PT), and partial flexor digitorum superficialis (FDS). The median and at times the ulnar nerve have neuropathic sensory loss. Extrinsic-plus posture of the wrist and digits is present. The severe type involves not only the flexor compartment but also the extensors and intrinsics (see Chapter 45).

Operative intervention is indicated with incomplete recovery between 3 and 12 months postinjury. The options are muscle slide, tendon transfers, and free functional

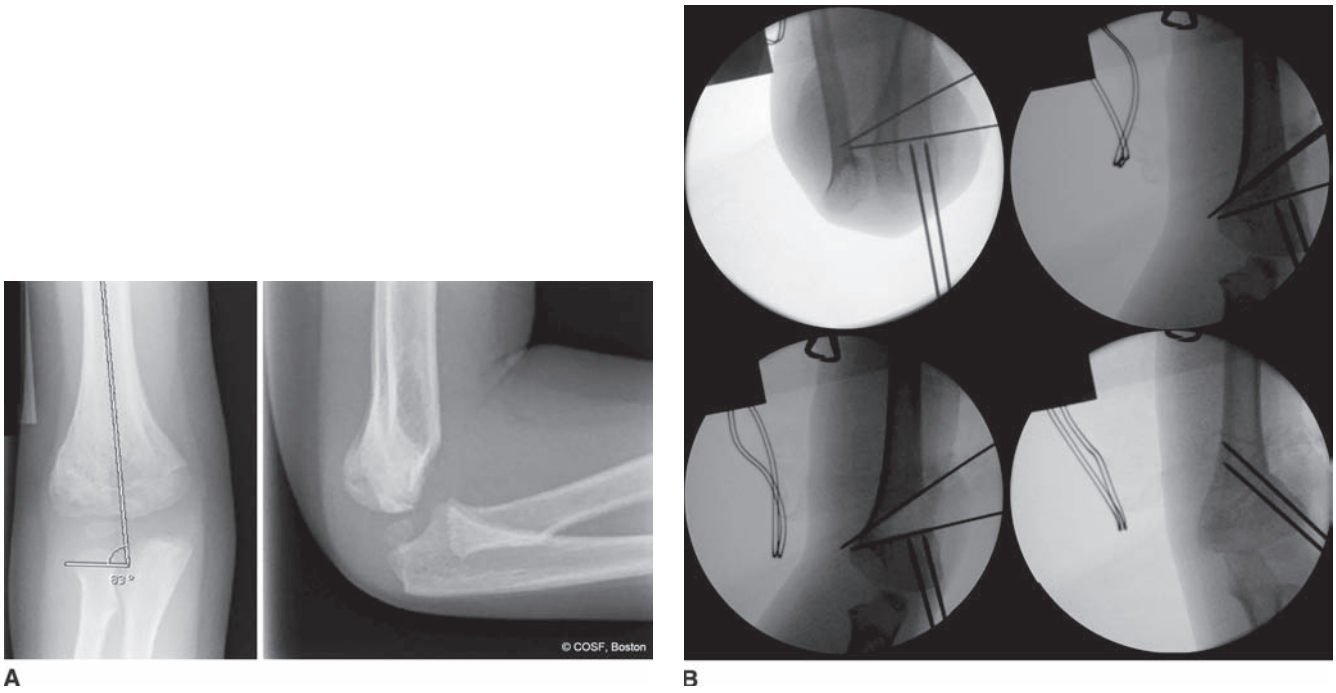


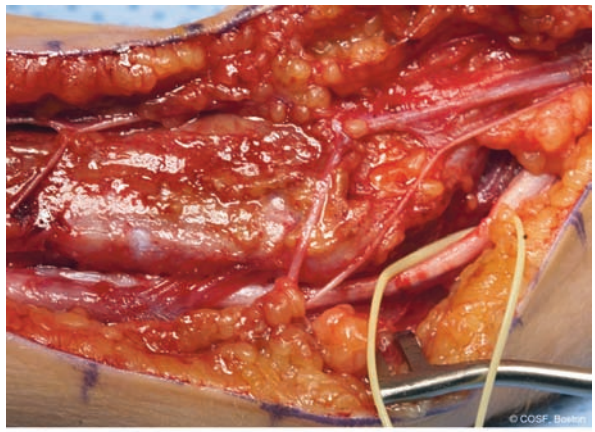
FIGURE 27-25 Sequential steps for distal humerus osteotomy for cubitus varus malunion. **A:** Preoperative radiographs. **B:** Intraoperative fluoroscopic images with smooth wires outlining osteotomy; fixation pins in place from distal to proximal to the level of the osteotomy; oscillating saw cuts from lateral closing wedge resection; and wedge removal just before final rongeuring of bone and closure of osteotomy and pin fixation.

muscle transfer. A muscle slide is indicated for the moderate Holden type I patient. An extensile classic Henry exposure is used. The ulnar nerve is isolated and decompressed at the elbow (Figure 27-26A). The median nerve is exposed proximal to the elbow and dissected distally. The lacertus fibrosus is released, and the median nerve is decompressed through the two heads of the PT and through the FDS arcade (Figure 27-26B). The brachial artery is similarly decompressed and protected (Figure 27-26C). The fibrotic muscle mass of the deep volar compartment is identified (Figure 27-26D). The muscle slide is quite extensive while protecting the nerves. The PT, flexor carpi radialis (FCR), palmaris longus (PL), flexor carpi ulnaris (FCU), FDS, and FDP are all elevated subperiosteally off the ulna all the way to the interosseous space (Figure 27-26E). Digital flexion and extension aids in the release. The FPL may need subperiosteal elevation as well. The interosseous vessels are protected during this extensile release. The nerves are decompressed throughout the length of the forearm. The goal is marked improvement in digital and wrist contractures and some return of sensibility and flexor active motor function. The other option is a free, functional muscle transfer for the severe form (see Chapter 45).

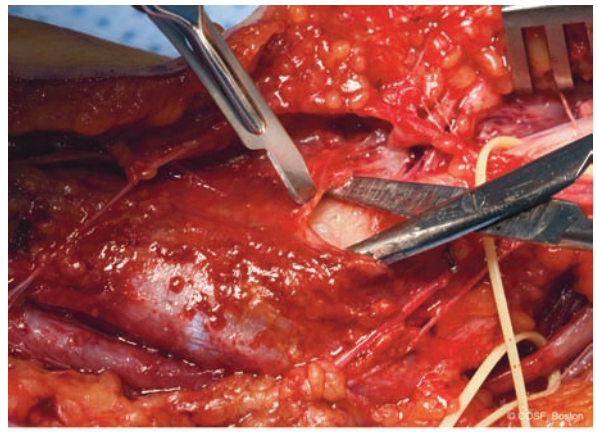
POSTOPERATIVE

Care of nondisplaced and stable supracondylar fractures does not entail hospitalization but does require brief immobilization for up to 3 weeks until healed. Minimally displaced type II fractures can be treated as day surgery CRPP procedures as long as the dressing/splint/bivalve is not tight, and thorough instructions regarding cast, pin, and neurovascular problems are given. Type III fractures without neurovascular compromise are watched overnight after CRPP but do not need follow-up until the cast and pin removal at 3 to 4 weeks.[118] Pink pulseless hand patients are observed in hospital for 1 to 2 days to be certain there is no development of a compartment syndrome. Vascular reconstruction patients are placed on low-dose aspirin for 3 weeks, are observed in the hospital for up to 5 days, and have a wound inspection and dressing and/ or cast change at 10 to 14 days. In all these patients, before pin and/or cast removal, AP and lateral radiographs of the distal humerus are assessed for maintenance of alignment and periosteal healing. Physical therapy is not necessary in the supracondylar patients postoperatively. Near full restoration of motion occurs in the anatomically reduced fractures over the first 6 to 12 weeks postinjury.[119,120]

Transphyseal fractures from nonaccidental trauma are maintained in hospital after CRPP until a safe social environment is guaranteed. T-condylar patients are started on continuous passive motion (CPM) in hospital until full flexion-extension is achieved (2 to 5 days) and then maintained on the CPM at home up to 23 h/d for 3 weeks followed by part-time CPM for another 3 weeks. The active



A



B1

B2

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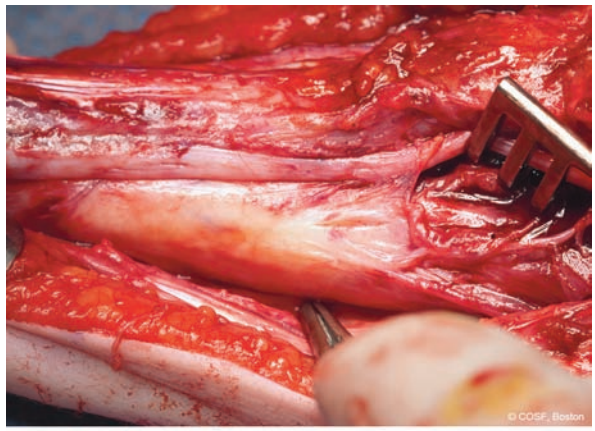
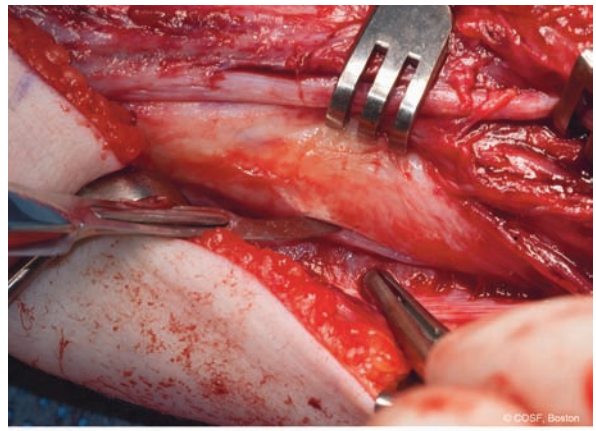
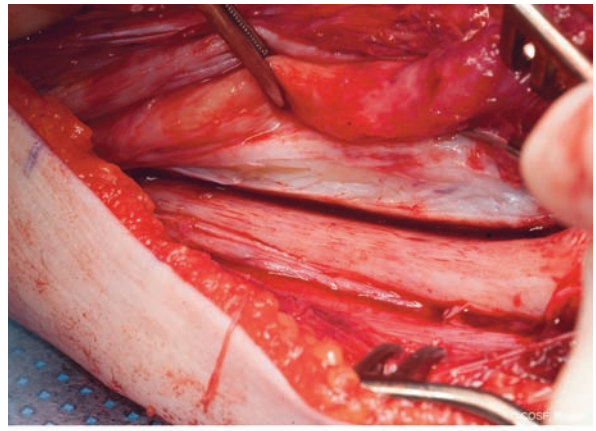


D



E1



E2

FIGURE 27-26 Sequence of operative steps for ischemic contracture decompression and release. **A:** Identification of ulnar nerve at elbow. Decompression of the ulnar nerve from elbow to hand will be performed. **B:** The median nerve and brachial artery are isolated in the distal humerus. The lacertus fibrosus is released and decompressed through the pronator muscle bellies and FDS arcade. **C:** The brachial artery is isolated, protected, and decompressed. **D:** The fibrotic deep volar flexor compartment is evident. **E:** An extensile slide off the ulna bone is performed.

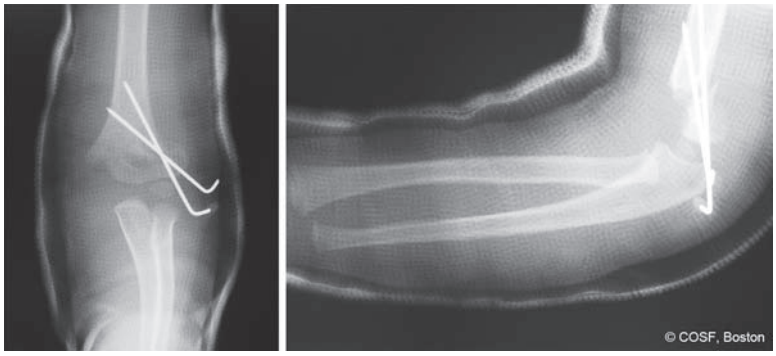


FIGURE 27-27 Inadequate CRPP is noted on these radiographs.

movement portion of postoperative therapy is performed in a hinged elbow brace with full motion allowed.[31,99]

ANTICIPATED RESULTS

Perform at your best when your best is required. Your best is required every day.
—John Wooden

Although challenging, distal humerus fractures can be among the most satisfying pediatric and adolescent musculoskeletal problems to treat.[50] Patients with these injuries will do well if we all follow the strategic steps outlined and change according to the variations each patient presents to us. If treated properly, supracondylar fractures will heal anatomically, the motion will come back, and the nerve injuries will recover with observation about 98% of the time. Avoiding Volkmann ischemic contracture, malunion, and permanent neurologic loss is imperative for a healthy future for the affected child.

Patients with T-condylar humerus fractures similarly should do well. Perfection is sought with fixation. Rigorous physical therapy with CPM and active movement is required to avoid a marked elbow contracture. A mild (10-degree) flexion contracture is anticipated in the best of results.

COMPLICATIONS

Sometimes you get the bear. Sometimes the bear gets you.
—Commander William T. Riker

Now for the bad news. Supracondylar humerus fractures can get very problematic for the patient, family, and surgeon (Figure 27-27). Major complications such as (1) malunions (cubitus varus and hyperextension) (Figure 27-28),[121–123] (2) compartment syndromes,[124] (3) disastrous Volkmann ischemic contractures (Figure 27-29),[125–128] (4) permanent neurologic loss, (5) iatrogenic nerve injuries (Figure 27-30), (6) osteonecrosis of the trochlea (Figure 27-31),[129,130] and (7) limited hand and arm function for life still occur. We can eliminate, avoid, or have a positive effect on most of these problems by our rapid and skilled responses. Caring for children with severe supracondylar fractures is not for the casual or inattentive-to-detail surgeon or center.

Refracture, lateral condylar fractures, and shoulder instability occur rarely in association with cubitus

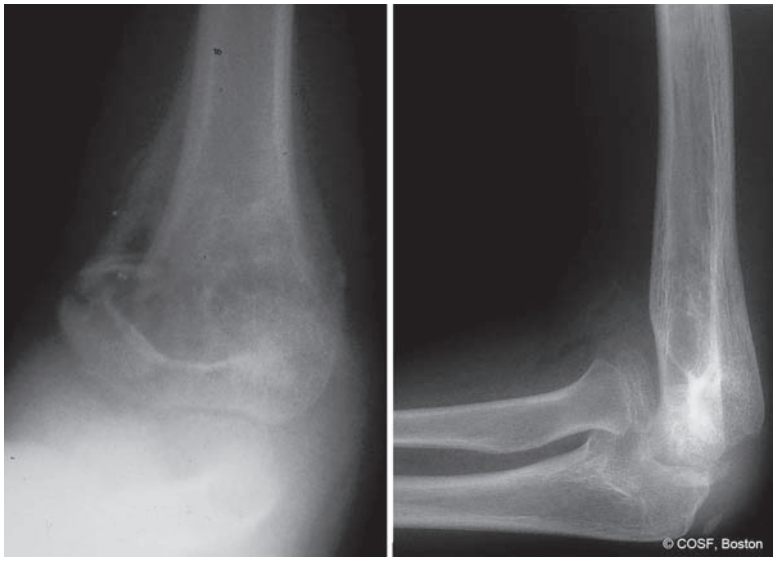
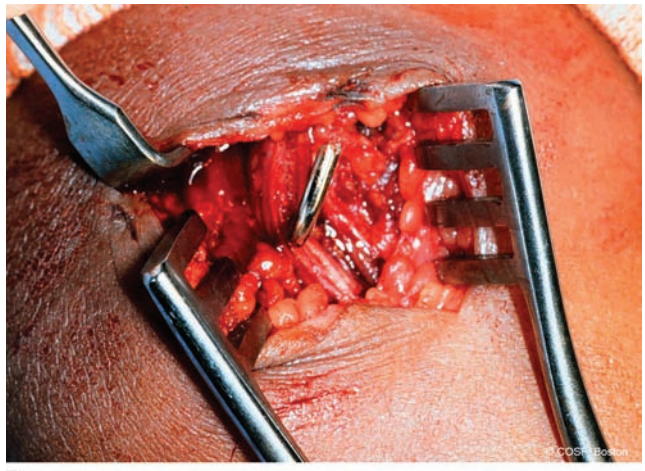


FIGURE 27-28 AP and lateral radiographs of an early malunion.

FIGURE 27-29 Volkmann ischemic contracture noted clinically.

A



B

FIGURE 27-30 **A:** Percutaneous medial pin was placed without protective incision. The patient had immediate ulnar nerve palsy. **B:** After referral, exploration was performed, and the pin was noted to penetrate the ulnar nerve.

varus.[131–133] Minor complications such as pin migration or infection (<1% to 3%)[134] are not common and easy to handle with pin removal, local wound care, and oral antibiotics. Deep-spaced infection in the elbow joint or bone is more complicated; requires operative intervention, initial intravenous, and long-term oral antibiotics; and gets worse if there is delay in treatment.

Aside from the vascular compromise cases, which can truly make you sweat (see Sidebar 1 and "Managing the Avascular Limb" section), caring for the neurologically impaired patient can also be stressful.[135–138] Optimal treatment of these patients really starts at the beginning. Did you, or someone you really trust, do a comprehensive exam of the motor and sensory function of the ulnar, median, and radial nerves before the patient was under anesthesia? If not, you are at risk postoperatively. It is why these children never enter the operating room without an exact physical exam by us. We need to know the status of each of those nerves before that child goes to sleep so we can be precise in our treatment of a nerve that is not functional postoperatively. If the nerve is out preoperatively, we expect it to be out postoperatively. We anticipate it has been contused by the fractured bone at the time of maximal displacement with the injury and that the traction ischemia that the nerve endured (from playground to outside hospital to our hospital emergency department to our operating room) until reduction will result in a neurapraxia for up to 6 weeks. The anterior interosseous nerve is the most common nerve to be injured.[139–141] Direction and degree of fracture displacement greatly affect specific nerve injuries with median neurapraxia being most common with posterolateral displacement, radial with posteromedial displacement, and ulnar with flexion injuries. Indeed, 98% of nerve injuries with supracondylar fractures recover by natural history.[8,90,91]

However, if the nerve was clearly intact preoperatively, and then impaired postoperatively, that nerve is at high risk for iatrogenic pin injury or entrapment in the fracture site with reduction. For us, that nerve needs an immediate exploration. There are times where we have returned immediately from the recovery room to the operating room to fix the problem. There is no benefit to that child and that nerve in waiting if it is entrapped, lacerated, kinked, or penetrated by a pin. Ulnar nerve injuries with medial pins get the most press and play from the podium,[68,142] but we have cared for complete median and radial iatrogenic nerve injuries from supracondylar fracture treatment.[143,144] Any pin, screw, plate, or sharp instrument can traumatize

FIGURE 27-31 **A:** Radiographs of a healed supracondylar humerus fracture treated with cast immobilization at outside insitution with mild malunion. **B:** Two years later, there is an extensive avascular necrosis of the trochlea noted.

a nerve if you go too far, enter at the wrong anatomic site, and/or fail to mobilize the nerve out of harm's way. Just so you know, even lateral entry pins have been placed too deep and have injured the median nerve, so attention to detail is required at all times with a powered or sharp instrument in your hands.

Finally, we are always ready to be wrong in our assumptions. Not every nerve that we thought was a neurapraxia is. A rare one is entrapped, kinked, or compressed and needs surgical decompression. You either explore them all (clearly not necessary as up to 98% recover fully on their own), or you keep your eyes open for the missed, entrapped, or lacerated nerve. If there is no advancing Tinel sign away from the fracture site down the arm, if there are not signs of progressive motor recovery from proximal to distal over the first 3 to 4 months postinjury, that nerve needs exploration at 6 months at the latest. Decompression, neuroma resection and grafting, or nerve transfers may be required and should be anticipated in the discussion with the family, surgical consent, and planning. We have never regretted exploration and nerve reconstruction when there are no signs of recovery by 6 months. Waiting longer only risks permanent motor end-plate demise and chronic weakness and sensibility limits.[145]

CASE OUTCOME

The patient was taken to the operating room emergently. Under general anesthesia, a gentle closed reduction was attempted, including a milking maneuver. There was an uncomfortable sense with the controlled attempted reduction that there was soft tissue interposition in the fracture site. The fracture alignment improved but was not anatomic, and the pulse was still absent. The closed reduction was abandoned and an open reduction performed through a transverse, anteromedial incision at the fracture site. Careful soft tissue dissection revealed that the median nerve and brachial artery were entrapped by surrounding soft tissue beneath the distal aspect of the proximal fragment. The NVB was gently teased out of the fracture site, and vascular flow to the hand was restored. The entrapped periosteum was extracted from the fracture site, and an anatomic open reduction and pinning of the fracture was performed.

SUMMARY

Caring for children with fractures of the distal humerus is a high-risk, high-yield pediatric orthopaedic surgical endeavor. The risks of malunion and Volkmann ischemic contracture in supracondylar fractures; intra-articular incongruity in T-condylar fractures; and leaving a child abuse victim with a transphyseal fracture in an unsafe social environment are real. The benefit of restoring normal bone and joint alignment, elbow and hand function, and a hopeful childhood is the reason most of us get out of bed when the pager beeps.

SIDEBAR 1

The Pink Pulseless Hand

Treatment of the pink pulseless hand is still debated. Is it a risk for compartment syndrome? Is the blood flow through the collateral blood vessels around the elbow to the hand rather than via the brachial artery directly? If it is collateral flow, is it sufficient to prevent cold intolerance or, at the worst, risk of late amputation similar to traumatic adult elbow dislocations with occlusion of the brachial artery? Should the artery be explored to look for intimal damage or thrombosis like in an adult knee dislocation? Or, it is safe to watch as the pulse returns over the next 24 to 48 hours? The pink pulseless hand poses the risk of a missed compartment syndrome in juxtaposition to potentially unnecessary surgery or making the blood flow more impaired by unsuccessful revascularization.

Our review of the clinical evidence and extensive clinical experience indicates that in the absence of median neuropathy, the pink pulseless hand will be viable both short term and long term in a child (Figure 27-32). We do not explore the brachial artery in a patient when an anatomic reduction leads to instantaneous capillary refill and a truly pink hand with normal pulp turgor at the fingertips. A triphasic Doppler radial pulse can be reassuring as can 100% O_2 saturation by finger monitoring. However, we do hedge our bets a bit and keep them in hospital for 1 to 2 days if there is any question.

If there is a less than ideal blood supply to the hand and/or the fracture reduction, we ask for a No. 15 surgical scalpel and explore the NVB through an aesthetic transverse incision. The benefit of an anatomic open reduction, completely decompressed median nerve and brachial artery, and permanently viable hand through that aesthetic incision is minimal compared to the alternative of a missed entrapped, kinked, or compressed artery.

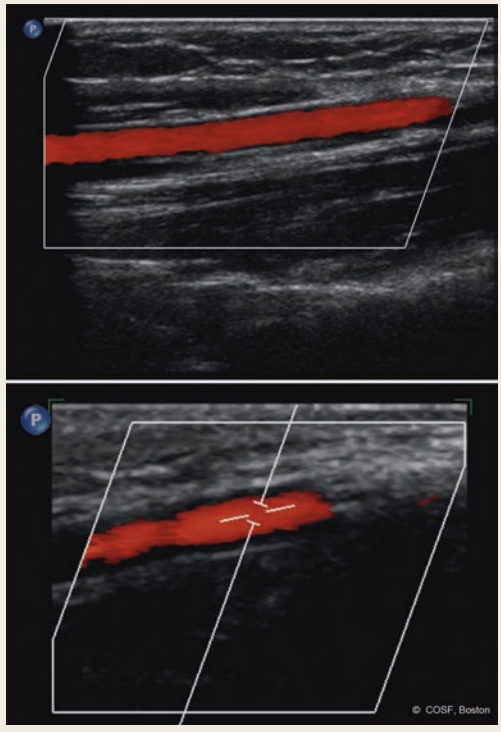


FIGURE 27-32 Ultrasound of a patent brachial artery at 3-year follow-up of a pink pulseless hand.

SIDEBAR 2

Traction

There was a time when skin or skeletal traction was a common form of treatment for displaced supracondylar humerus fractures.[146] Due to the high cost of lengthy in-hospital care; loss of the knowledge base on traction treatment among the new generation of pediatric orthopaedic technicians, nurses, trainees, and attending staff; and higher risk of malunion and skin problems, the traction methods have diminished. Overhead olecranon wing nut traction is now used less than once a year in our institution for patients with severe open fractures, medical conditions that prohibit acute operative fracture care and anesthesia, and/or excessive swelling.[147–150]

COACH'S CORNER

When Do You Get Out of Bed?

Not only is there more to life than basketball, there's a lot more to basketball than basketball.
—Phil Jackson

There have been several trends in the care of pediatric fractures over the past two decades that have resulted in major practice changes. Fracture care, like subspecialty care before it, has become concentrated in the medical centers. Within the orthopaedic surgery of a generation ago, community-based general orthopaedic surgeons performed CRPPs regularly for supracondylar fractures. Now these patients are sent

(*Continued*)

and/or their parents request transfer regularly to our pediatric facilities. Another change is that operative fracture care is provided by attending physicians and faculty with all trainee surgical experience being directly supervised in most pediatric facilities. The burden on pediatric orthopaedic surgery staff, day in, night out, has increased. Our policy before was that every displaced supracondylar humerus fracture was a surgical emergency. Now that would require that our surgical, anesthesia, and operative nursing staff be up almost every night caring for these fractures. In response, pediatric orthopaedic surgeons and medical centers have devised processes and systems that enable them to care for fewer of these children in the middle of night. Daytime trauma operating rooms, revolving daytime pediatric orthopaedic trauma surgeons (our OOW or orthopaedist of the week), and even trauma-based programs are operational in many facilities. The risk of these new policies is a missed Volkmann ischemic contracture: a compartment syndrome that could have been avoided by emergent surgery. So, when do you have to get up, go in, and provide emergent care? Any avascular limb, open fracture, fracture with skin puckering and compromise are no-brainers. Displaced fractures with neuropathy (especially posterolateral displacement and median neuropathy) are serious candidates for emergency, and we advocate they all be done at night. If not, be certain that (1) a trained professional watches that patient closely overnight and calls you in if the situation worsens and (2) you have a guaranteed operating room, available surgeon, anesthesiologist, and nursing surgical team starting at the light of day.

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CHAPTER

28

Lateral Condyle Fractures

CASE PRESENTATION

A 6-year-old female presents with a swollen elbow after a fall from playground equipment. Her lateral elbow is ecchymotic and tender, and she refuses to move it. Her neurovascular exam is intact. Radiographs (Figure 28-1) reveal a displaced lateral condylar fracture of the distal humerus.

CLINICAL QUESTIONS

- How are humeral lateral condylar fractures classified?
- What are the associated injuries?
- What radiographs are most useful for diagnosis and management planning?
- When is a MRI or CT scan indicated?
- What are the indications for closed treatment?
- When is closed reduction percutaneous pinning (CRPP) indicated?
- When is an intraoperative arthrogram useful?
- Which fractures should be treated with open reduction internal fixation (ORIF)?
- What are the risks of ORIF?
- What are the complications of lateral condylar fractures and their treatment?

THE FUNDAMENTALS

Etiology and Epidemiology

Lateral condylar fractures of the distal humerus occur less frequently than supracondylar fractures, accounting for 15% to 20% of all pediatric elbow fractures. Like most children's upper limb injuries, they occur secondary to a fall or traumatic collision with another person or immobile (ground, building, tree) or mobile (car, bike) solid object. There is some debate as to whether during the injury the radial head "pushes off" the lateral condyle with a compression force or the forearm and extensor-supinator muscle origins "pull off" the lateral condyle with valgus-extension stress. The controversy makes for interesting academic discussion and paper publications[1–3] but really matters little in the simple "bone be broke, bone needs to be fixed" clinical scenario that we, the surgeon, the affected child, and his or her family confront.

Clearly understanding the distal humeral articular anatomy and soft tissue attachments about the elbow is key to proper diagnosis and management of this problem. The extensor-supinator muscle mass of the forearm, wrist, and hand originates from the metaphysis of the lateral condyle of the humerus. The lateral collateral ligament complex consists of the radial collateral ligament (from the isometric point on the lateral epicondyle to the annular ligament), lateral ulnar collateral ligament (from the lateral epicondyle to the crista supinatoris), and annular ligament (Figure 28-2).

Clinical Evaluation

A child with an elbow fracture invariably presents with a swollen, tender elbow. The lateral condylar fracture patients do not have as much deformity as the supracondylar fracture or elbow dislocation patients. Tenderness and ecchymosis on the lateral elbow are very helpful in proper clinical diagnosis, especially in the stable and/or minimally displaced fractures.[4] There may be crepitus with range of motion, though most children will not tolerate movement of the elbow in the acute setting. The diagnosis is really made by radiographs, with specific anteroposterior (AP), lateral, and internal oblique views of the distal humerus being necessary for accurate diagnosis of fracture displacement and risk of further displacement with cast treatment.[5]

The capitellum is the first secondary center of ossification to appear, usually between 1 and 2 years of age. The diagnosis of a lateral condylar fracture can be made accurately by plain radiographs. It can be confused with a posterolateral elbow dislocation, distal humerus physeal, or supracondylar fracture if the clinician does not properly define the alignment of the radius and ulna, distal humerus articular and physeal structures, and distal humerus metaphyseal region to one another. The fracture starts in the lateral condylar metaphyseal region and

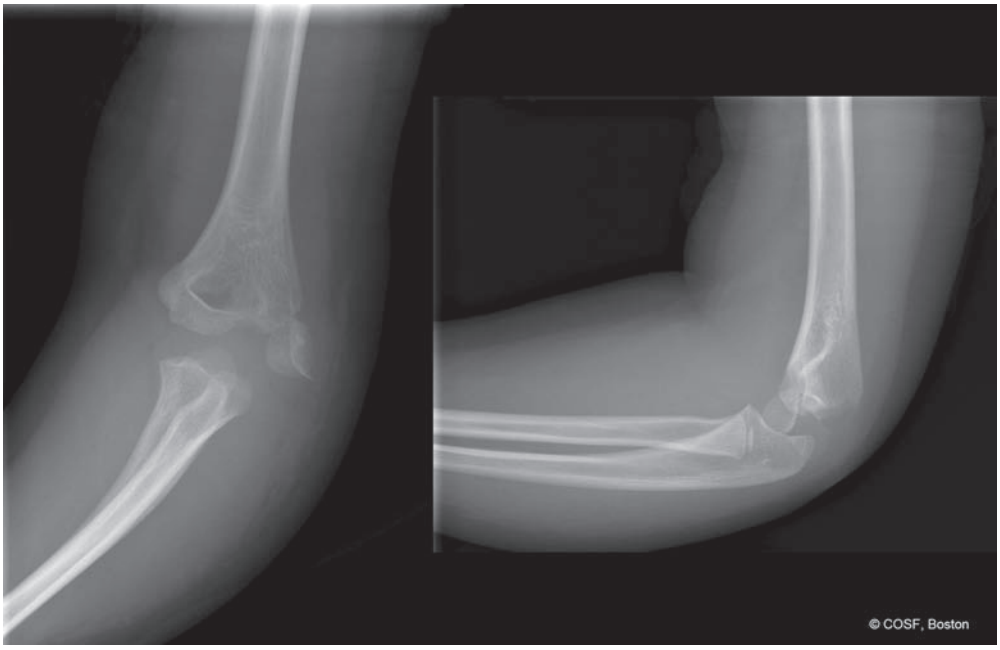


FIGURE 28-1 Radiographs show a displaced type III lateral condylar humerus fracture.

extends distally and medially to or through the articular surface. The radiographic classification systems are based on the path of the fracture through the distal humerus and the degree of displacement. The Milch classification (Figure 28-3) distinguishes a type I fracture directly through the secondary center of ossification from a type II fracture that extends over medially and exits through the ulnar-trochlear groove. Mirsky et al.[6] have added a third type of fracture that extends even more medially and exits through the physis. The transphyseal fracture is harder to distinguish by x-ray due to the lack of ossification medially at a young age. We rarely use the Milch system but teach it to our trainees, as certifying exams continue to ask about it, and it does help trainees better understand the distal humeral articular anatomy. The Jakob classification[1] (Figure 28-4) is more useful for treatment decision making as it is based on the degree of displacement and, therefore, implies fracture stability and defines articular alignment. Type I fractures are displaced <2 mm; with type II fractures, the articular surface is displaced >2 mm but is not malrotated; and type III fractures have more

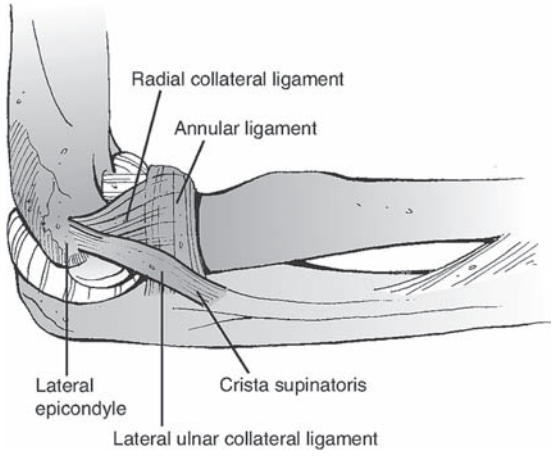


FIGURE 28-2 Ligamentous anatomy of the radiocapitellar joint and proximal radioulnar joint (PRUJ). The lateral collateral ligament extends from the isometric point on the lateral epicondyle to the crista supinatoris on the proximal ulna. The radial collateral ligament and the annular ligament stabilizing the PRUJ are noted. (From Bucholz RW, Court-Brown CM, Heckman JD, Tornetta P. *Rockwood & Green's Fractures in Adults.* 7th ed. Philadelphia, PA: Lippincott Williams & Wilkins, 2010, with permission.)

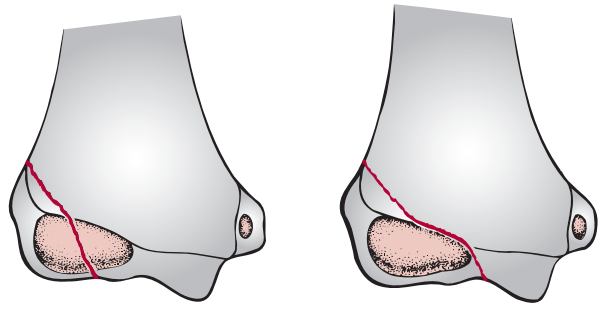


FIGURE 28-3 Milch classification of lateral condylar humerus fractures with type I (**A**) extending into the joint through the capitellar ossification center and type II (**B**) entering the joint at the ulnar-trochlear groove. (From Beaty JH, Kasser JR. *Rockwood & Wilkins Fractures in Children.* 7th ed. Philadelphia, PA: Lippincott Williams & Wilkins, 2010, with permission.)

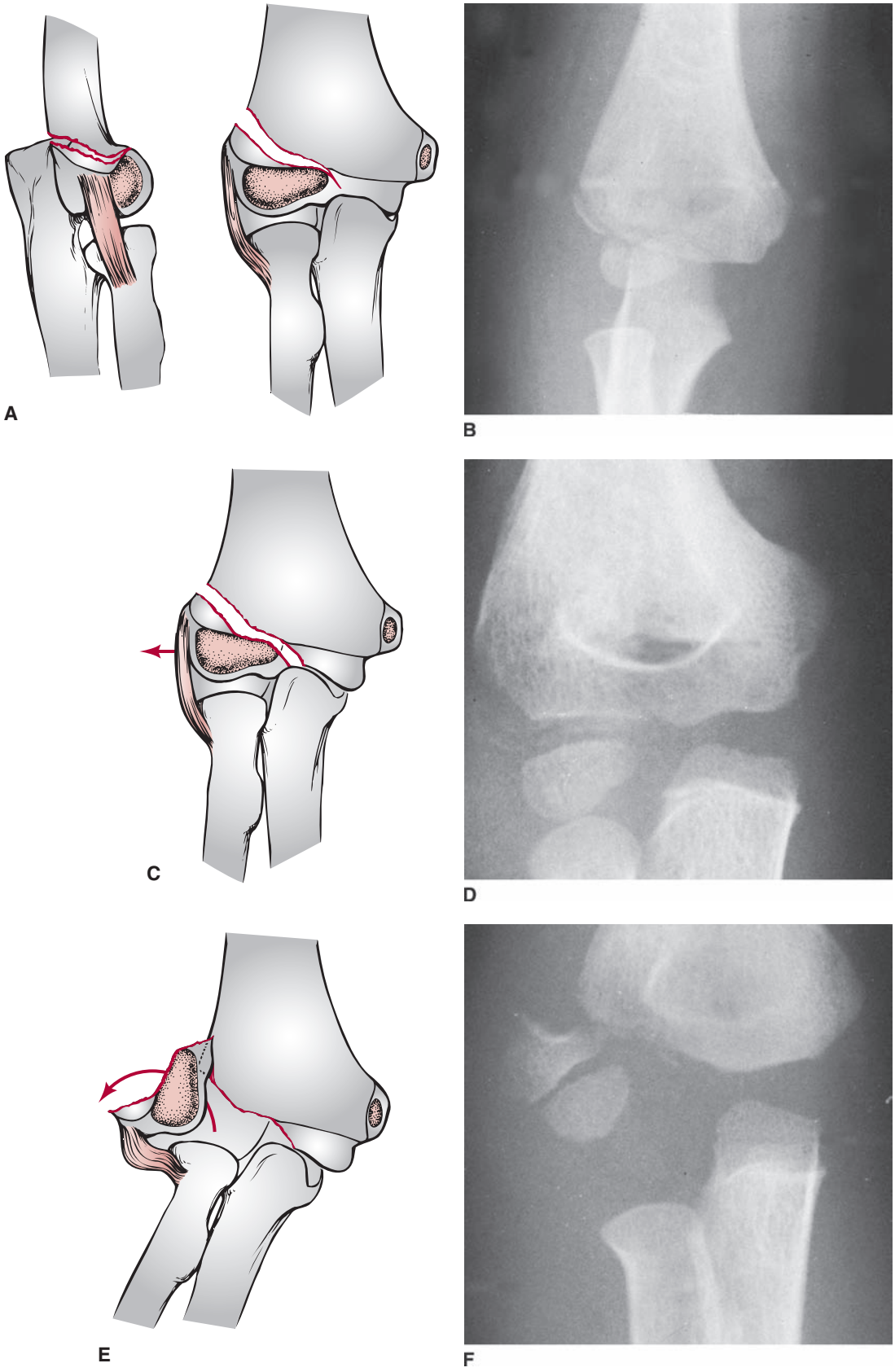


FIGURE 28-4 Jakob classification of lateral condylar humerus fractures in children with type I (<2 mm displacement) hinging the joint but not entering the joint; type II entering the joint with displacement of >2 mm but no malrotation; type III with complete displacement and malrotation. (From Beaty JH, Kasser JR. *Rockwood & Wilkins Fractures in Children*. 7th ed. Philadelphia, PA: Lippincott Williams & Wilkins, 2010, with permission.)

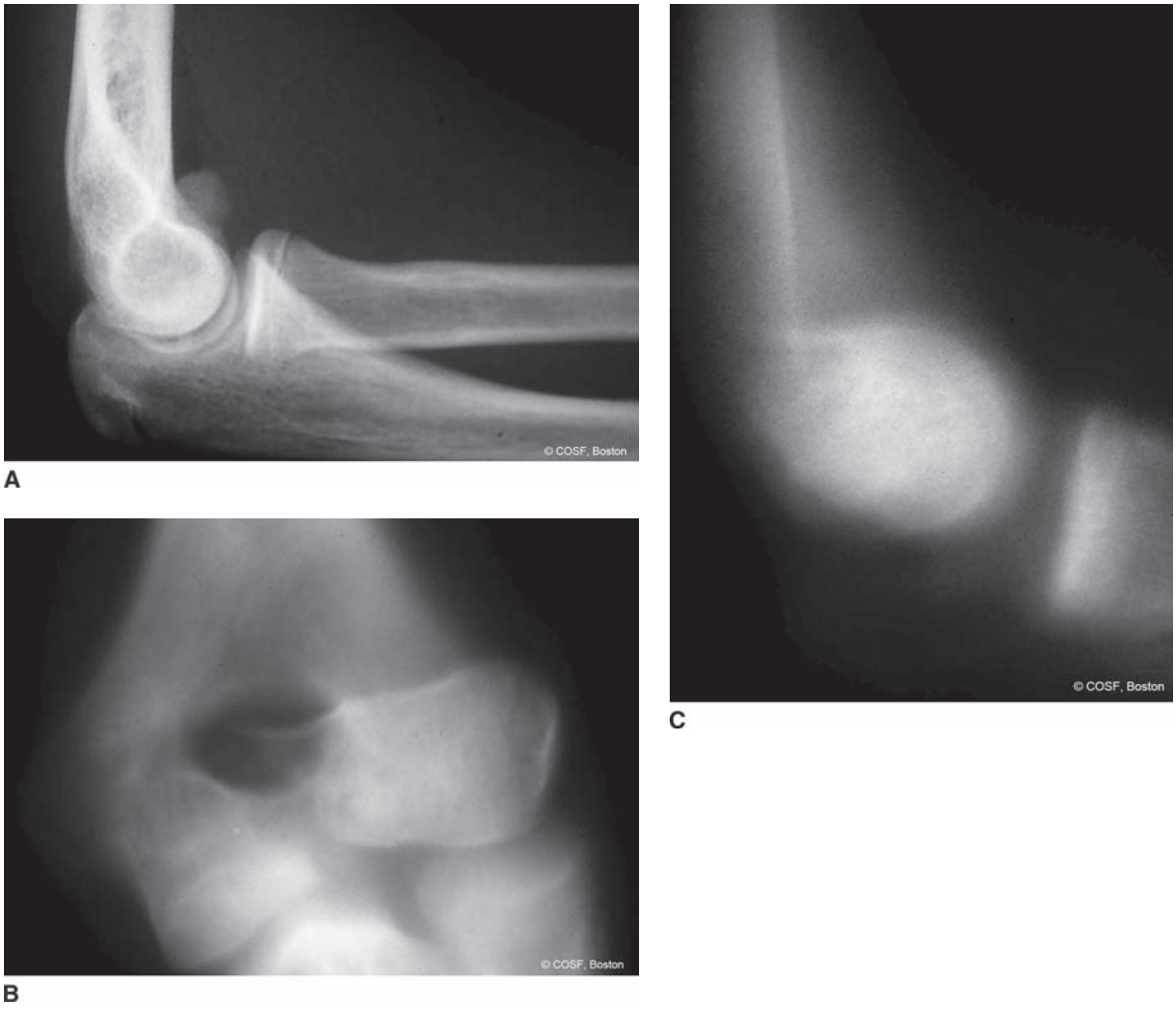


FIGURE 28-5 **A:** Lateral x-ray of a displaced capitellar shear fracture. **B, C:** Tomograms of displaced capitellar shear fracture on AP (**B**) and lateral (**C**) views.

marked displacement including malrotation. The accuracy of articular malalignment has been confirmed using magnetic resonance imaging (MRI) and computed tomography (CT).[7–10] It can be difficult to define fracture stability with minimally displaced fractures. Oblique radiographs will reveal maximum displacement and should be obtained in all lateral condylar humerus fractures. Besides initial and serial radiographs, ultrasounds, MRI, and CT scans have been used to better define stability in order to avoid malunion or nonunion consequences in unclear situations.[10–13] The treating surgeon has to define the articular displacement and fracture instability in order to make the appropriate treatment decisions for each patient with a lateral condylar humerus fracture.

Associated injuries need to be defined. Although rare, radial neck, olecranon, and Monteggia fractures; elbow dislocations; and floating elbow injuries all do occur in conjunction with lateral condylar humerus fractures. Finally, the capitellar shear fracture is a separate entity that can be missed on plain radiographs (Figure 28-5). This fracture is high risk for long-term complications, even with early accurate diagnosis and appropriate ORIF. Analysis with CT scan is very helpful to define the fracture location, pattern, and size of the fracture fragment in preparation for surgery.

Surgical Indications

A lateral condylar humerus fracture with articular incongruity >2 mm (Jakob II and III fractures) needs surgical reduction and stabilization. Often the reduction and stabilization can be anatomically performed by percutaneous techniques in the mild type II fracture. With the very unstable type II fracture or with marked articular surface malrotation (type III), ORIF is indicated.

SURGICAL PROCEDURES

It isn't the mountains ahead to climb that wear you out; it's the pebble in your shoe.
—Muhammad Ali

Nonoperative Treatment

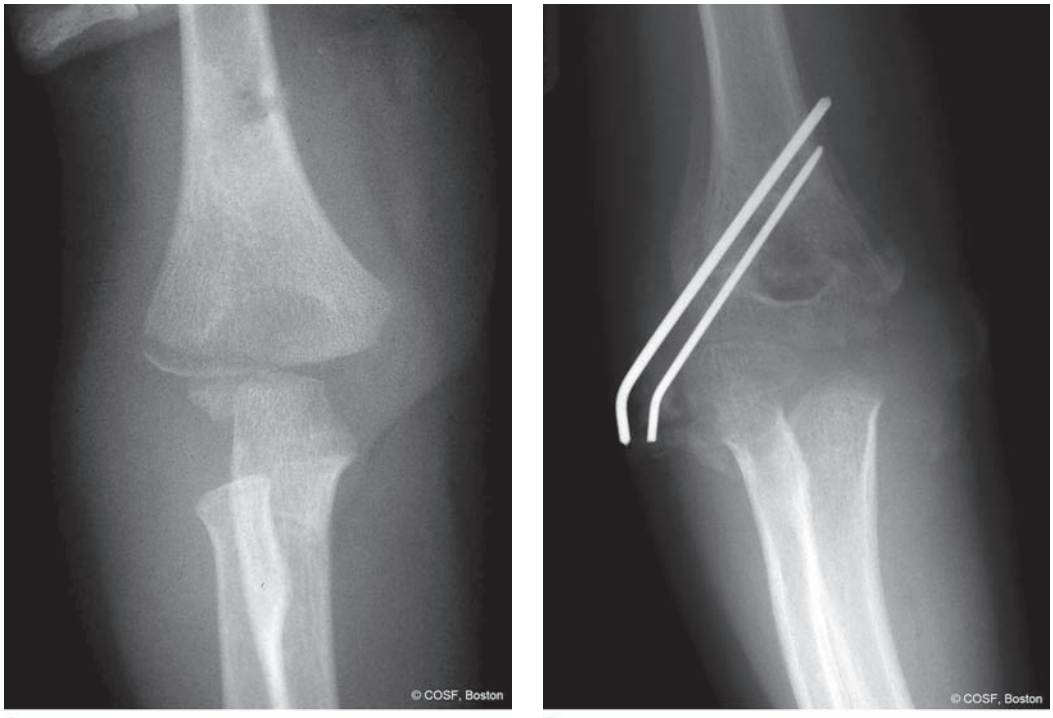
Minimally displaced (<2 mm) lateral condylar fractures (Jakob type I) as confirmed by AP, lateral, and oblique radiographic views are ideal candidates for closed treatment. Bivalved long-arm cast, collar and cuff, splint and sling have all been used successfully.[14–16] The fracture will heal in 3 to 6 weeks. Immobilization in forearm supination and wrist extension has been used to lessen muscle tension on the lateral condyle and therefore the risk of fracture displacement. These nondisplaced fractures should be stable, and supination and wrist extension positioning may be overkill. However, there will be a rare fracture that you never expected to displace, yet it does.[17] Vigilant use of close, follow-up radiographs is necessary to catch the "rule breaker." The false assumptions in these rare situations are that: (1) the articular surface is always intact and stable and (2) the soft tissue injury is minor. Protective immobilization should continue until there are clinical and radiographic signs of bony healing. If the fracture displaces or fails to heal in a timely manner, then CRPP is required (Figure 28-6).

CRPP or Screw Fixation with Arthrogram

If you make every game a life-and-death proposition, you're going to have problems. For one thing, you'll be dead a lot.
—Dean Smith

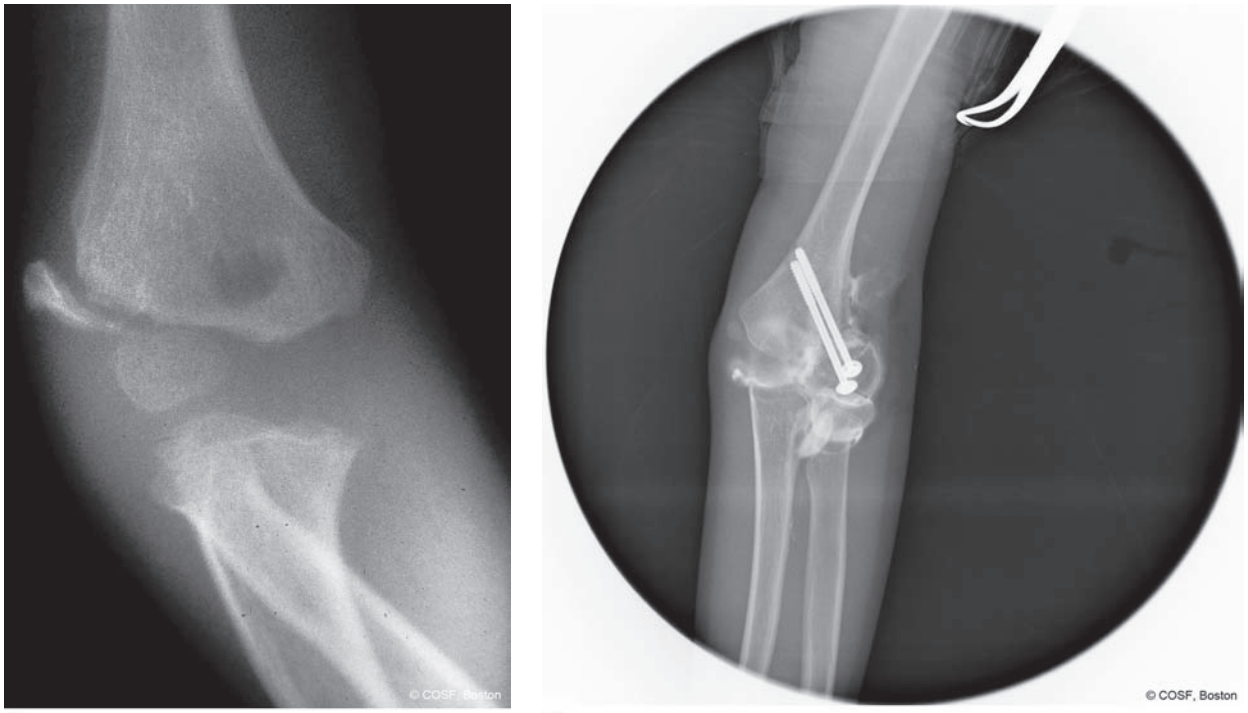
Closed reduction of almost all type II and some rare, malrotated type III lateral condylar fractures is feasible.[5] Varus stress with the forearm supinated is utilized for reduction. Elbow extension with the varus stress and supination position is most reliable for reduction of most fractures. After successful closed reduction, percutaneous pin fixation is performed to stabilize the fracture. The results of CRPP are better than closed reduction and immobilization in terms of malunion and nonunion.[18] Two divergent, lateral entry pins that penetrate the far cortex (similar to supracondylar fractures [see Chapter 27]) are used (Figure 28-7).[19] A third pin parallel to the joint from the lateral to the medial condyle helps with articular reduction and stability. In situations when there is uncertainty about the articular reduction and/or stability, an arthrogram for confirmation and stress testing is indicated.[20]

If the metaphyseal fracture is large enough, cannulated compression screw fixation can be used.[21] There is usually only room enough for one screw, and it should never violate the olecranon fossa. A second smooth pin separate from the compression screw guide pin will prevent



A B

FIGURE 28-6 **A:** Minimally displaced type II lateral condyle fracture, preoperative for CRPP with arthrogram to confirm anatomic joint reduction. **B:** Similar healed fracture treated with CRPP.



C D

FIGURE 28-6 *(continued)* **C:** Type II fracture presenting late with delayed union. Plan is preoperative MRI to assess joint alignment and, if feasible, intraoperative CRPP or percutaneous screw fixation with arthrogram. **D:** Another case of delayed malunion treated with percutaneous screw fixation and arthrogram.

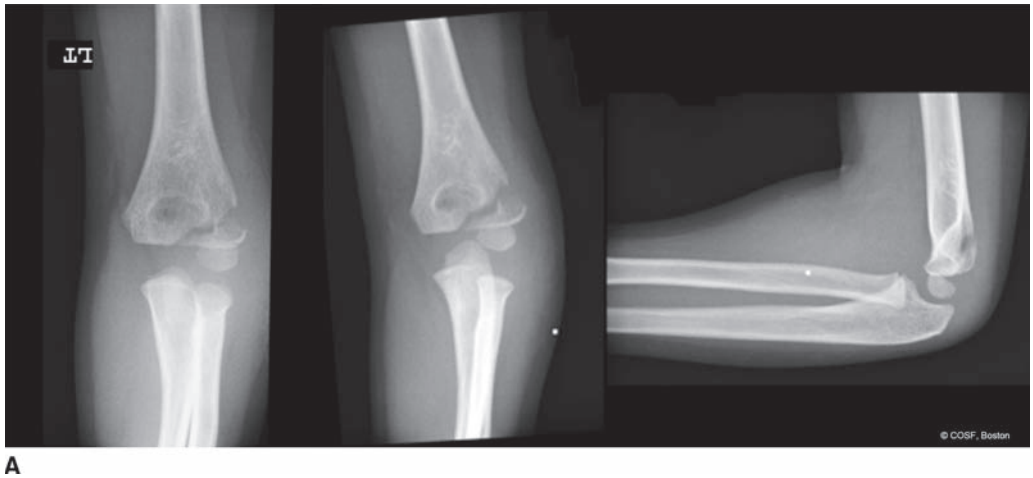
malrotation of the fragment during compression of the screw and fracture. That second pin can be removed in the operating room or later depending on the stability of the fracture fixation. We use a washer for broad compression. These screws usually need to be removed in 6 months in the day surgery unit due to local irritation.

Some surgeons will even violate the lateral condylar physis with a screw as they do not consider lateral physeal growth arrest a risk or a problem. There is insufficient evidence to be completely reassuring on that point.

Open Reduction Internal Fixation

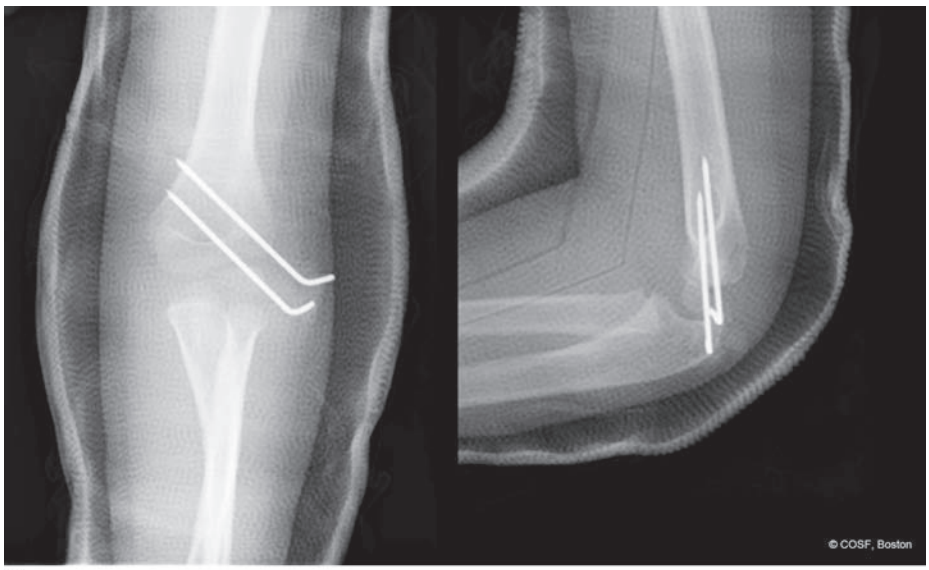
Most ball games are lost, not won.
—Casey Stengel

Although many lateral condylar fractures can be treated with CRPP, type III fractures with marked malrotation and fragment instability are still best treated with ORIF by most surgeons. There is marked soft tissue disruption with the type III fracture that makes percutaneous reduction



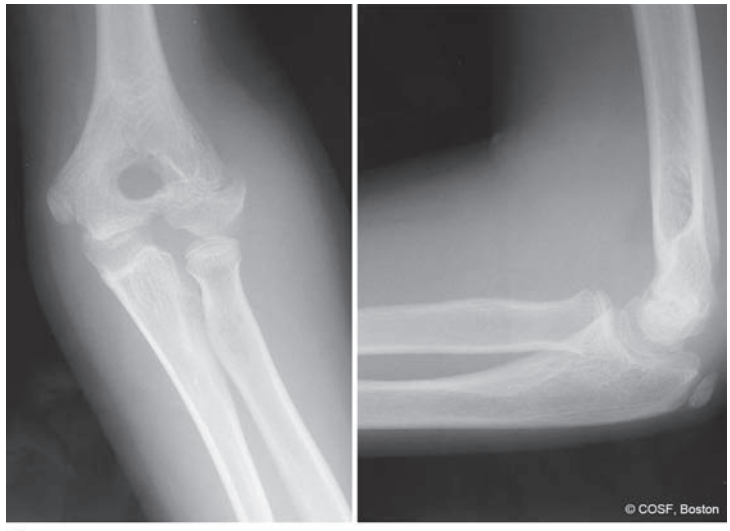
A

FIGURE 28-7 **A:** AP and lateral radiographs of type II displaced lateral condylar humerus fracture.

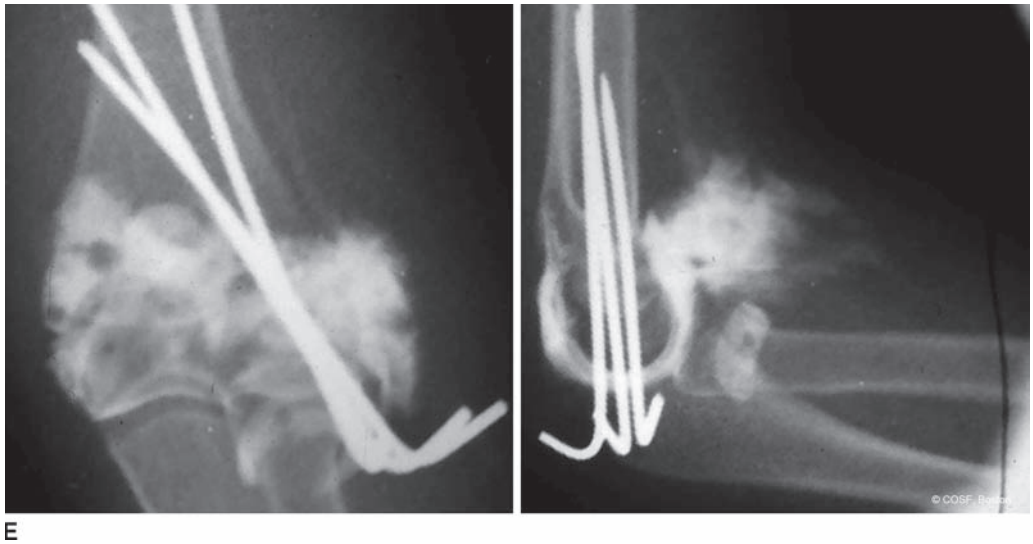


B

C



D



E

FIGURE 28-7 *(continued)* **B:** CRPP with two pins. **C:** Radiographs after pin removal. There is a small lateral spur present. **D:** Displaced lateral condylar fracture in an older child treated with (**E**) three-pin CRPP and arthrographic confirmation of joint reduction.

difficult. Arthroscopic techniques are not for every surgeon or every patient.[22,23] Articular congruity and stability must be restored, and an open reduction has the highest likelihood of a successful outcome in the type III fracture.

The patient is positioned supine with the arm abducted on a fluoroscopic arm table. Doing this operation on the fluoroscopic image intensifier as one would for a supracondylar fracture is too limiting and runs the risk of fracture malreduction. The entire arm is prepped, and, if necessary, a sterile rather than nonsterile tourniquet is used for maximum visualization. A direct posterolateral approach directly over the fracture is used.[24,25] The incision can be extensile but generally is in the 4- to 8- cm range. There is always a large fracture hematoma that leads directly to the joint. Blunt finger dissection will usually find the path into the joint without extensive dissection beyond the skin and subcutaneous incision. Gently untwisting the malrotated lateral condyle while maintaining soft tissue blood supply to the fracture fragment is critical. While the fragment is unkinked but not reduced, the joint is cleansed of all hematoma. Repeat irrigation and suctioning are very helpful. The articular surfaces are inspected for other injuries. The soft tissues, including neurovascular bundles, are lifted off the anterior humeral surface. Retractors are placed subperiosteally across the front to visualize the joint reduction. An anatomic ulnar-trochlear groove reduction has to be felt and seen. Posterior soft tissue dissection of the fragment is not performed to avoid increasing the risk of avascular necrosis (AVN). Once manually reduced (our young partners will attest that this is not always an easy task), the fracture needs to be held anatomically in place during pin fixation. Some use a bone-holding towel clamp. We often continue the Dr. John Hall tradition of a "dinner fork" reduction with a large double skin hook or truly adapted fork with two missing central prongs. Divergent pins are placed in sequence while manually maintaining reduction. One pin is parallel to the joint; one extends up the lateral column. Both need to penetrate the medial cortex while avoiding the neighboring neurovascular structures. A third pin can be added across the olecranon fossa as necessary. After completion of the pinning, anatomic articular reduction is again confirmed by palpation and limited direct visualization. Arthrographic or arthroscopic confirmation can be used. You cannot leave the operating room with a malreduced fracture. Stay until it is verified anatomically. Limited soft tissue repair and stabilization are performed to reattach the extensor-supinator origin. This can be performed before or after pinning depending on rotational fracture stability. The pins are left out of the skin as doing this carries less risk of pin track infection than with buried pins.

Delayed Union CRPP or Screw Fixation

Some untreated or immobilized treated patients will present late with impending nonunion or malunion. If the joint is aligned, then cast treatment until healing can be successful in many cases.[26–28] However, pin or screw fixation is most expedient and has the lowest risk of malunion or nonunion. A preoperative MRI scan will define the articular alignment. Most patients will merely have diastasis but not malangulation or malrotation. Manual reduction and pin fixation or compression screw reduction and fixation will reduce and secure the joint. Arthrographic confirmation is appropriate if a closed technique is used. The methods are similar to the description of CRPP or screw fixation above (Figure 28-8).

If the joint is malaligned or malrotated and closed techniques are not feasible, open reduction is indicated. The sooner you get to this, the better. The joint malalignment is not magically going to disappear. Late open reduction is more complex[1,16,29–32] and without question carries the risks of osteonecrosis and limited motion and function. Soft tissue dissection of the fracture fragment is purposefully delicate, especially posteriorly where the blood supply to the lateral condyle is located. Gentle mobilization and reduction are required. Careful removal of fracture callus while maintaining the bony and articular cartilage integrity is performed. After anatomic reduction of the joint, pin or compression fixation as noted above is performed. Compression screw fixation is preferred if feasible to allow for early, stable, protected mobilization in a hinged brace while the fracture is healing.

ORIF Capitellar Shear Fracture

If you screw things up in tennis, it's 15-love. If you screw up in boxing, it's your [butt] [edited for children and their doctors].
—Randall "Tex" Cobb

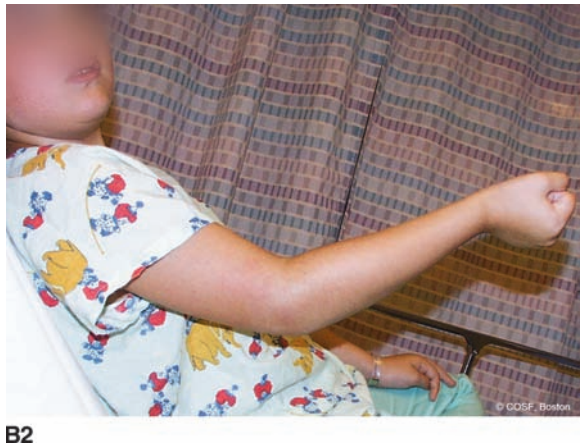
Capitellar shear fractures are difficult to diagnose and to treat. The minimally displaced (often flexed) fracture can be missed on plain radiographs due to its small size, minimal bone involved, location with overlap of the distal humerus, and inexperience of the image reader. The completely displaced fractures are hard to miss. Since the fracture occurs by the radial head pushing off the capitellum in a vertical shear, there may be associated proximal radius injuries apparent on the film.[33,34] Tomograms (old school) or a CT scan is the best method for accurate diagnosis and surgical planning (Figure 28-5). Of note, an acutely traumatic capitellar shear fracture is different than an osteochondral loose body from prolonged osteochondritis dissecans (see Chapter 41).

A posterolateral approach to the displaced capitellar fracture is used. The anconeus-extensor carpi ulnaris or more anterior wrist extensor splitting incision is utilized while maintaining lateral collateral ligamentous integrity. After lateral arthrotomy, the hematoma is debrided and the fracture fragment size and displacement assessed. There is often only a minimal amount of cancellous bone attached to the capitellar articular surface. The fracture is often impacted and superiorly displaced. With gentle mobilization for reduction, it usually becomes a free piece. This

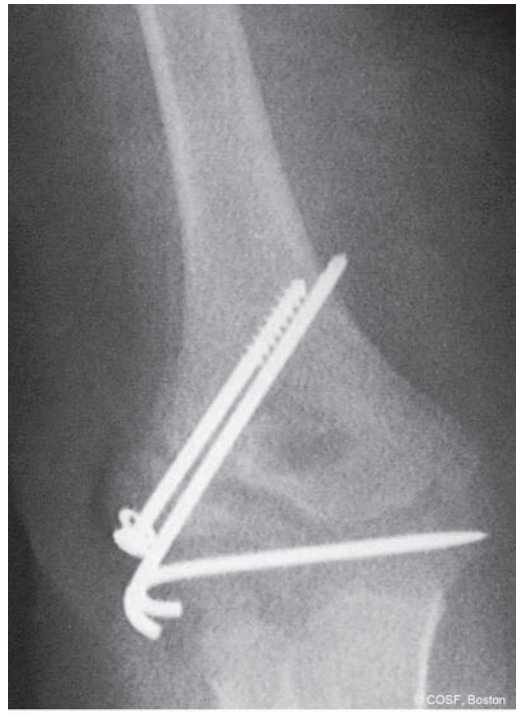
A1

A2

B1



B2



C

FIGURE 28-8 **A:** AP and lateral radiographs of a delayed union, early malunion. **B:** Preoperative clinical photographs of maximum flexion of this patient. **C:** Reduction and hybrid screw and pin fixation method to achieve union.

is why osteonecrosis from this fracture and its treatment is such a high risk. Anatomic joint reduction is required. Temporary pin fixation is performed with posterior to anterior smooth pins. These pins are usually pins for a cannulated screw system. Confirmation of the anatomic reduction (nothing less is acceptable) is obtained with fluoroscopic images and direct visualization with elbow flexion-extension. Compressive screw fixation with two intraosseous headless (Acutrak, Acumed, Hillsboro, OR; Herbert, Zimmer, Inc., Warsaw, IN; or Synthes, West Chester, PA) or one cancellous (Synthes, West Chester, PA) screw(s) is performed. The fixation is almost always posterior to anterior to avoid violation of the anterior articular surface. There are some rare fractures in the young

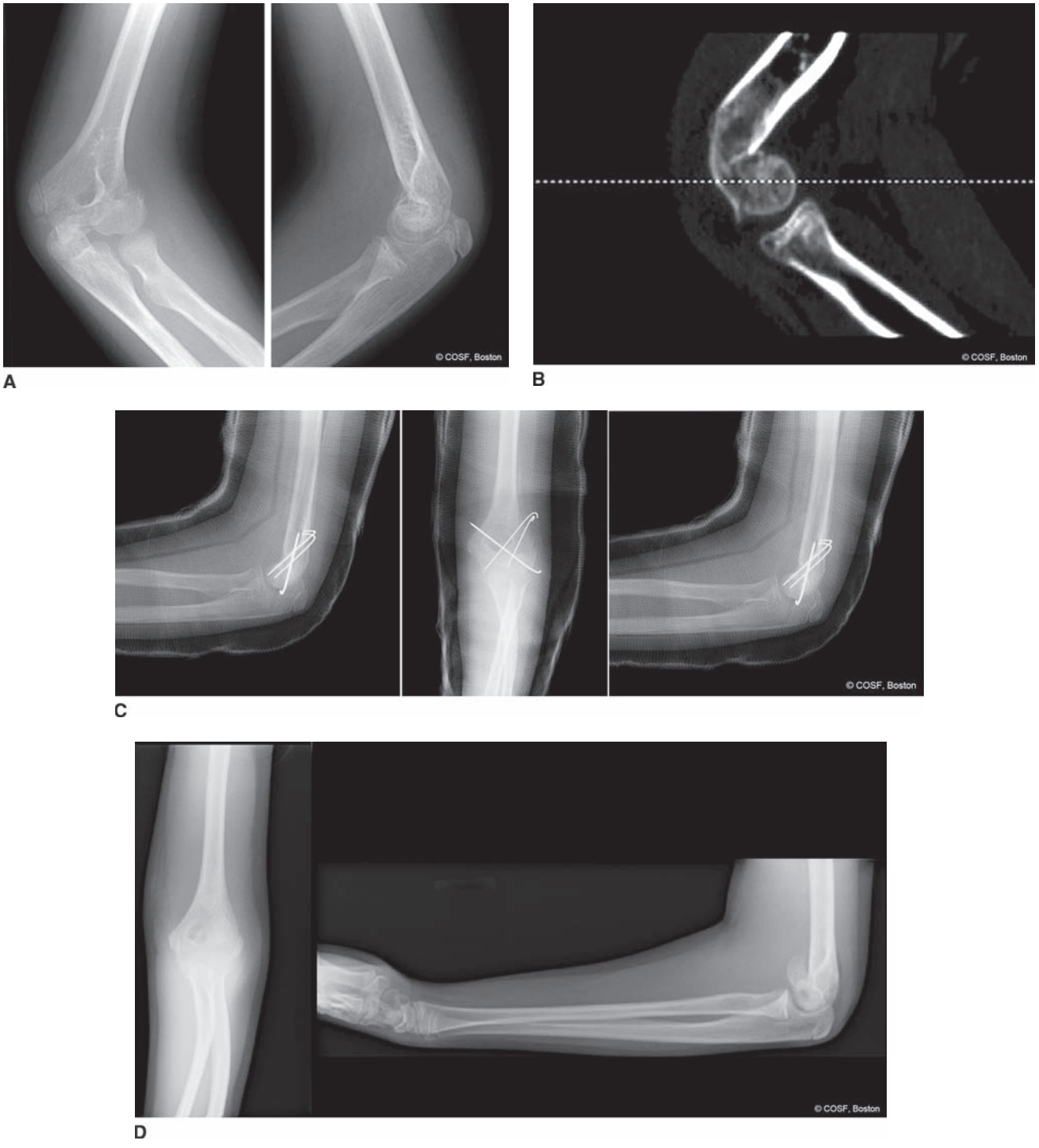
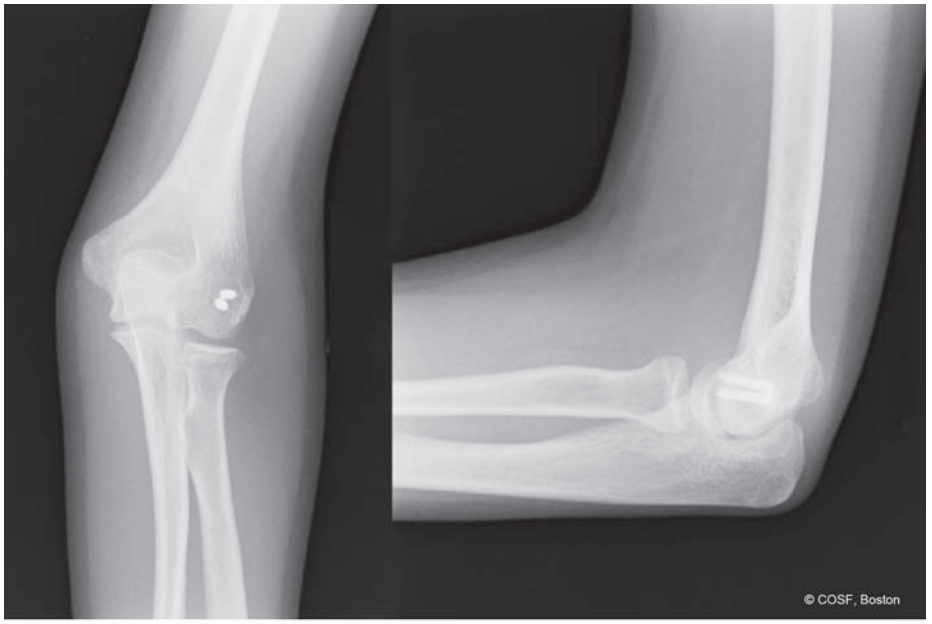


FIGURE 28-9 **A:** Preoperative radiographs of capitellar shear fracture. **B:** CT scan confirming flexion deformity of capitellar fracture. **C:** ORIF with pins. **D:** Preoperative radiographs of capitellar shear fracture treated with (*continued*).



E

FIGURE 28-9 *(continued)* **(E)** ORIF and intraosseous screws.

that can be treated with smooth pins or suture repair (Figure 28-9). If the fixation is stable, and the patient and family are trustworthy, then hinged elbow brace mobilization is progressed during fracture healing. Return to sports is slow with prolonged rehabilitation, and radiographs are obtained for 6 to 12 months postoperatively due to the high risk of osteonecrosis (Figure 28-10).

◆ ORIF Nonunion, Staged Osteotomy

Nonunions of lateral condylar fractures are defined by failure of bony healing by 3 months postinjury. There is a wide spectrum in timing of presentation and the degree of bone and joint malalignment in nonunion patients. The more prolonged the nonunion, the more there can be proximal migration of the fragment, articular malalignment, cubitus valgus deformity, and eventual ulnar nerve palsy. Treatment is dependent on the symptoms, degree of deformity, and motion and functional limitations of the patient. The risk with any surgical intervention is making the situation worse, in this case with osteonecrosis, loss of motion, and/or worsening pain. The earlier established nonunions without proximal migration of the fragment can be treated with in situ compressive screw fixation and bone grafting. The later-presenting nonunions with proximal migration and cubitus valgus can be (1) left alone if the patient is not bothered by pain, functional limitations, ulnar nerve impairment, and/or the aesthetics of the cubitus valgus; (2) treated with staged in situ fusion and fixation of the nonunion and ± ulnar nerve transposition followed by second-stage varus osteotomy of the distal humerus (Figure 28-11); or (3) ulnar nerve transposition alone in adulthood.[35–41]

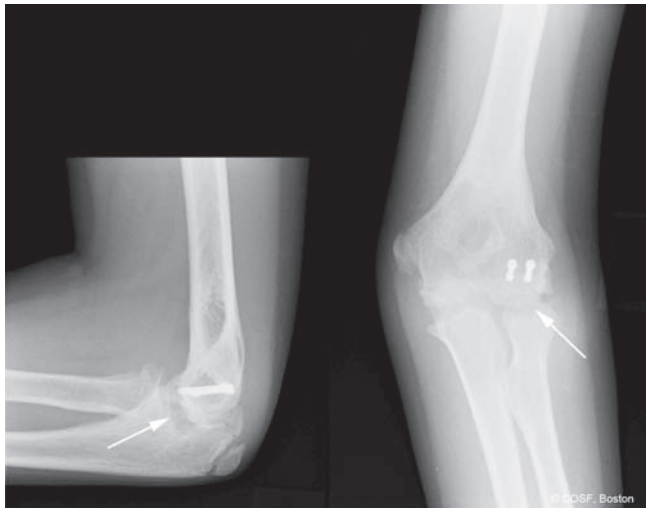


FIGURE 28-10 AVN that developed in a capitellar shear fracture treated with ORIF. Arrow points to area of AVN and collapse on lateral view.

We determine if the patient's elbow motion is truly through the joint rather than the nonunion site by fluoroscopic exam before proceeding with reconstruction. In situ fixation and bone grafting are performed by the previously described posterolateral approach. The fracture fragment is not mobilized or dissected free of soft tissues to lessen the risk of AVN. To minimize the dissection, the nonunion site is entered from above after defining its location with a 25-gauge needle and fluoroscopic images. The nonunion is debrided of fibrous tissue along the metaphysis of the humerus and the fragment. If necessary for healing, iliac cancellous bone graft is obtained by trapdoor technique and densely packed in the extra-articular parts

FIGURE 28-11 **A:** AP radiograph of lateral condylar humerus nonunion with valgus deformity. **B:** In situ screw fixation and bone graft to achieve union. **C:** Healed nonunion site with persistent valgus but ulnar neuropathy resolved. **D:** Intraoperative osteotomy with varus, extension, and translation correction. **E:** Healed osteotomy after plate removal.

of the nonunion.[38] With fluoroscopic guidance and confirmation, compressive screw fixation is obtained. Motion is checked after fixation to be certain the operative intervention has not caused loss of functional elbow motion and that the fixation is stable enough to allow for protected early mobilization in a hinged elbow brace postoperatively. Layered closure is performed.[42,43]

If the ulnar nerve is symptomatic (positive Tinel sign, elbow flexion test, numbness of ulnar fourth and both sides of the fifth digit, and/or intrinsic weakness), then an ulnar nerve decompression and transposition is performed. Through an anteromedial approach, the ulnar nerve is identified and decompressed. The incision is centered just anterior to the medial epicondyle and extends 6 to 8 cm. The medial

brachial and antebrachial cutaneous nerves that cross the operative field are identified and protected throughout the surgery. The ulnar nerve is isolated proximal to the medial epicondyle while maintaining longitudinal vascularity. The nerve is decompressed proximally by releasing the arcade of Struthers. Distally Osborne fascia is incised between the medial epicondyle and the olecranon. The flexor carpi ulnaris (FCU) fascia is released into the forearm. The medial intermuscular septum is resected off the humerus while protecting the horizontal veins beneath the septum. The nerve is now decompressed, which in itself may be sufficient treatment of a symptomatic or impaired nerve. If the nerve is to be transposed, then it needs to be sufficiently mobile (without tension or kinking) while still maintaining motor branches to the FCU. The nerve can be maintained in a position anterior to the medial epicondyle all by itself or with either a submuscular or subcutaneous transposition and fascial flap. Since the evidence is limited as to which is best, the surgeon can choose. We tend to do a subcutaneous transposition with a flexor-pronator fascial flap in the young.

After the patient heals from his or her first-stage surgery and gets back his or her elbow motion, a second stage can be considered. The interval is usually 6 months with a range of 3 to 12 months. Since the medial epicondyle is usually markedly elongated, a simple closing wedge osteotomy of the medial column will often result in a distorted elbow appearance.[44] A combined wedge and transposition osteotomy, as described by Milch, is required for functional and aesthetic correction. Rigid internal fixation and bone grafting are necessary.

◆ Intra-articular Osteotomy for Malunion

Playing polo is like trying to play golf during an earthquake.
—Sylvester Stallone

One of the hardest operations we do is an intra-articular humeral osteotomy for malunion. This surgery is a high-risk endeavor. Surgery can make matters worse. The earlier the surgery, the better. There are some situations that may indeed be better left alone, because even in the most skilled of hands, complications do occur. However, we think in the young child, going back, even late, and getting it right is to the benefit of most children so afflicted. There are some really rare situations in which the malunion is minor, and serves as a block to motion with an articular flap tear, arthroscopic debridement will improve motion and pain (Figure 28-12).

Thorough study of all the patient's radiographs from injury through treatment to presentation to you as the superskilled specialist is imperative. Preoperative CT (including three dimensional) and MRI scans are mandatory to visualize exactly both the problem and your planned solution. You have to see it in your mind's eye before you can proceed. Extensile exposure, which may include very deliberate but worrisome soft tissue stripping, is required (Figure 28-13). You have to make the pieces fit exactly. To do so necessitates distinguishing between fracture callus, exostosis, and anatomic bone and cartilage, but this is easier said than done. Rigid internal fixation with compression screw fixation is performed once temporary fixation confirms impingement-free motion and anatomic radiographic alignment. No doubt, osteonecrosis is a risk, so these rare cases are followed for at least 1 year. Early rehabilitation for motion is important but not at the risk of fracture collapse. Each case is to some degree unique.

POSTOPERATIVE

Uncomplicated lateral condyle fractures are immobilized in a long-arm cast until healed. The healing time for most fractures is in the range of 4 to 6 weeks. Due to the limited vascularity of the fragment and intra-articular synovial fluid around the fracture, some fractures can be slow to heal (6 to 12 weeks). We caution against discharging the patient from your care until there is complete radiographic healing. Fractures treated in a cast that show signs of a delayed union should be stabilized operatively.

Pins left out of the skin have fewer infection complications than buried pins. At the time of fracture fixation, there is extensive soft tissue injury and swelling. As the swelling recedes, buried pins can become more prominent and erode through the overlying skin, while pins left exposed are less of an issue.[45]

Capitellar shear fractures are protected initially in a cast or splint until wound healing is completed. Then protected elbow hinged mobilization is performed until the fracture is healed. These fractures are followed for 6 to 12 months radiographically for signs of AVN.

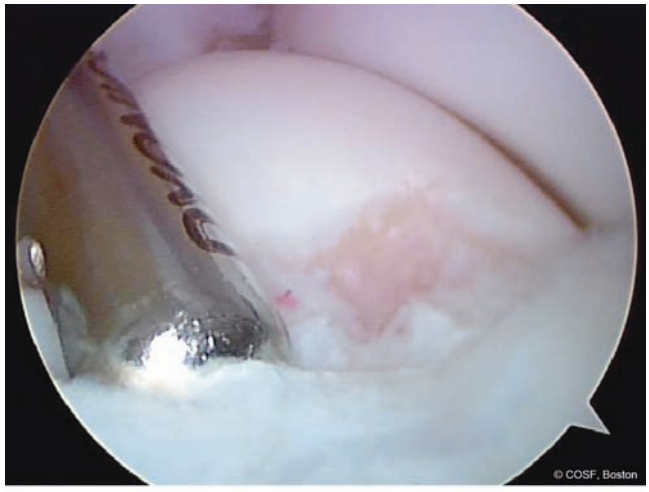
ANTICIPATED RESULTS

Lateral condylar humerus fractures should heal anatomically. If they do, the risk of arthrosis; growth arrest; and limited motion, function, or strength is minimal at worst. Do it right the first time, follow it closely to be certain the healing is progressing as predicted, and these lateral condylar fractures will do well in both the short and long term.

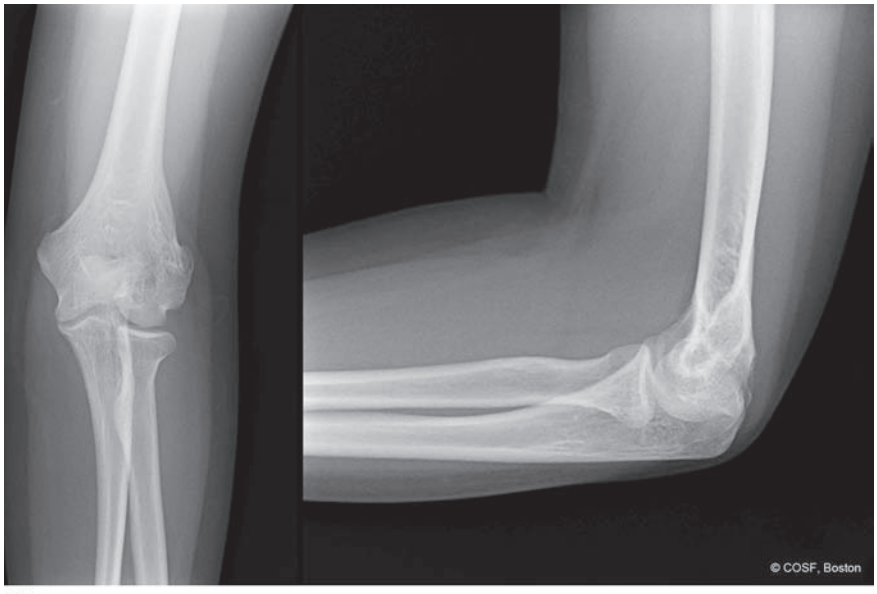
COMPLICATIONS

The major complications of nonunion and malunion and their treatment have been described in the preceding surgical techniques sections. Superficial pin track infections and/or pin migration are more common in lateral condylar fractures than supracondylar humerus fractures, especially if the pins are buried. Pin removal and oral antibiotics resolve the superficial infection and skin problems. Deep-spaced infections need intravenous (IV) antibiotics and operative care.

A1



B



A2

FIGURE 28-12 **A:** MRI and radiograph images of lateral condyle treated with ORIF and now with motion-related joint pain. There is mild articular incongruity. Options are leaving this alone, arthroscopic debridement, or intra-articular osteotomy. **B:** Arthroscopic debridement of minor articular incongruity resulted in improved flexion and less pain.

Lateral spur formation is almost universal from lateral condylar fractures and their healing. The spur can simply be palpable and visible fracture callus that is just beneath the skin. The spur can also be due to mild malrotation, translation, and/or varus malangulation of the lateral condylar fragment. The spur is of no functional consequence, but educating the patient and family early on saves questions and potential loss of trust in your treatment later.

Cubitus valgus and cubitus varus both occur with lateral condylar fractures. Cubitus varus is actually quite common.[43,46,47] Fortunately, cubitus varus in lateral condylar fractures rarely requires an osteotomy. There are some rare patients in whom the resultant radiocapitellar joint malalignment is a source of pain, and arthroscopy and/or corrective osteotomy is appropriate. Cubitus valgus is uncommon and is discussed in the nonunion treatment section of this chapter.

The situation of AVN of the distal humerus (the so-called fishtail deformity) does occur rarely even in nondisplaced fractures. The blood supply to the central portion of the distal humerus physis, epiphysis, and articular surface is vertical and with minimal cross-anastomosis. This limited blood supply makes AVN of the trochlea a potential risk with all distal humerus fractures. Unfortunately, these children will not become symptomatic until years after fracture healing due to slow biologic process and resultant collapse and growth disturbance. They will present with pain, limited motion, and functional loss (see Coach's Corner).

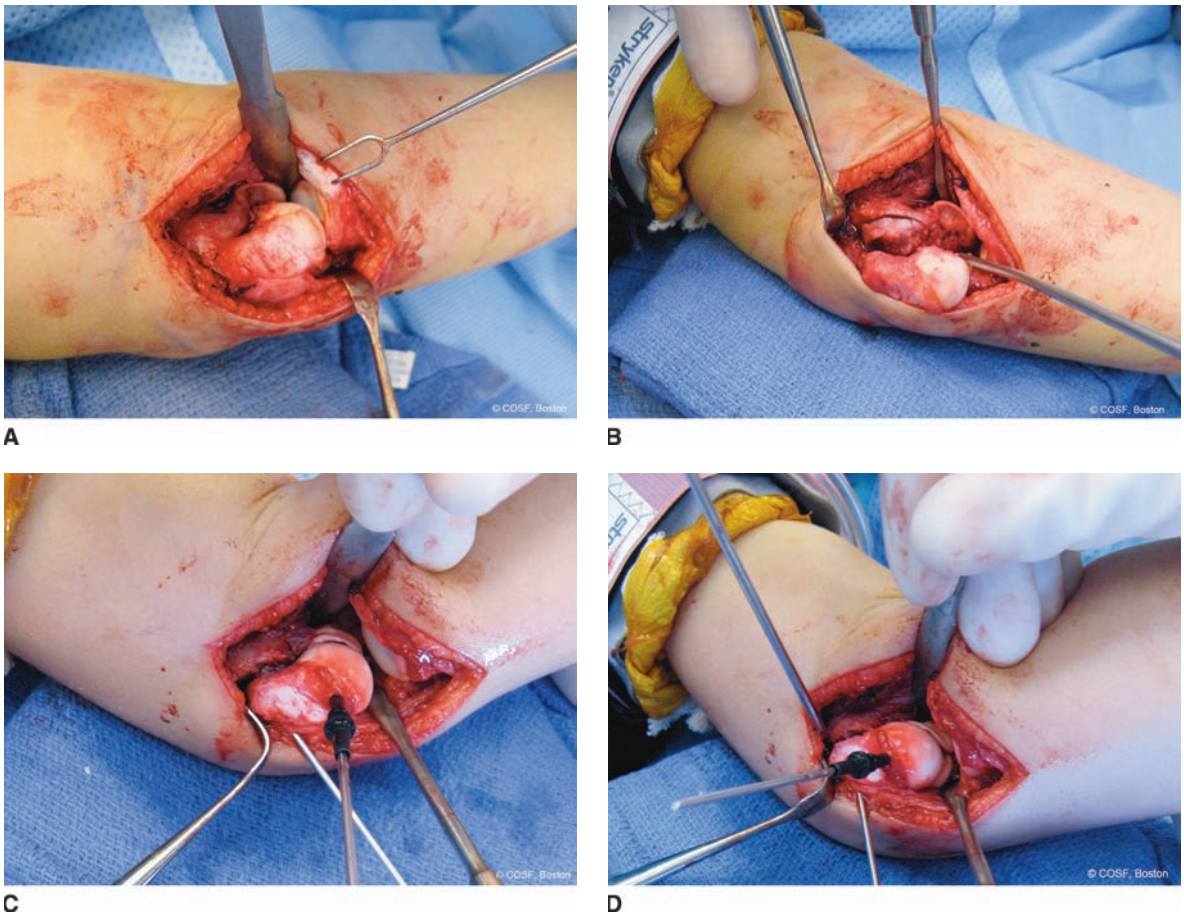


FIGURE 28-13 **A:** Intraoperative extensile exposure revealing lateral condylar intra-articular malunion for lateral condyle intra-articular osteotomy. **B:** Mobilization of intra-articular malunion. The joint has delicately been mobilized through the malunion site. **C:** The joint has been reduced with temporary pin fixation up the lateral column and across the joint. **D:** View of temporary reduction of joint from distal. After temporary fixation, compressive screw fixation is appropriate.

A growth disturbance unrelated to AVN is rare and is very unlikely to cause problems.[48] Since only 20% of the growth of the humerus comes from the distal physis, and minor limb length discrepancy is well tolerated in the upper limb, a growth arrest of the distal humerus is just not a common clinical problem despite the frequency of distal humerus physeal fractures.

CASE OUTCOME

The patient was treated with ORIF as described in the techniques section (Figure 28-14). No complications occurred. The patient regained full strength, motion, and returned to all activities without limits.

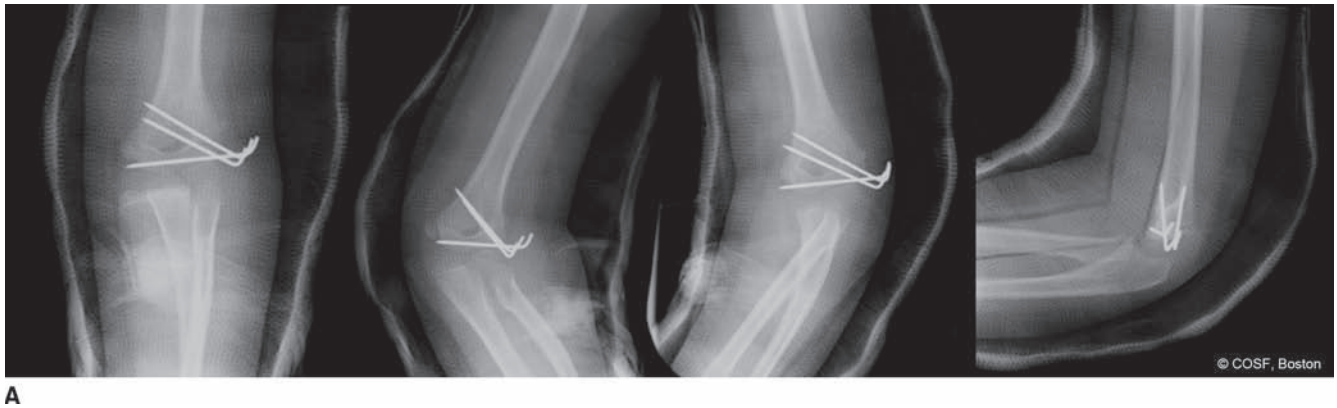
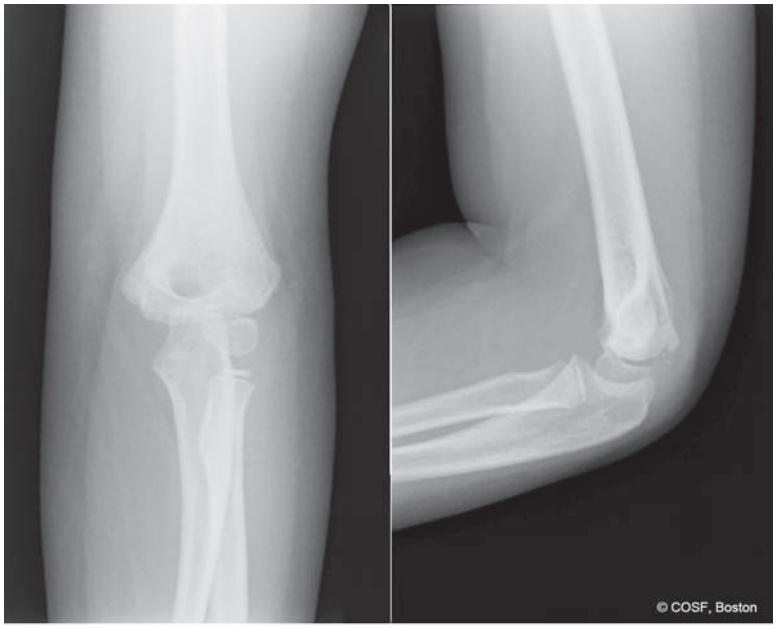


FIGURE 28-14 **A:** ORIF with three pins utilized.



B

FIGURE 28-14 *(continued)* **B:** Radiographs after pins out 2 months postinjury.

SUMMARY

Lateral condylar fractures comprise about 15% to 20% of the distal humerus fractures. Diagnosis is made radiographically, and the degree of displacement determines treatment: (1) <2 mm and stable indicates cast treatment with close follow-up to assess for rare displacement; (2) >2 mm without malrotation indicates CRPP with arthrogram confirming restoration of articular congruity; and (3) >2 mm with malrotation requires ORIF with limited posterior dissection to prevent AVN. Nonunion and articular malunion are the major complications of lateral condylar humerus fractures and their treatment.

SIDEBAR

Elbow Arthrography

There are pediatric elbow fractures and/or dislocations in the very young that benefit from intraoperative elbow arthrography. Injuries in which articular fracture alignment (lateral condylar fractures) or joint reduction (radial head fractures) is unclear due to skeletal immaturity of the patient are candidates for an elbow arthrogram. An 18- to 22-gauge needle with IV extension tubing is used. The options for joint entry are either the lateral soft spot between the lateral condyle, olecranon, and radial head or the olecranon fossa posteriorly. The key is not to have inadvertent dye injection in the subcutaneous tissues that obscures the images from a subsequent true joint injection. The needle is placed in the joint by feel, though fluoroscopic guidance can be used as necessary. We use a cannulated spinal needle. After joint entry, sterile saline is injected first, and free backflow is tested to confirm joint penetration and entry. Without this confirmation, injection errors will occur that impair your analysis. While maintaining the needle position in the joint, diluted (50% saline, 50% dye) arthrographic dye is injected under spot fluoroscopic visualization. The IV tubing lessens the radiation dosage to the surgeon's hands during injection and fluoroscopy. Sufficient dye for anatomic analysis is injected, but joint leakage from torn articular soft tissues is limited. Anatomic assessment of articular alignment, joint reduction, and pin placement in physeal cartilage is possible. Appropriate adjustments can be made if necessary. Intraoperative elbow arthrograms can prevent malreduction complications in certain injuries.

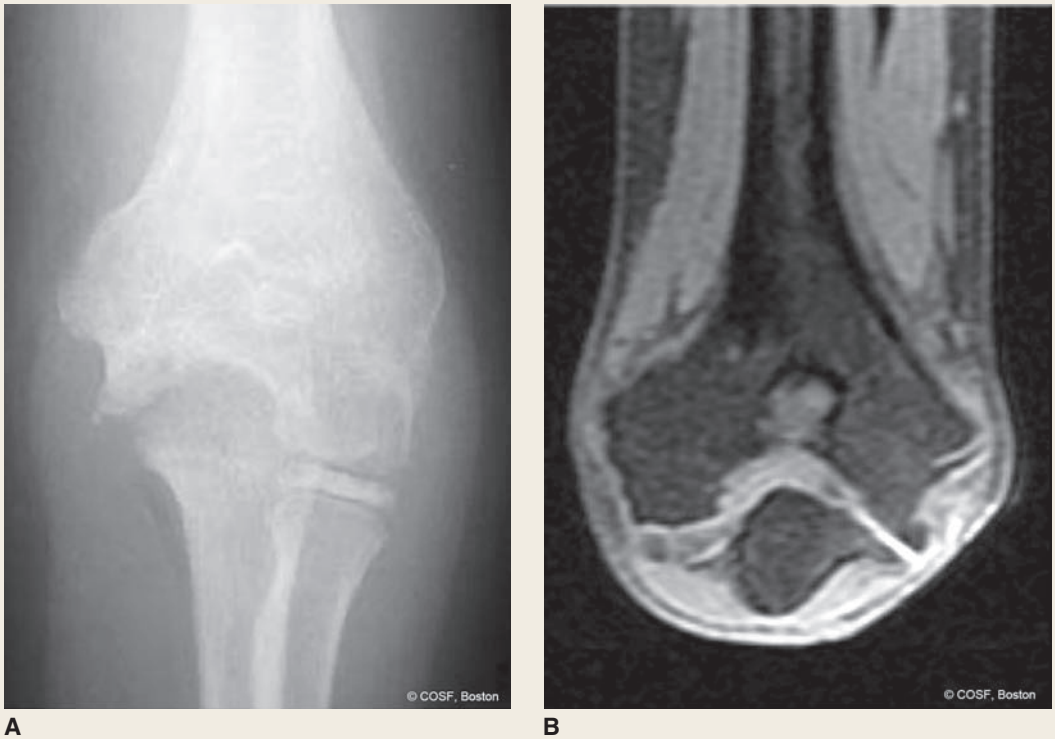
COACH'S CORNER

Fishtail Deformity

Routine long-term follow-up radiographs of supracondylar fractures are not necessary because this [fishtail deformity] is highly unusual and the fishtail deformity does not compromise function.
—James Beaty MD and James Kasser MD

Which of the distal humerus fractures you have treated is a sitting time bomb for AVN and the development of fishtail deformity? One of them is. How can we tell early on which one it is, so we keep careful watch on the patients with impaired blood supply to the trochlea? Isn't this analogous to the hip and the slipped capital epiphysis injury and treatment sequelae? At present, elbow joint incongruity and arthrosis in the young have less of a solution than femoral head AVN and hip joint incongruity. And yet, we do not pay much prospective attention to this risk from distal humerus fractures. Why? Is it because the incidence is so low and the cost of detection too high right now? Is it because we do not have a champion educating us on the value of detection and early intervention? Is it because there are limited options for successful treatment of these patients? The publications on fishtail deformity of the distal humerus are few. You can just about read them all in the time it takes you to drink your morning coffee. The publications are predominately small retrospective case series. The time from avascular insult to clinical presentation with trochlear AVN and joint malalignment is months to years later. The case series are a smattering of lateral condylar, medial condylar, and supracondylar fractures; nondisplaced fractures treated in cast; and displaced fractures treated with both CRPP and ORIF. The connection between injury type and treatment is vague. And yet, when the fishtail deformity patients present years after their original fracture for new evaluation and care, their elbow can be a mess (Figure 28-15). The central trochlea is V or U shaped with lateral and/or medial column overgrowth. The proximal forearm can be subluxed into the olecranon fossa and often mistaken for a missed Monteggia or dislocated radial head at first glance (Figure 28-16). There is marked limitation of flexion-extension arc of motion and often pain with motion and activities. Loose osteochondral bodies in the joint are not uncommon.

The status of the joint (amount of osteochondral loss and proximal migration of the forearm) and the patient's skeletal maturity determine the clinical complaints and treatment options in an established fishtail deformity. Minimal joint



A B

FIGURE 28-15 **A:** U-shaped fishtail deformity in patient presenting 3 years after nondisplaced lateral condylar humerus fracture with pain, locking, and reduced motion. **B:** MRI reveals olecranon positioned in distal humerus AVN.

(continued)

Coach's Corner *(continued)*

A

C

B

FIGURE 28-16 **A:** Lateral radiograph of AVN that can mimic type I Monteggia. **B:** MRI reveals radial head proximal displacement, site of radiocapitellar impingement that is source of osteochondral loose bodies. **C:** Arthroscopic image of radial head anteriorly subluxed and the annular ligament displaced over the anterolateral aspect of the radial head.

A

B

FIGURE 28-17 **A:** AVN presenting 2.5 years after displaced lateral condylar fracture treated with CRPP. There is significant growth remaining. Distal humerus epiphysiodesis was performed. **B:** Arthroscopy at the time of epiphysiodesis reveals the "V" of the distal humerus fishtail. Cartilage surface is healthy.

Coach's Corner *(continued)*

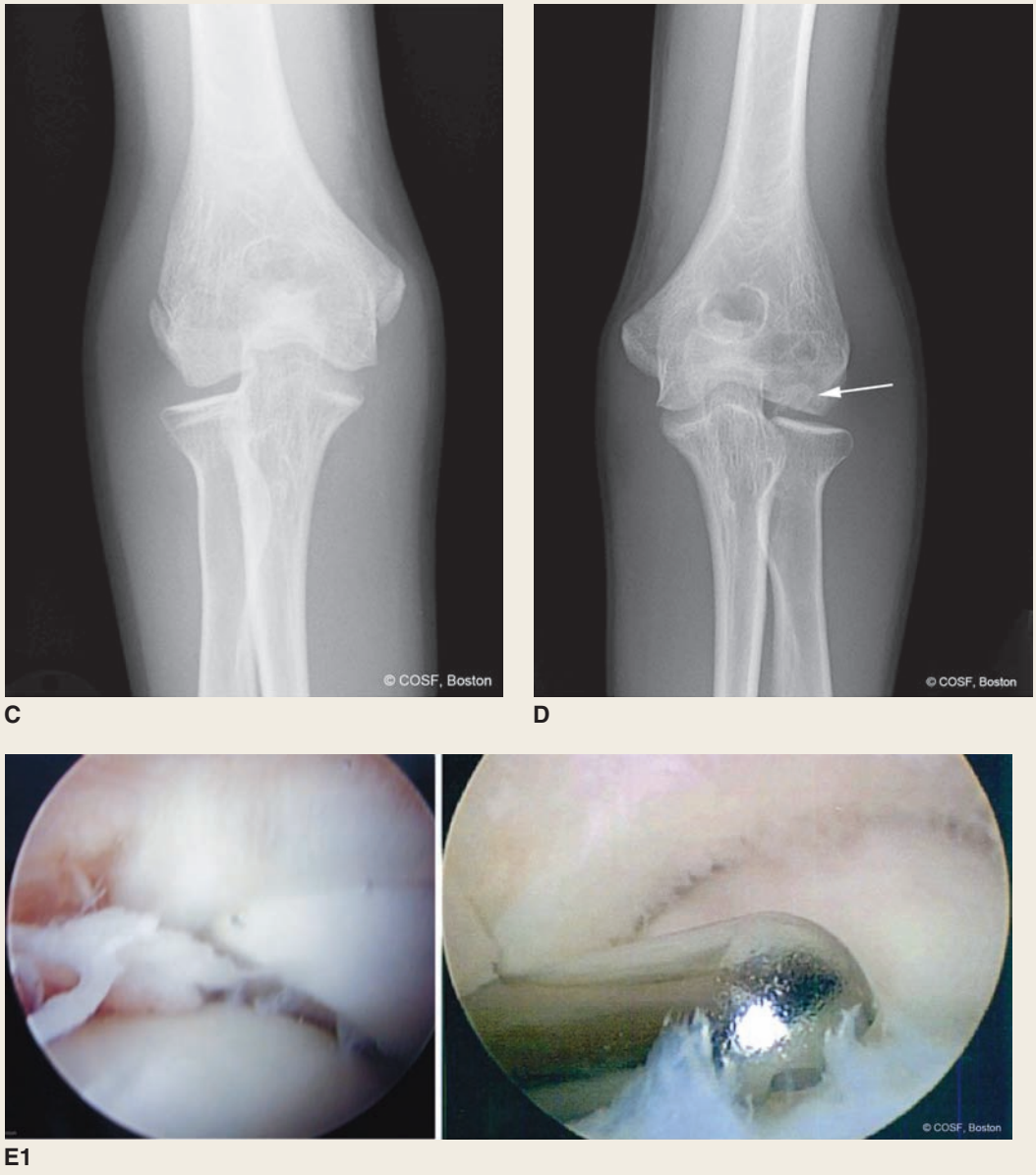


FIGURE 28-17 *(continued)* **C:** At 1.5 years after epiphysiodesis with more normal contour to distal humerus. **D:** The same patient now presenting with osteochondral loose body denoted by arrow after unadvised return to wrestling. **E:** Arthroscopic images of osteochondral loose body (**E1**) during excision of loose body and joint debridement.

involvement will have limited pain, motion restrictions, and mechanical symptoms. More extensive osteochondral loss will likely have marked restriction of motion, pain, and locking. If the patient is very young, arrest of the medial and lateral columns will prevent progression of the deformity (Figure 28-17). In patients with mechanical symptoms of locking and osteochondral loose bodies, elbow arthroscopy, loose body excision, and joint debridement will provide short-term relief of joint impingement and internal derangement (Figure 28-17). In patients with large defects and severe internal derangement, interposition arthroplasty, mechanical arthroplasty, and vascularized composite grafting have been proposed. These rare patients need a sustaining replacement of the central portion of their trochlea, joint reduction, and restoration of joint stability with motion. The severe fishtail deformity problem needs better analysis and solutions.

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CHAPTER

29

Medial Epicondyle Fractures and Elbow Dislocations

CASE PRESENTATION

An 11-year-old right hand dominant gymnast presents with left elbow pain, swelling, and limited range of motion after a vaulting injury. There is no history of prior elbow injury or pain, and she denies any distal numbness, tingling, or weakness. Examination reveals swelling over the medial elbow and limited short arc of elbow flexion-extension without crepitus. The hand is well perfused, and distal median, ulnar, and radial nerve function are intact. Radiographs are shown in Figure 29-1.

CLINICAL QUESTIONS

- How common are medial epicondyle fractures?
- What are the associated injuries seen with medial epicondyle fractures?
- What are the surgical indications for the treatment of medial epicondyle fractures?
- What are the anticipated results of nonoperative and surgical care for medial epicondylar fractures?
- What are the potential complications of medial epicondylar fractures and strategies for their avoidance?
- What are the most common patterns of elbow dislocations in children and adolescents?
- What are the associated injuries seen with "simple" elbow dislocations?
- What are the anticipated results and potential complications of elbow dislocations?

THE FUNDAMENTALS

Medial epicondyle avulsion fractures are common in older children and adolescents, typically arising from sports and high-energy mechanisms of injury. Associated injuries are common, and surgical indications continue to evolve, as our understanding of these injuries—and their potential long-term sequelae—improves.

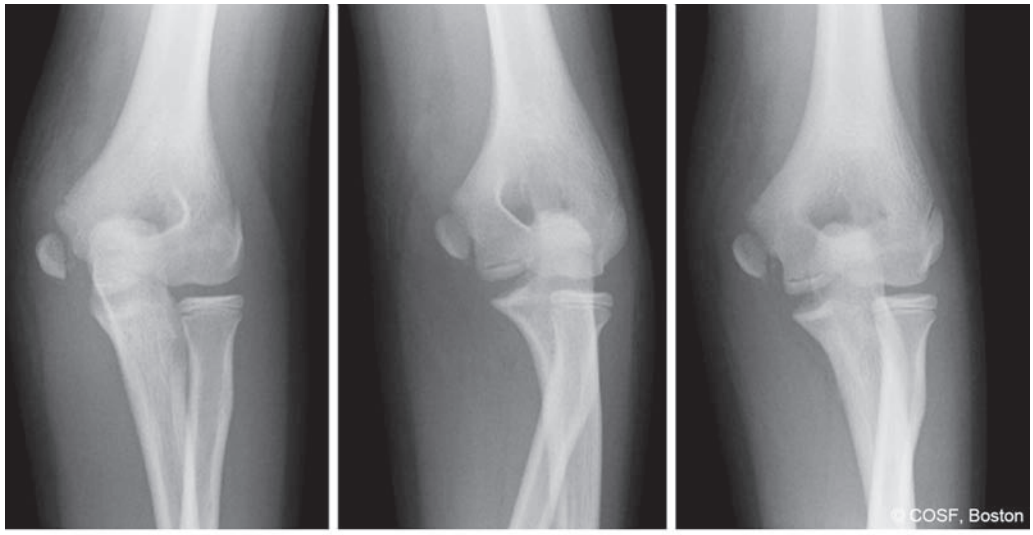
Elbow dislocations similarly occur in pediatric patients after high-energy injuries and are often associated with obvious or occult osteochondral injuries about the elbow. Timely recognition of associated injuries and adherence to surgical treatment principles are essential to optimize clinical results and avoid complications.

Etiology and Epidemiology

Medial epicondyle fractures are technically avulsion injuries of the medial epicondylar apophysis. While the medial epicondylar apophysis is extra-articular and contributes little to the longitudinal growth of the humerus, it does serve as the origin of the flexor-pronator mass. Avulsion fractures, therefore, typically result from high-energy forces imparted on the flexor-pronator muscles with the elbow under valgus stress. These injuries may occur as a result of sudden, vigorous traumatic events, or from less forceful mechanisms in the patient with underlying apophysitis due to repetitive overuse.

Medial epicondylar avulsion injuries represent the third most common injury pattern in the skeletally immature patient, comprising approximately 10% to 15% of all elbow fractures.[1–3] Peak incidence occurs in patients between 10 and 12 years of age, slightly older than seen with supracondylar or lateral condylar fractures of the distal humerus.[1,4–8] Due to the associated high-energy mechanisms of injury, medial epicondylar apophyseal fractures are seen with concomitant elbow dislocations in up to half of cases, and associated elbow fractures (particularly radial neck and head fractures) are also common.[1,8]

Elbow dislocations are relatively uncommon in skeletally immature patients (Figure 29-2). Again, mechanisms of injury include high-energy falls or sports-related events, explaining in part the predilection for adolescent patients.[9,10] Elbow dislocations most commonly occur with extension-valgus stress and result in tears to the ulnar collateral ligament complex, anterior capsule, brachialis muscle, and potentially fractures of the medial epicondyle, coronoid, and/or radial head or neck. Participation in competitive and extreme sports at younger and younger ages is changing the incidence of elbow dislocations and the severity of associated injuries about the elbow.



A

B

FIGURE 29-1 **A, B:** AP, oblique radiographs and lateral radiographs of a displaced medial epicondyle fracture.

Clinical Evaluation

Many of life's failures are people who did not realize how close to success they were when they gave up.
—Thomas Edison

Patients will typically present with medial elbow pain, swelling, and varying degrees of limited elbow motion after acute fractures. History should be taken regarding hand dominance, functional demands including sports participation, prodromal symptoms consistent with overuse apophysitis, and chronicity of symptoms if present. Physical examination will usually elicit tenderness over the (displaced) medial epicondylar fracture fragment, with or without associated swelling, ecchymosis, and limited elbow flexion-extension. A thorough neurovascular examination is critical to rule out evidence of peripheral neuropathy, particularly involving the ulnar nerve.

In patients with acute elbow dislocations, the clinical presentation is less subtle. Patients will present acutely with pain, obvious deformity, and fixed elbow position after a fall or high-energy injury. Neurovascular examination is important to identify primary nerve palsies due to the injury and establish a baseline against which post-treatment examinations may be compared. Careful assessment of median and ulnar nerve function is critical. Vascular insufficiency is quite uncommon.

Radiographic evaluation will confirm the diagnosis. Standard anteroposterior (AP) and lateral radiographs will identify the medial epicondylar avulsion fracture and characterize displacement. Oblique radiographs, including the external rotation oblique, will assist in radiographic assessment of fracture displacement as it brings the normally posteromedial medial epicondyle into profile. It is important to recognize that the flexor-pronator mass acts to displace the medial epicondylar apophysis distally and often anteriorly, not laterally, and therefore the magnitude of fracture displacement cannot be quantified on AP radiographs. Indeed, recent information suggests that plain radiographs do not allow for accurate measurement

FIGURE 29-2 AP and lateral radiographs of a posterolateral elbow dislocation in a 9-year-old female gymnast.

of displacement, and that intra- and interobserver reliability of medial epicondylar fracture displacement is low.[11,12]

Medial epicondylar fracture fragments can be entrapped in the elbow joint. The trochlear ossification is usually irregular, often fragmented. The medial epicondyle is ovoid and regular. At times, the entrapped medial epicondyle can be mistaken for a trochlea and the diagnosis of an entrapped medial epicondyle missed. Look for the medial epicondyle in or near its anatomic posteromedial location. If it is not there, look for it in the joint. If necessary, compare elbow films of the affected and unaffected side. An entrapped medial epicondyle is a diagnosis not to be missed.

In cases of displaced medial epicondylar apophyseal fractures, joint stability may be assessed using gravity valgus stress views (Figure 29-3). This radiographic technique involves placing the patient in the supine position with the shoulder abducted 90 degrees, elbow extended, and the forearm maximally supinated (the thumb points to the ground). An AP view of the elbow is taken, and the medial joint space is assessed. Medial joint widening of >3 mm is suggestive of valgus instability.

Plain radiographs, including obliques, will also clearly diagnose simple and complex elbow dislocations and characterize the direction of displacement. Elbow dislocations in general are described anatomically according to the position of the forearm in relationship with the distal humerus (e.g., posterolateral, posteromedial, anterior, medial, lateral). "Simple" dislocations denote pure joint dislocations, whereas "complex" dislocations are used to describe joint instability with associated bony or chondral fractures.

Advanced three-dimensional imaging is rarely required in acute cases of medial epicondylar fractures but may provide important additional information in cases of chronic injuries or elbow dislocations with suspected chondral or osteochondral shear fractures (Figure 29-4). Imaging with magnetic resonance imaging (MRI) is particularly useful in these latter situations, especially when nonoperative management is being considered.

Surgical Indications

There are only two options regarding commitment. You're either in or out. There's no such thing as a life in-between.
—Pat Riley

The indications for surgical treatment of medial epicondylar avulsion fractures are controversial and continue to evolve. Historically, almost all displaced fractures of the medial epicondyle were treated nonoperatively with reportedly acceptable results. Farsetti et al.[13] previously reported on 42 children and adolescents with displaced medial epicondyle fractures followed to an average age of 45 years. Patients treated nonoperatively had similarly good long-term results as those treated with open reduction internal fixation (ORIF). Based upon this information, the authors and others suggest that displaced medial epicondylar fractures may be successfully treated nonoperatively.[14] This and other similar reports have established the dogma by some that medial epicondylar avulsion fractures are nonsurgical injuries.

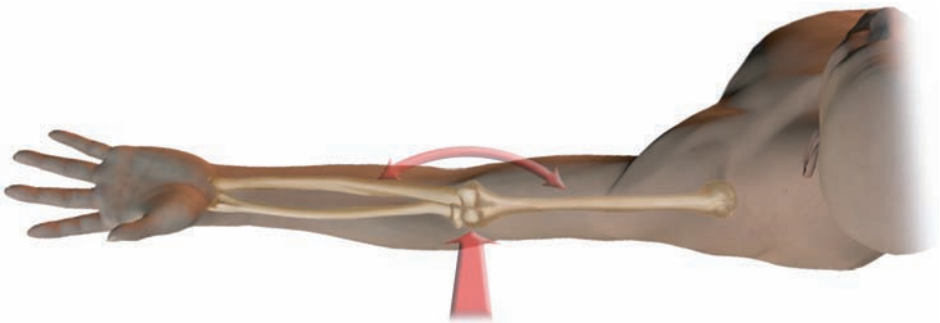


FIGURE 29-3 Schematic representation of the valgus gravity stress radiograph. With the patient supine, the shoulder abducted 90 degrees, elbow extended, and the forearm maximally supinated (the thumb points to the ground). An AP view of the elbow is taken by directing the beam parallel to the ground, and the medial joint space is assessed.

FIGURE 29-4 Complex elbow dislocation with chondral shear fracture. **A:** AP and lateral radiographs demonstrate a mildly angulated radial neck fracture and subluxation and incongruity of the ulnohumeral joint. **B:** Sagittal MRI images depicting an intra-articular loose body (*small arrow*) from a chondral shear injury to the trochlea (*arrowhead*) with a dislocated ulnohumeral articulation.

It is clear that patients with medial epicondyle fracture dislocations in whom the fracture fragment is incarcerated within the elbow joint should be treated with expeditious ORIF. Relative indications include displaced fractures with associated ulnar neuritis/neuropathy or fractures affecting the dominant limb in throwing or overhead athletes. We tend to be surgically aggressive for displaced medial epicondyle fractures, given the safety and efficacy of acute surgical treatment and the functional limitations and surgical challenges of symptomatic nonunions or malunions.[15–17] We prefer anatomic alignment of the fracture, rigid fixation with elbow joint stability restored, and early motion rehabilitation to avoid a flexion contracture.

Occasionally patients will present for first consultation to the pediatric hand and upper extremity surgeon after closed reduction of an elbow fracture dislocation by a referring caregiver. The previous care can cloud the decision-making process. If the elbow joint is unstable and/or the fracture is still displaced, we tend to proceed with ORIF to provide stability for early range of motion and avoid late complications. Clearly chronically entrapped medial epicondylar fracture fragments require extraction and ORIF no matter how late those patients present for evaluation and care.

In cases of elbow dislocations, it is clear that acute simple elbow dislocations should be treated with prompt closed reduction, either under conscious sedation or under general anesthesia. Surgical indications include complex elbow dislocations with associated nerve injury or entrapment, associated osteochondral fractures, or joint instability precluding appropriate postinjury rehabilitation. Surgical repair of the collateral ligaments and/or muscles is not necessary following successful closed reductions of simple dislocations.[18–20]

SURGICAL PROCEDURES

Closed Treatment of Medial Epicondyle Fractures and Elbow Dislocations

As cited above, nonoperative treatment is appropriate for nondisplaced or minimally displaced medial epicondylar fractures without ulnar neuropathy in patients without high functional demands of the affected elbow (e.g., baseball pitchers, gymnasts, cheerleaders) (Figure 29-5). Nonoperative care consists of a brief period of splint or cast immobilization (no longer than 2 weeks), followed by hinged elbow brace protection and advancement of elbow range of motion in brace until 6 weeks postinjury. Physical therapy may be initiated at 6 weeks, if needed, to regain the remaining elbow motion and strength. Sports participation is limited until elbow motion and strength normalizes, usually at 2 to 3 months.

One error in nonoperative treatment of medial epicondylar fractures lies in excessive immobilization. The amount of soft tissue and capsular injury cannot be accurately assessed on initial clinical evaluation or radiographs. Stiffness is a risk, even with seemingly innocuous fractures. If nonoperative treatment is chosen—and therefore no intent to achieve anatomic fracture reduction—early protected range-of-motion exercises are critical to avoid functionally limiting stiffness.

The other problem with nonoperative treatment of displaced fractures is symptomatic nonunions or malunions. If the medial epicondylar fragment heals in a displaced distal and anterior position, it will limit motion (especially extension) and function. Some nonunions cause symptomatic valgus instability, especially in gymnasts and throwing athletes.

Closed reduction of simple elbow dislocations follows principles similar to adults. Conscious sedation or general anesthesia is preferred to mitigate the effects of muscle spasm, avoid excessive force, which imparts risk of producing iatrogenic osteochondral shear fractures, and provide maximum patient comfort. In general, for the most common posterior dislocations, closed reduction maneuvers may be divided into "pull" or "push" techniques.[21–29] With the brachium stabilized and the patient either in the supine or in the prone position, the elbow is flexed and forearm supinated to unlock the radial head and reduce tension on the biceps. Longitudinal traction is then provided distally along the axis of the humerus, with simultaneous anteriorly directed force. Hyperextension is avoided, as it further tensions the anterior capsule and flexor muscles and may lead to iatrogenic shear fractures of the radial head, coronoid process, trochlea, or capitellum. Reduction with extension also increases the risk of entrapment of the median nerve in the joint. Alternatively, distally directed pressure may be applied to the prominent olecranon process and radial head with the elbow flexed and forearm supinated to "push" the forearm back into position. Following reduction, careful radiographic evaluation is performed to confirm a congruent joint reduction and rule out associated fractures, which may not be apparent on initial injury films. The stable arc of motion is assessed and the limb immobilized in a long-arm bivalved cast or posterior splint with the forearm in pronation. The postreduction immobilization needs to be quite bulky

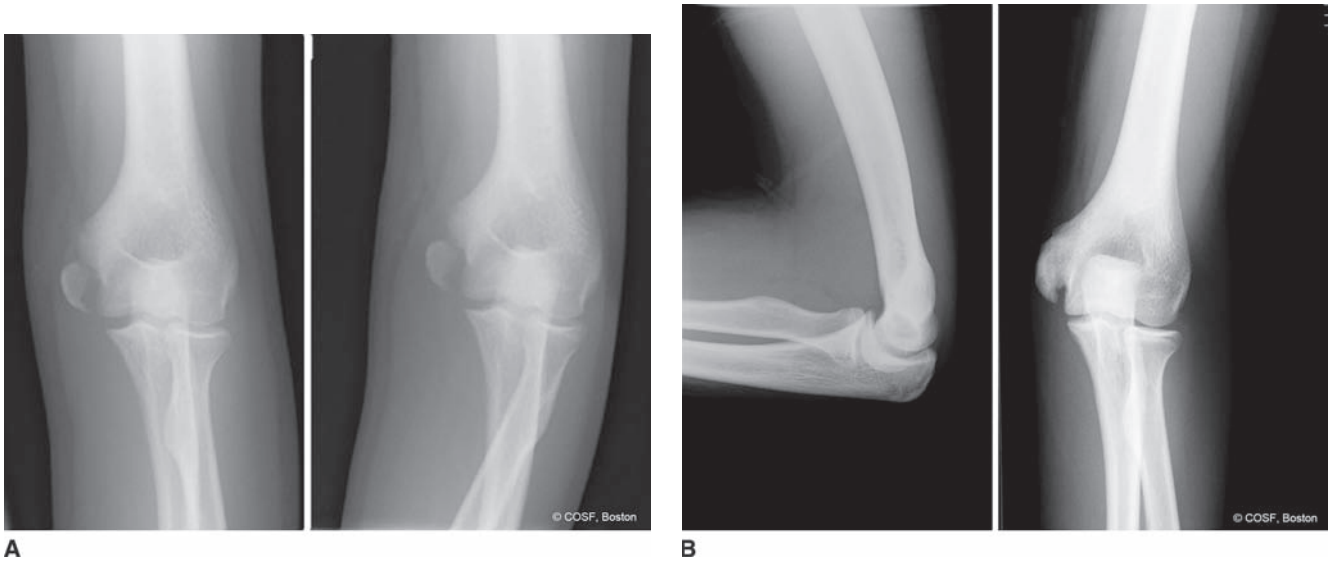


FIGURE 29-5 Nonoperative treatment of a displaced medial epicondyle fracture involving the nondominant limb of a 14-year-old male. **A:** Initial AP and lateral radiographs demonstrate a displaced medial epicondyle apophyseal avulsion. **B:** Follow-up radiographs 3 months postinjury demonstrate evidence of bony union with exostosis. At times this can lead to ulnar nerve compression.

as elbow dislocations will have considerable soft tissue swelling in the first week postinjury.

ORIF of Medial Epicondylar Fractures

An ORIF of displaced medial epicondylar apophyseal fracture fragments is performed under general anesthesia and tourniquet control (Figure 29-6). In cases of fracture dislocations with the fracture fragment incarcerated in the elbow joint, initial attempts at closed manipulation may be performed under general anesthesia before proceeding to open repair.[30,31] With valgus stress imparted on the elbow and forearm supinated, the wrist and digits are maximally extended. Tension on the extrinsic flexors and pronators, in theory, will allow for fragment extraction. Fluoroscopy will confirm success or failure of closed manipulation.

A medial longitudinal incision is created along the distal humerus, centered on the fracture site. It is easy to make this incision too anteriorly, which will in turn cause greater difficulty in reducing the displaced fracture to the normal posteromedial apophyseal location. Skin flaps are raised and blunt dissection performed down to the level of the fracture; in acute settings, this subcutaneous dissection often involves only a sweep of the surgeon's finger, as the injury itself has developed the appropriate planes of dissection. Protect the crossing cutaneous nerves. The medial epicondyle fragment is identified, preserving its distally attached flexor-pronator muscles, and the fracture site and joint are entered from above the fragment while maintaining the soft tissue integrity. A heavy nonabsorbable suture (No. 1 Ethibond, Ethicon, Inc., Somerville, NJ) is passed in a figure-of-eight fashion through the proximal aspect of

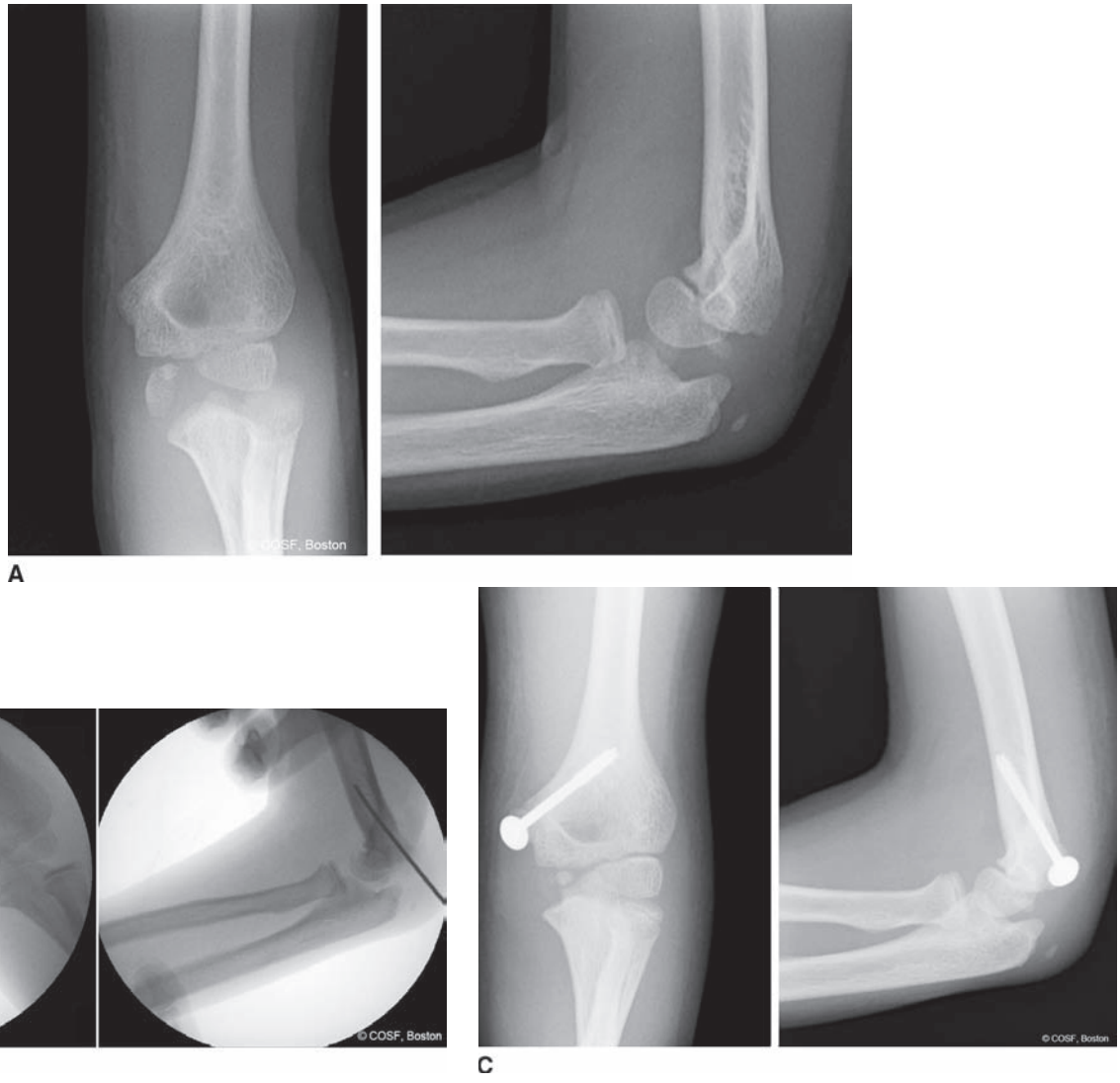


FIGURE 29-6 Open reduction and cannulated screw fixation of a displaced incarcerated medial epicondyle fracture in an 11-year-old male. **A:** Injury AP and lateral radiographs depict an incarcerated medial epicondyle within the ulnohumeral joint. **B:** Intraoperatively, after fragment extraction and reduction, a guide pin is used for provisional fixation and subsequent cannulated screw placement. **C:** Following postoperative radiographs demonstrating reduction and fixation with a partially threaded cannulated screw with washer. Note is made of the appropriate posterior-to-anterior trajectory of the screw on the lateral projection.

the fracture fragment and periosteal sleeve, which is used for traction as well as subsequent soft tissue repair. Careful dissection is performed proximally and posteriorly to the origin of the medial epicondylar apophysis, and the ulnar nerve should be retracted and protected at all times during the course of the procedure. The elbow joint is inspected for associated osteochondral injuries, and the intra-articular hematoma is debrided with saline, suction, and fine-tipped forceps. The fracture is then mobilized, and confirmation is made that an anatomic reduction can be achieved (Sidebar).

With the fracture reduced, a threaded guide pin from a cannulated screw set is placed in the center of the fracture fragment and then driven across the fracture into the medial column of the distal humerus. In general, a 3.5- or 4.5- mm screw is used. Often, the bony piece available for fixation is much smaller than the size of the apophysis that is palpated, as much of the avulsed fragment is comprised of cartilage surrounded by soft tissue. Care must be taken to place the guide pin through the center of the bone without fragmenting it. At times, the medial epicondylar fracture fragment is predrilled before reduction, and the drill is used to aid in anatomic reduction. Another useful method is to suture the medial epicondyle in place before pin placement. Intraoperative fluoroscopy is then used to confirm adequacy of the reduction and guide pin trajectory (which is posterior to anterior in the lateral projection). A second guide pin may then be placed in a parallel fashion for provisional rotational control. Measurements are taken, the central guide pin overdrilled, and a partially threaded 3.5- or 4.5- mm cannulated screw is inserted with a washer. With the use of a partially threaded screw, purchase of the far cortex is not needed, and a 40- to 50- mm length screw is typically used. If a fully threaded cortical screw is used, the screw should engage the far anterolateral cortex to achieve fracture compression and stability. Following fixation, fluoroscopy is again used to confirm fracture reduction, joint stability including valgus stress, and implant placement. The ulnar nerve is again checked to ascertain that no kinking or compression has occurred during screw fixation. Range of motion is checked to be certain there are no limits to the flexion-extension arc and the ulnar nerve does not impinge on the screw. The wound is closed in layers. Patients are immobilized in a hinged elbow brace, posterior elbow splint, or a long-arm cast that is bivalved widely to allow for postoperative swelling.

◆ ORIF of Osteochondral Fracture

As stated above, osteochondral fractures are associated in up to half of all elbow dislocations in pediatric patients.[32–35] For this reason, careful radiographic evaluation after closed reduction to look for apophyseal avulsion or osteochondral fractures is imperative (Figure 29-7). While fractures of the medial epicondyle and radial neck,

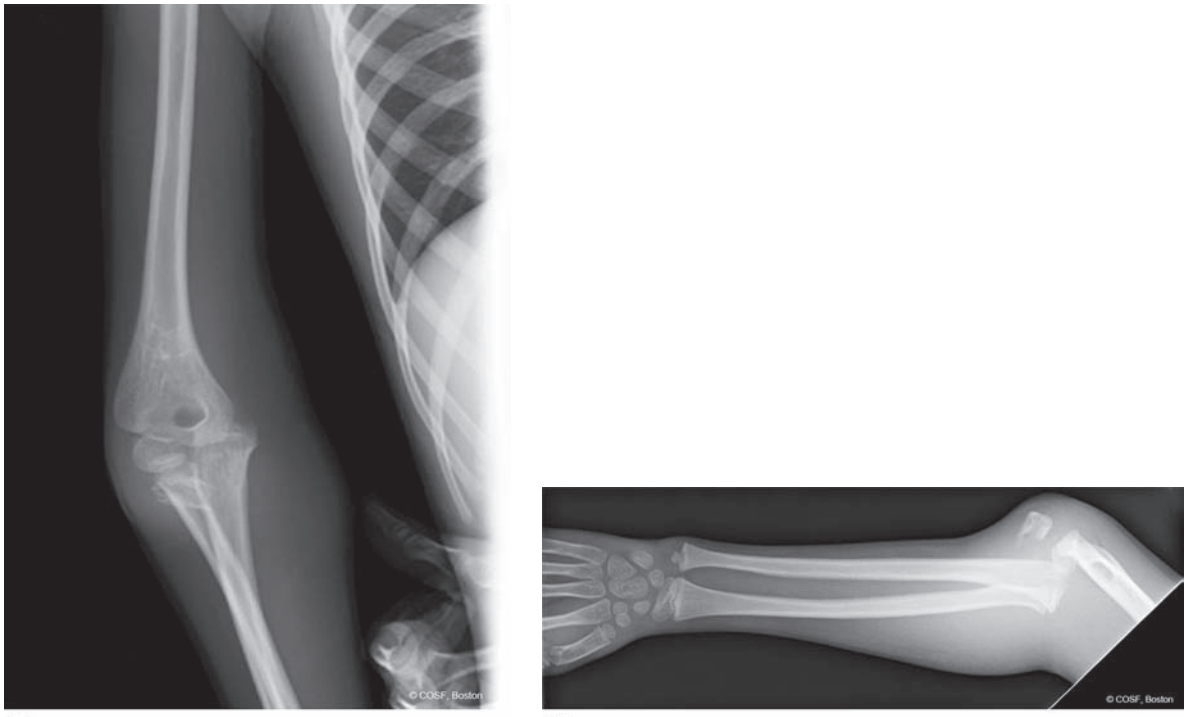


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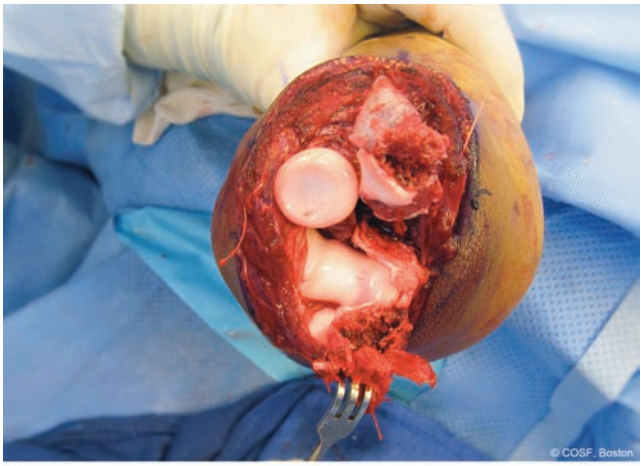
FIGURE 29-7 Osteochondral injuries associated with an elbow fracture dislocation in a 7-year-old male following a fall down stairs. **A:** Injury AP and lateral radiographs demonstrate an anterior elbow dislocation with olecranon fracture. Note is made of the extensive soft tissue swelling.



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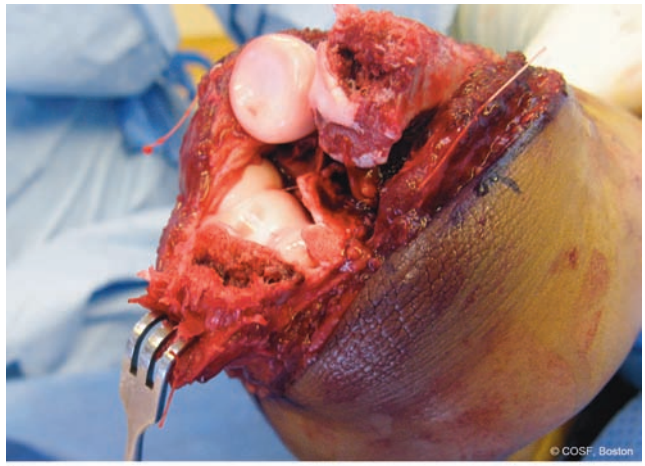

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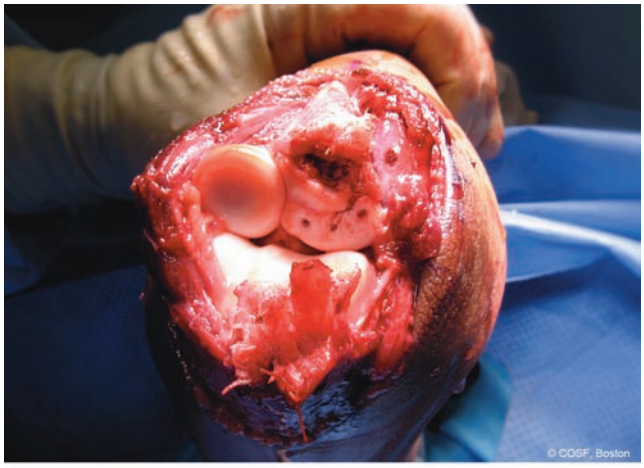

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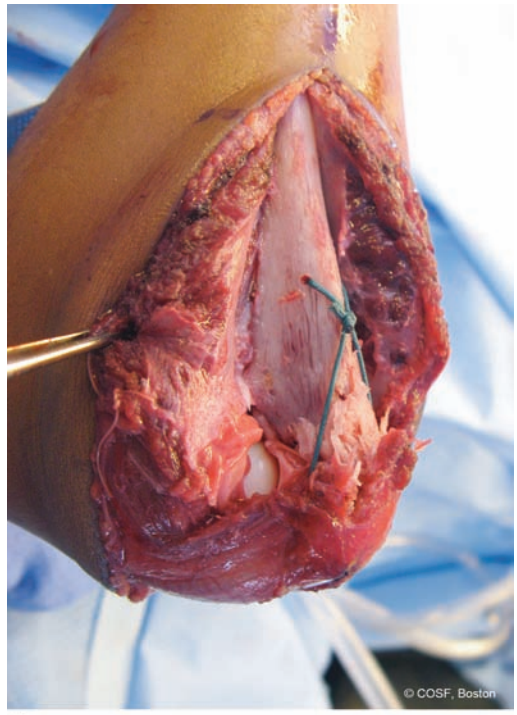

E

FIGURE 29-7 *(continued)* **B, C:** Intraoperative photographs of the elbow joint, exposed through the olecranon fracture, demonstrate multiple osteochondral fractures of the ulna with loose bodies. **D:** Initial restoration of the articular surface is performed with reduction and fixation of the osteochondral fragments using bioabsorbable implants. **E:** Final reconstruction demonstrating restoration of the articular surfaces and tension band fixation of the ulna.

for example, are quite obvious, osteochondral injuries may only be manifest by subtle, thin radiopacities or soft tissue shadows on plain radiographs. Advanced imaging is appropriate in any suspected case of osteochondral injury, particularly if there is suspicion of intra-articular loose bodies. This is particularly true of elbow dislocations due to high-energy trauma in patients <10 years of age, in whom the articulating surfaces of the humerus, radius, and ulna are predominantly cartilaginous.

In cases of complex elbow dislocations with osteochondral fractures, ORIF of the articular fragments is performed. Surgical exposure is individualized for each patient and each injury, with options including lateral and medial approaches as well as the Bryan-Morrey triceps slide and olecranon osteotomy.[36] After isolation of the osteochondral fragments, an intraoperative decision is made regarding excision versus internal fixation. Internal fixation may be performed using bioabsorbable implants (Smartnail, CONMED Linvatec, Largo, FL), variable pitch compression screws (Acutrak, Acumed, Hillsboro, OR; Herbert, Zimmer, Inc., Warsaw, IN; or Synthes, West Chester, PA), or countersunk small-diameter titanium screws (Synthes, West

Chester, PA), depending upon the fragment dimensions and amount of attached subchondral bone. Given the risk of post-traumatic stiffness, stable fixation is preferred to allow for early range-of-motion exercises.

◆ Chronic Medial Epicondylar Fracture Malunion or Nonunion

Some patients treated nonoperatively for displaced medial epicondylar apophyseal avulsion fractures will present with pain and functional limitations—particularly with sports activities—in the setting of radiographic nonunion. In these situations, ORIF is done to repair the nonunion, restore elbow stability, and alleviate pain.[17] Fragment excision alone is insufficient and should not be done due to the associated poor results.[13,37] The nondisplaced, symptomatic nonunion can be treated with in situ compression screw fixation.

The surgical approach and operative technique are similar to ORIF of acute fractures with a few corollaries. First, ulnar nerve function should be carefully assessed preoperatively, as it may be the primary factor contributing to pain, restricted motion, and disability. A low threshold should be maintained for ulnar nerve decompression and/or transposition in cases of ulnar neuritis, compressive neuropathy, or instability. Second, for cases with a displaced, symptomatic nonunion, diligent and careful mobilization of the nonunion fragment must be performed during surgery. The flexor-pronators are often contracted and the fragment surrounded by scar tissue. In rare situations, musculotendinous fractional or Z-lengthening may need to be performed to obtain adequate fragment mobilization and reduction. Furthermore, concomitant procedures about the elbow may need to be performed, including capsular release and heterotopic ossification (HO) excision. These may be performed via the medial incision after the ulnar nerve and medial epicondyle are identified, mobilized, and protected.[38] Both the posterior and anterior capsule require release. Finally, as with ORIF of acute fractures, aligned symptomatic nonunions treated with compression screw fixation have brief postoperative immobilization followed by early protected range-of-motion exercises in a hinged elbow brace to avoid stiffness. More extensive surgery with a displaced symptomatic nonunion requires immediate mobilization, sometimes with a continuous passive motion (CPM) machine postoperatively.

For any chronic incarcerated intra-articular fragments discovered late, ORIF is indicated. These patients present with marked restriction of motion and pain. Some have been put through extensive therapy to try to resolve their elbow contracture. The most common of these rare cases is the chronically entrapped medial epicondyle. Radiographically, the incarcerated medial epicondyle has been mistaken for the normal trochlea on the original and/or postreduction images.[39–41] An extensile medial approach is required. The ulnar nerve path will be distorted around the elbow due to the medial epicondylar entrapment and abundant localized fibrous tissue. Isolate the nerve proximally, and carefully follow it distally. Identify and protect the crossing cutaneous nerves. The ulnar nerve will usually be compressed and kinked near the elbow joint. Release of the Osborne's fascia and the flexor carpi ulnaris fascia will free the nerve. With fluoroscopic guidance, the elbow joint is opened from above the fragment. Valgus stress greatly aids the dissection. The fracture fragment can be extracted by both "outside-in" and "inside-out" techniques: either pulling it out by grasping the flexor-pronator soft tissues or reaching in and extracting the fragment atraumatically with a Freer elevator or grasper. After extraction, the piece and joint are debrided. The fragment is reduced and stabilized with sutures and then rigid internal fixation. Postfixation motion is checked along with ulnar nerve alignment and decompression. If necessary, the ulnar nerve is transposed. Protected motion is utilized postoperatively.

◆◆ Entrapped Median Nerve Chronic Dislocation

Start by doing what is necessary, then do what is possible, and suddenly you are doing the impossible.
—St. Francis of Assisi

Median nerve entrapment is a well-described complication of simple or complex elbow dislocations, and pediatric hand and upper extremity surgeons will undoubtedly encounter this condition in the course of their careers.[42–49] Three patterns of median nerve entrapment have been described (Figure 29-8). Type I injuries affect patients with medial epicondylar apophyseal avulsion fractures and elbow dislocations, in which the median nerve is displaced posteriorly between the trochlea and ulna. This situation may occur in posterolateral dislocations in which forearm translation is not corrected prior to ulnohumeral relocation. One radiographic feature of type I injuries is the Matev sign, or oval radiolucency seen on the posterior aspect of the medial condyle, which represents the course of the median nerve directly apposed to the underlying bone.[50] Type II injuries refer to median nerve entrapment between the displaced medial epicondylar apophysis and its metaphyseal site of origin. In these situations, new bone will form around the nerve, and a Matev sign may or may not be seen. Type III injuries denote median nerve entrapment anteriorly between the trochlea and coronoid and are thought to be the least common pattern of nerve incarceration.

In patients with new median nerve palsies after elbow reduction—particularly in the setting of medial epicondyle fractures, neuropathic pain, or markedly limited range of elbow motion—entrapment of the median nerve

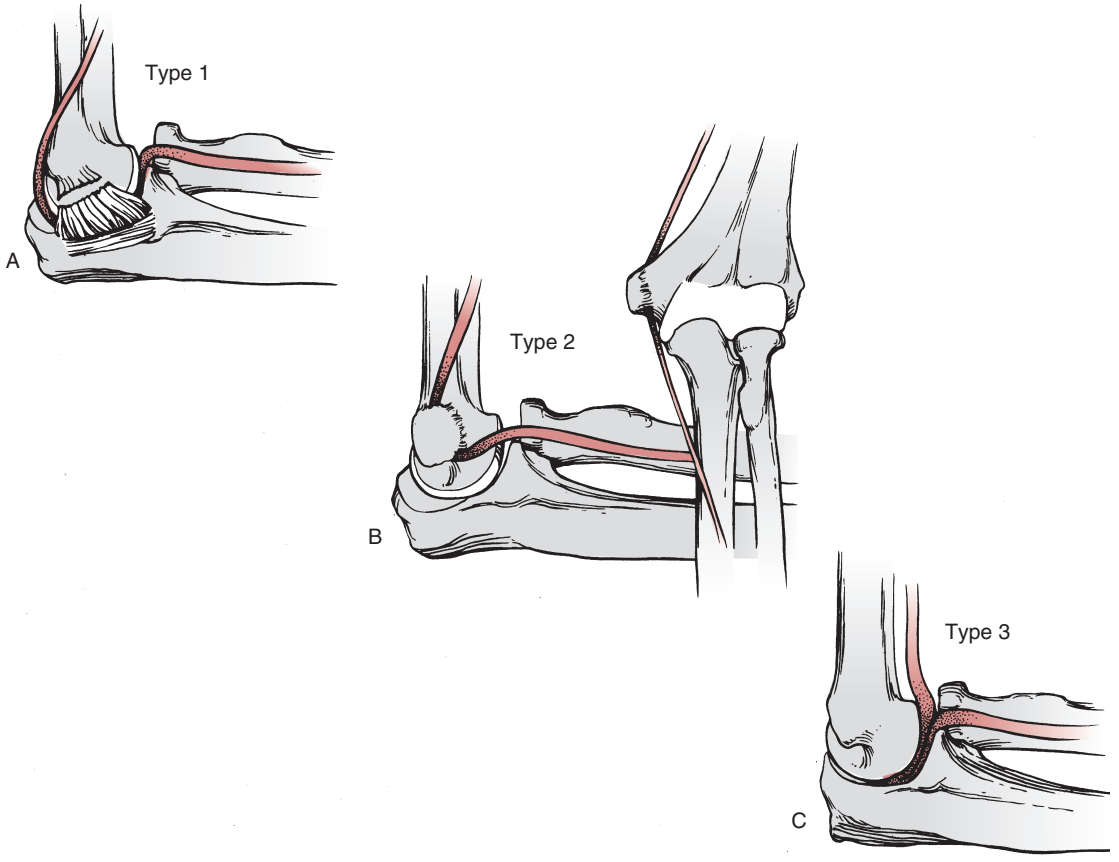

FIGURE 29-8 Schematic representation of the three patterns of median nerve entrapment in the setting of medial epicondylar apophyseal avulsion fractures. (From Beaty JH, Kasser JR. *Rockwood & Wilkins Fractures in Children*. 7th ed. Philadelphia, PA: Lippincott Williams & Wilkins, 2010.)

should be strongly considered. With chronic median nerve entrapment, the child will have an elbow contracture and marked resistance to motion. In essence, each attempt at motion creates neuropathic pain that the child may be unable to articulate precisely. Surgery is indicated to explore and liberate the median nerve. After extraction, a decision regarding decompression alone (rarely enough), neuroma resection, and either direct repair or nerve grafting has to be made to maximize the potential for functional recovery.

Surgery is performed under tourniquet control via an extensile medial or anteromedial approach. The median nerve is identified proximally within the intermuscular groove above the zone of injury and carefully traced toward the elbow. In type I and III injuries, the nerve is extracted from the joint; in type II injuries, medial epicondylar osteotomy or bony decompression is required. The nerve is then carefully inspected under loupe or microscopic magnification. If there is fascicular continuity and appropriate distal response with intraoperative nerve stimulation, decompression alone may suffice. In cases of nonconducting neuromas or transection, neuroma excision and direct repair or sural nerve grafting are performed. When performed early, the prognosis for median nerve recovery is guarded but good.[45,47,50,51]

◆◆ Release of Post-traumatic Elbow Contracture

Stiffness is a common complication of elbow fracture dislocations in children and adults. While the majority of cases will resolve with physical therapy, static and dynamic splinting, and manipulation, some patients will have persistent functionally limiting elbow stiffness despite maximization of nonoperative care. Historically, an elbow arc of motion between 30 and 130 degrees has been considered adequate for most activities of daily living.[52] The functional impact of elbow contractures, however, is highly individualized.

In patients with functionally limiting elbow contracture despite a minimum of 6 months of aggressive physical therapy, surgical release may be indicated.[38,53–56] For surgical treatment to be successful, the patient and the family need to be deeply committed to the postoperative rehabilitation. If they are not, a contracture successfully released in the operating room will recur over time. Patient selection is critical to success.

Under general anesthesia, previous surgical incisions are used and extended when present; in patients undergoing their first operation, an extensile medial approach is created. The medial ligamentous structures are preserved and the ulnar nerve decompressed and/or transposed when appropriate. Anterior and posterior capsular releases were then performed. Any HO or osteophytes restricting motion are excised, and the olecranon fossa is thoroughly debrided if necessary. Retained implants, if present from previous fracture fixation, should be routinely removed. In rare cases where adequate range of motion could not be obtained following these measures, musculotendinous lengthenings of the brachialis and/or flexor-pronator muscles are performed. The triceps and biceps musculotendinous units should be kept intact in all cases. Arc of motion is carefully documented in the operating room, with the limiting factor often being excessive traction in elbow extension on the neurovascular structures traversing the elbow joint. Usually safe, full motion can be obtained in the operating room with persistence and careful dissection.

Postoperative management is critical, as every effort is made to preserve the motion achieved during the surgical release. All patients are placed in a CPM device (Kinetec, Smith & Nephew, Inc., Germantown, WI) to the affected elbow for a total of 6 weeks. A CPM regime is initiated in the recovery room and used for 23 hours per day for the first 3 weeks, followed by nighttime CPM for the ensuing 3 weeks. In addition to CPM, physical therapy is initiated on all patients during their in-patient hospitalization for active and active-assisted range-of-motion exercises within the range of elbow motion attained intraoperatively.

Effective analgesia is equally critical in the immediate postoperative phase. A regional anesthetic or indwelling brachial plexus catheter may be utilized after confirmation is made regarding neurovascular status postoperatively. Patients remain hospitalized following surgical release until they are able to tolerate CPM and physical therapy within the range of motion attained in the operating room while on oral analgesics. For us, the average postoperative inpatient stay is 4 to 5 days. We do not use postoperative radiation therapy for HO prophylaxis, given the concerns regarding malignancy after excessive radiation exposure. Anti-inflammatory medications are used for 6 weeks postoperatively if HO was resected. No strengthening exercises are performed for at least 6 weeks, until completion of the postoperative CPM regimen. After 6 weeks, patients were gradually progressed to all activities as tolerated.

In our prior published series of 13 adolescents who underwent post-traumatic elbow contracture releases, average arc of motion improved from 53 to 107 degrees. This continues to be representative of our practice and experience. As with any post-traumatic reconstruction, appropriate patient selection is critical, and there should be extensive discussion with patients and families regarding the rigor of postoperative rehabilitation and realistic expectations of motion improvement.

POSTOPERATIVE

In patients with stable medial epicondyle fractures or reduced elbow dislocations, brief cast or splint immobilization is followed by early protected range-of-motion exercises in a hinged elbow brace. Elbow motion should be initiated within the first 2 weeks of injury and ideally as soon as possible. Postoperative care is similar, with protected elbow motion initiated within 2 weeks of surgery when sufficiently stable fixation has been performed. Bracing is discontinued at 6 weeks, followed by gradual strengthening and resumption of activities. Patients are restricted from sports activities for 3 to 6 months postinjury.

ANTICIPATED RESULTS

As cited above, both nonoperative and surgical management of medial epicondylar fractures is associated with favorable clinical outcomes.[5,8,13–16,57,58] While minor loss of terminal elbow extension does occur in some patients, pain-free elbow stability and resumption of activities is the norm, even in cases with apparent radiographic nonunion. The key is to prioritize motion early and often.

COMPLICATIONS

Although conceptually simple injuries, medial epicondylar apophyseal avulsion fractures and elbow dislocations are prone to a variety of complications.

Stiffness is the most common complication after medial epicondyle fracture and/or elbow dislocation.[4,18–20,59] Indeed, loss of elbow motion (particularly terminal extension) may be thought of more as an expectation than complication. Early range-of-motion exercises are critical to minimize post-traumatic stiffness, regardless of whether nonoperative or surgical treatment is pursued.

Ulnar neuropathy is seen in up to 15% of all patients with medial epicondyle fractures, with higher incidences seen in patients with associated dislocations or joint incarceration.[1,31,60] Risk of ulnar nerve complications may be reduced with avoidance of excessive closed reduction maneuvers, prompt surgical reduction and fixation of incarcerated medial epicondyle fractures, and careful retraction and protection of the ulnar nerve during surgical fixation procedures.[61]

Valgus laxity or instability is a common occurrence, though typically only functionally compromising in the throwing or overhead athlete. For this reason, we advocate acute ORIF in higher demand patients.

HO (not myositis ossificans) may occur following traumatic elbow dislocations, though this may be difficult to distinguish clinically and radiographically from

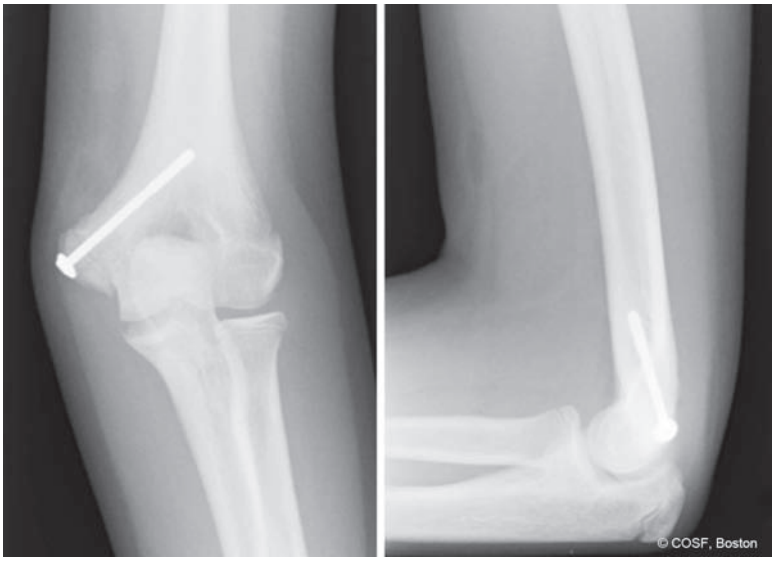

FIGURE 29-9 Follow-up radiographs of the patient presented in Figure 29-1, demonstrating anatomic reduction, screw fixation, and bony healing.

periosteal bone formation secondary to soft tissue stripping.[20] In extreme situations, the HO may be associated with a marked elbow joint contracture that requires extensive release, surgical excision, and rehabilitation to improve motion and function.

CASE OUTCOME

After a discussion with the patient and family regarding treatment options, ORIF of the displaced medial epicondyle fracture was performed (Figure 29-9). Elbow range-of-motion exercises were initiated at 10 days postoperatively in a hinged elbow brace, and strengthening commenced at 6 weeks postoperatively. The patient went on to pain-free, full elbow motion and strength, with return to activities including sports at 6 months postoperatively.

SUMMARY

Medial epicondyle fractures are common injuries in older children and adolescents and are frequently seen with elbow dislocations and other periarticular fractures. ORIF is recommended in situations of incarcerated fragments, ulnar neuropathy, or displaced injuries in high-demand athletes. Stable cannulated screw fixation will allow for early rehabilitation and preservation of elbow motion.

SIDEBAR

Technical Pearls for ORIF

Although the technique of ORIF for displaced medial epicondylar apophyseal avulsion fractures is straightforward, a number of technical obstacles may be encountered. First, while visualization of the fracture site is easily accomplished, maintaining fracture reduction during screw fixation can be challenging. The medial elbow is typically exposed with valgus stress, which makes anatomic reduction difficult. Although elbow flexion, forearm pronation, and varus stress will lessen tension on the flexor-pronator mass and allow for easier reduction, this position inhibits visualization of the fracture. Furthermore, due to the relatively small size of the bony fragment, it is often difficult to hold the fragment reduced and simultaneously drill the guide pin for the cannulated screw.

A few technical maneuvers may overcome these small obstacles. While our preference is to perform ORIF with the patient supine and the affected limb supported by a hand table, others advocate fracture reduction and fixation in the prone position. With the patient prone, the shoulder may be internally rotated, elbow flexed, and the hand placed on the lower back. This position allows for access to the medial side and imparts a varus force to the elbow, facilitating fracture reduction. In addition, a number of instruments have been used to hold the fracture reduced during pin and screw placement, including a sterilized dinner fork with the middle tines removed. Alternatively, drill holes may be created separately in the free medial epicondylar fragment and in the intended path up the medial column prior to fracture reduction. The screw with washer may then be inserted through the medial epicondyle, and the screw tip may then be used to engage and enter the medial column, in essence using the screw as the reduction tool. Finally, an Esmarch elastic bandage may be rolled from the distal to proximal aspect of the forearm to "milk" the flexor-pronator mass and lessen the soft tissue tension on the medial epicondylar fragment.[62]

COACH'S CORNER

Beware of the Medial Condyle Fracture (See Figure 32-5)

In very young patients in whom the trochlea has not completely ossified, displaced medial condyle fractures may be mistaken for innocuous medial epicondyle apophyseal fractures or even elbow sprains (see Chapter 32). In these situations, the appropriate diagnosis is often missed and definitive surgical treatment delayed. Great caution and a high index of suspicion are needed. A number of clinical and radiographic findings should alert the examiner to the presence of a more extensive elbow injury. First, medial condyle fractures tend to occur in younger patients, whereas epicondylar apophyseal fractures typically affect adolescents. In addition, medial condyle fractures are associated with more pain, swelling, and ecchymosis than typical medial epicondylar apophyseal avulsions. The range of motion is often severely restricted and associated with crepitus. Radiographically, there is usually great soft tissue swelling localized to the medial elbow, associated with an elbow effusion. Careful inspection will also reveal that the longitudinal axis of the forearm/ulna does not align with that of the humerus. Finally, patients will often have persistent pain even after acute immobilization. Recognition of these "warning signs" will help keep the pediatric hand and upper limb surgeon out of trouble and on the right track.

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CHAPTER

30

Monteggia Fracture Dislocations

CASE PRESENTATION

A 6-year-old female presents with mild forearm pain after a fall from a playground swing. She denies any distal numbness, weakness, or tingling. On examination, she has mild swelling and tenderness over her ulna. Initial evaluation includes forearm radiographs shown in Figure 30-1.

CLINICAL QUESTIONS

- What is a Monteggia fracture dislocation?
- How are Monteggia lesions classified?
- What are the most common associated injuries?
- What are the indications and surgical principles for acute Monteggia injuries?
- What are the anticipated outcomes of acute Monteggia care?
- What are the potential complications of missed Monteggia lesions?
- What are the indications and contraindications for reconstruction of chronic lesions?
- What are the principles and surgical techniques for chronic Monteggia reconstruction?
- What are the anticipated results and risks of recurrent instability following chronic Monteggia reconstruction?
- What are the potential complications of chronic reconstruction?

THE FUNDAMENTALS

Despite increased understanding of the epidemiology, clinical presentation, treatment options, and potential complications, Monteggia fracture dislocations remain challenging conditions for the pediatric hand and upper extremity surgeon. In 1943, Sir Watson-Jones wrote that "…no fracture presents so many problems; no injury is beset with greater difficulty; no treatment characterized by more general failure."[1] While these injuries are now treated with greater success than 70 years ago, the complexity and clinical challenges—particularly for chronic Monteggia lesions—persist.

As with any traumatic injury in the child, prompt diagnosis and timely treatment continue to be the keystones for successful Monteggia care. A high index of suspicion combined with appropriate radiographic imaging and sound surgical treatment will result in successful outcomes in the vast majority of acute injuries. Furthermore, despite the discouraging initial results, current strategies for reconstruction of the chronic lesion can lead to successful results in the majority of patients. In treatment of both acute and chronic situations, the principles of restoring ulnar length and alignment, while ensuring radiocapitellar stability, guide surgical care.

Etiology and Epidemiology

Originally described by Giovanni Battista Monteggia in 1814, Monteggia fracture dislocations refer to fractures of the ulna associated with proximal radioulnar joint (PRUJ) dissociation and radiocapitellar dislocations.[2,3] These injuries comprise <1% of all pediatric forearm fractures, typically affecting patients between 4 and 10 years of age. The mechanism of injury is classically described as a fall onto an outstretched hand with forced rotation of the forearm.[4] The exact position of the limb and rotational forces imparted will dictate the characteristic patterns of injury.

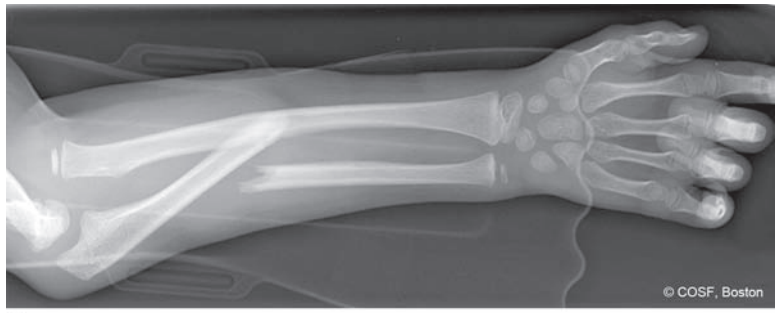
Clinical Evaluation

One chance is all you need.
—Jesse Owens

Acutely, patients will present with pain and swelling, often but not always, accompanied by forearm deformity and limitations in elbow motion. A thorough neurovascular examination is critical, as 10% to 20% of patients may exhibit a neurologic deficit at presentation, most commonly involving the posterior interosseous nerve (PIN).[5–9]

The diagnosis is made radiographically. Isolated views of the ulna fracture are not sufficient; full-length anteroposterior (AP) and lateral radiographs of the forearm, including the elbow and wrist, are needed (Figure 30-1).

A



B

FIGURE 30-1 Acute Monteggia fracture dislocation. **A:** Lateral radiograph of the forearm demonstrates a short oblique mid-diaphyseal ulna fracture. **B**: AP forearm radiograph including the elbow and wrist demonstrates an associated anterior radial head dislocation.

Substandard or insufficient radiographic evaluation should not be accepted. The tenet that the adjacent joints (above and below) should be assessed in any long bone fracture should be followed. Meticulous attention to radiocapitellar alignment in all views is mandatory.

Unfortunately, despite the increased awareness and understanding of Monteggia fracture dislocations, the initial diagnosis is often missed, resulting in late presentation, challenging surgical reconstruction, and suboptimal outcomes. A number of published reports have documented a relatively high incidence of missed diagnoses.[5,10,11] Therefore, a high index of suspicion is paramount, and the adjacent joints should be carefully inspected with any single bone fracture of the forearm.

Normally, the longitudinal axis of the radius should bisect the capitellar ossification center on all radiographic views.[12,13] Cases of presumed "isolated" radial head dislocations must be scrutinized for abnormal ulnar bowing or plastic deformation; indeed >0.1-mm deviation from a straight ulnar border should alert the treating provider to a possible occult ulnar injury (Figure 30-2).[14–18] There are some situations where plain radiographs are concerning but equivocal; in these cases, fluoroscopic imaging and/or advanced imaging in the form of magnetic resonance imaging (MRI) or ultrasound may be useful to confirm or rule out a congruent radiocapitellar and proximal radioulnar joint reduction.

While congenital radial head dislocations may occasionally present as acute injuries, the presence of a hypoplastic capitellum and convex radial head will usually confirm the diagnosis.[19] Furthermore, it is important to note that statistically, most traumatic Monteggia lesions result in anterior radial head dislocation, whereas most (but not all) congenital radial head dislocations are posterior.[20–22]

An understanding of the pathoanatomy of Monteggia fracture dislocations is critical in providing appropriate treatment. In the majority of cases, the annular and quadrate ligaments are disrupted at the PRUJ; however, much of the interosseous membrane between the radius and ulna remains intact, as does the triangular fibrocartilage complex. Anatomic reduction of the ulna, therefore, will often restore PRUJ and radiocapitellar joint congruity. For this reason, treatment is predicated on the nature of the ulna fracture. In addition, the biceps, anconeus, and long forearm flexors exert deforming forces on the proximal radius and ulna, contributing to radial head dislocation, ulnar shortening, and apex radial angulation. Reversing or counteracting these forces is important during fracture manipulation and closed treatment.

Historically, the Bado classification, based upon the direction of the radial head dislocation and apex of the associated ulnar fracture, has been utilized to describe these injuries (Figure 30-3).[2] This classification scheme may aid both in describing the pattern of injury and guiding closed fracture care.

Bado type I injuries refer to anterior dislocation and angulation and are the most common patterns, representing

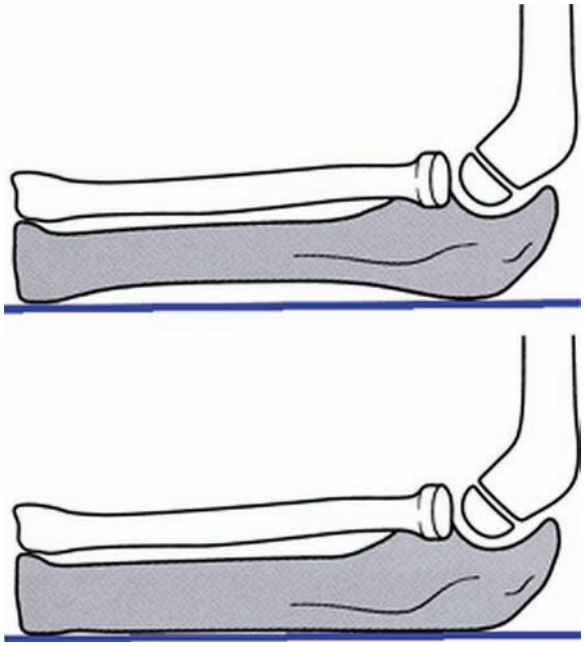


FIGURE 30-2 In cases of "isolated" radial head dislocation, the ulna should be evaluated for deviation from its normally straight dorsal border. Deviation from a straight line drawn along the ulnar border should alert the examiner of a prior ulnar fracture and Monteggia lesion. (From Beaty JH, Kasser JR. *Rockwood & Wilkins Fractures in Children*. 7th ed. Philadelphia, PA: Lippincott Williams & Wilkins; 2010.)

approximately 70% to 75% of all injuries. The mechanism of injury is thought to be due to a hyperextension injury combined with forearm pronation. Reduction, therefore, involves longitudinal traction, supination, posteriorly directed pressure over the radial head, and flexion of the elbow to 110 or 120 degrees to minimize the deforming effect of the biceps.

Bado type II injuries refer to posterior radial head dislocations with apex dorsal ulnar fractures. While common in adults, these injuries are relatively rare in children, accounting for 3% to 6% of pediatric Monteggia lesions. Thought to be caused by an axial load on a partially flexed elbow or direct blow to the proximal supinated forearm, the reduction maneuver involves longitudinal traction with the elbow flexed combined with an anteriorly directed force over the radial head.[2,7,23,24] There is a propensity for instability with the elbow flexed.

Bado type III injuries refer to lateral dislocations and varus fractures of the proximal ulna. Representing the second most common pattern in children, these too result from hyperextension and pronation with varus stress.[25,26] Among the various patterns, it is the Bado type III lesion that is most commonly associated with PIN palsies.[27–29] Combined longitudinal traction, elbow extension, and valgus stress will serve to reduce the deformity. The need for open reduction is common.[25–28,30,31]

Bado type IV lesions refer to radial head dislocations with fractures of both the radius and ulna. The fractures are typically mid-diaphyseal, with the radial fracture more distal than the ulnar fracture.[32] With similar mechanisms of injury as Bado type I injuries, these tend to be higher energy in nature and follow similar treatment principles.

Letts et al.[33] have described an alternative classification scheme based upon the pattern of ulnar fracture (Figure 30-4). This classification is helpful in surgical decision making.

The clinical presentation of missed or chronic Monteggia fracture dislocations is quite varied. Many patients will present weeks after injury, when during the course of cast treatment for an "isolated" ulna fracture, the radial head dislocation is noticed (see Sidebar). While distressing, the opportunity to effectuate meaningful restoration

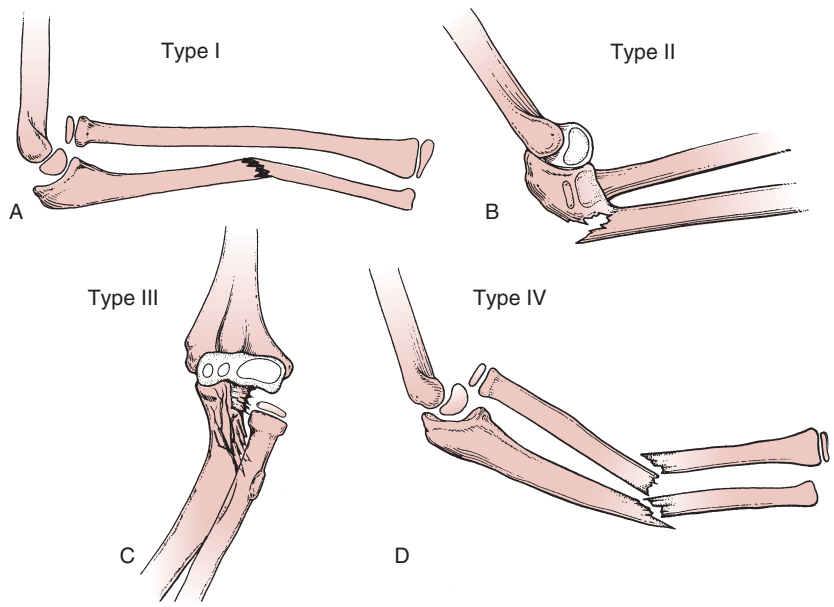


FIGURE 30-3 Schematic diagram of the Bado classification, based upon the direction of radial head dislocation and fracture angulation. (From Beaty JH, Kasser JR. *Rockwood & Wilkins Fractures in Children*. 7th ed. Philadelphia, PA: Lippincott Williams & Wilkins; 2010.)

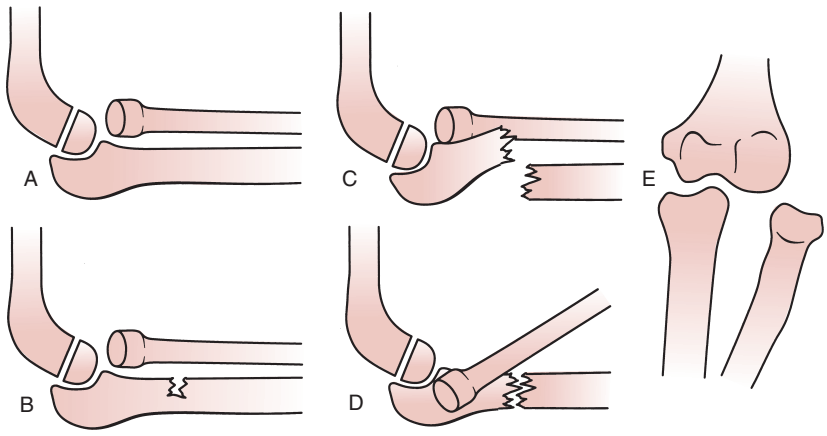


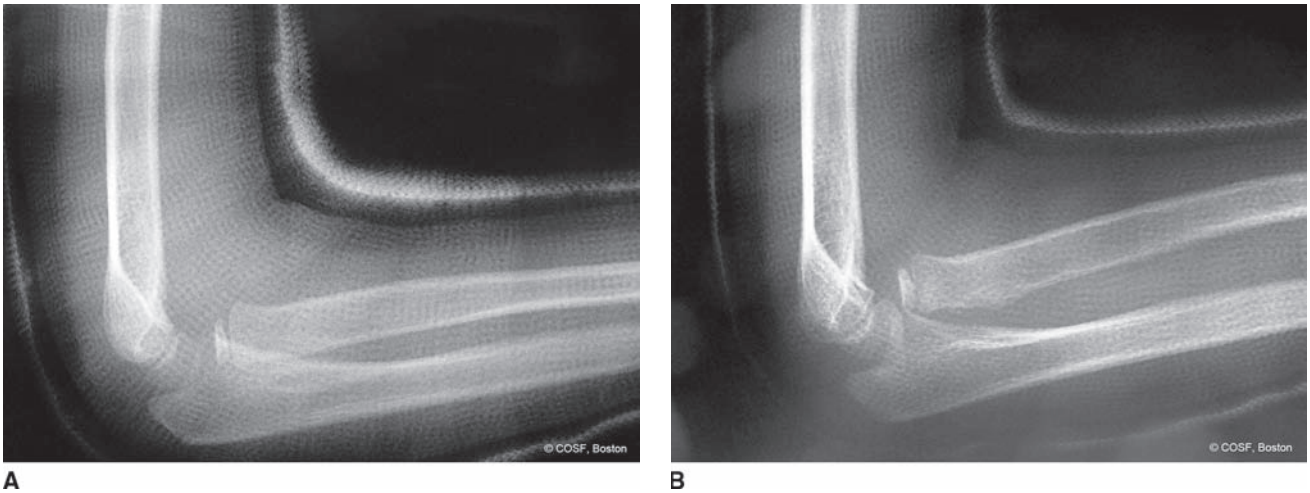
FIGURE 30-4 Letts classification of Monteggia lesions, based upon the ulna fracture pattern. (From Beaty JH, Kasser JR. *Rockwood & Wilkins Fractures in Children*. 7th ed. Philadelphia, PA: Lippincott Williams & Wilkins; 2010.)

of anatomy and functional potential remains great, as no secondary joint changes have occurred. Other patients will present months to years after injury, either with incidental radiographic diagnosis or for evaluation of new pain, noticeable loss of elbow flexion or forearm rotation, or with apparent deformity (e.g., a palpable radial head in the antecubital fossa or posterolateral elbow, progressive cubitus valgus). For many patients, there will be objective, but often minimally symptomatic, functional loss. Radiographs again confirm the diagnosis and guide treatment.

Surgical Indications

Set it and forget it.
—Ron Popeil

While all acute Monteggia fracture dislocations merit formal reduction, there are different methods by which this may be achieved. Closed reduction and cast immobilization alone has been advocated by many and is effective for plastic deformation and incomplete fractures, provided they are recognized acutely. However, simple closed reduction alone has a number of disadvantages. First, there is a high risk of recurrent instability due to loss of reduction with cast immobilization alone (Figure 30-5). This is further compounded by the challenges in serial radiographic evaluation of the quality of reduction while the limb is casted, particularly for Bado type III injuries, which require AP views to assess for lateral displacement of the radial head. Furthermore, effective immobilization of displaced Monteggia lesions often requires positioning the acutely injured, swollen limb in extreme positions. For the common Bado type I injuries, for example, hyperflexion is recommended, which may lead to issues with skin integrity and neurovascular compromise. For these reasons, among others, we advocate surgical reduction and stabilization of



A B

FIGURE 30-5 Loss of reduction with cast immobilization. **A:** Initial postreduction lateral radiograph of a Bado 1 Monteggia lesion. **B:** Loss of reduction is seen in cast. Notice the initial lateral was not perfectly reduced.

all acute Monteggia fracture dislocations with complete ulnar fractures.[28,34]

Chronic Monteggia lesions present a host of different challenges, due to the complexity of surgical steps needed to simultaneously reestablish a stable and mobile PRUJ and potential complications of operative treatment. This is further clouded by the paucity of long-term information regarding the natural history of unreduced Monteggia fracture dislocations.[35–37] It is known, however, that some patients with missed Monteggia lesions will develop pain, functionally limited loss of elbow motion, cubitus valgus, ulnar or posterior interosseous neuropathy, and/or arthrosis.[14,20,22,26,38–48] We believe that symptomatic patients with chronic Monteggia lesions are candidates for surgical reconstruction.

More important, perhaps, are the contraindications to chronic reconstruction. While some have discussed time from injury (<3 years) or patient age (<12 years of age) as discriminating factors, more important is the morphology of the radial head and capitellum.[11,49–51] Patients with radial head enlargement, loss of capitellar convexity, loss of radial head concavity, and/or cartilage loss and arthrosis may not have reducible joints and are not candidates for reconstruction. These are similar to the principles that guide congenital radial head dislocations.

SURGICAL PROCEDURES

Adhering to the principle that restoration of ulnar length and alignment will help obtain and maintain radiocapitellar joint reduction, the choice of surgery will depend upon the chronicity and pattern of ulnar injury.

In acute fractures, incomplete ulnar fractures (plastic deformation and greenstick injuries) have some inherent stability and are length stable; therefore, closed reduction and appropriate cast immobilization are performed. In complete transverse or short oblique fractures, closed reduction and intramedullary (IM) fixation will maintain alignment and preserve length without the additional concerns of open surgery or retained implants. In patients with long oblique or comminuted fractures, IM fixation is often insufficient; open reduction and rigid internal fixation using plate and screw constructs, even in very young patients, are performed instead.

Chronic Monteggia fractures present different challenges. In addition to restoring ulnar length and alignment, the long-standing nature of the radial head dislocation adds further complexity, including scar and soft tissue interposition within the PRUJ, potential for secondary deformity of the capitellum and radial head, and an often deficient annular ligament.

Controversy persists regarding the optimal approach to reconstruction for chronic Monteggia lesions, and to date the "correct" answer is unknown. Areas of continued debate and discussion center around: (1) whether gradual or single-stage correction of the ulnar malunion should be performed; (2) the way in which the ulna should be osteotomized (oblique, transverse, opening wedge); and (3) whether the annular ligament should be discarded, repaired, or reconstructed.[8,20,45,52–62] Clinical data exist to support various reconstructive strategies, and perhaps the most important decision-making factor is the experience and abilities of the treating surgeon. Experienced chronic Monteggia reconstruction surgeons throughout the world consistently feature ulnar osteotomy and thorough joint debridement as principal components of their treatment plans. Our preference is to perform an open ulnar osteotomy with plate and screw fixation, open reduction of the radiocapitellar joint with complete PRUJ debridement, and formal annular ligament repair or reconstruction.

Closed Reduction Incomplete/Plastic Deformation

In acute lesions, the method of treatment is determined by the pattern of ulnar fracture. In patients with plastic deformation, proximal varus buckle, or greenstick fracture of the ulna, closed reduction under general anesthesia is recommended. In these situations, closed reduction of the ulna is typically performed with a combination of longitudinal traction, forearm rotation, and direct pressure applied to the apex of the fracture. The radiocapitellar joint usually reduces spontaneously with this maneuver. The need for significant force applied to the radial head should raise suspicion for interposed soft tissue blocking radiocapitellar joint reduction. In the most common type I lesions, for example, the radial head is anteriorly dislocated, and the ulna has apex-volar angulation. Correction of the ulnar deformity followed by posteriorly directed pressure on the radial head, elbow flexion, and forearm supination is usually performed. Typically, the ulna fracture and radiocapitellar joint are stable after reduction of plastic deformation or incomplete fractures. This is tested manually and under fluoroscopy. A well-molded, bivalved above-elbow cast is then applied for 4 to 6 weeks. After radiographic and clinical healing is confirmed, supervised range-of-motion exercises may be initiated.

IM Fixation of Short Oblique or Transverse Ulna Fractures

In patients with complete transverse or short oblique fractures of the ulna, closed reduction alone can result in loss of reduction in a cast. Therefore, closed reduction and IM fixation of the ulna are recommended to facilitate maintenance of ulnar alignment and radiocapitellar reduction (Figure 30-6). In these cases, an age- and size-appropriate stainless steel K-wire or flexible titanium nail (Synthes, West Chester, PA) is selected. K-wires have the advantage of being inexpensive, universally available, and, due to their stainless steel composition and straight tip, allow for easy removal in the office without need for analgesia or

anesthesia. K-wires, however, can be too short to provide adequate fixation in older children with longer forearms.

Via a small longitudinal split in the triceps tendon overlying the olecranon process, the K-wire or flexible titanium nail is inserted into the IM canal of the ulna and advanced in an antegrade fashion to the fracture site. The ulnar fracture is closed reduced, and the nail is subsequently advanced into the IM canal of the distal fracture fragment, allowing for restoration of both ulnar length and alignment. During ulnar reduction and fixation, closed reduction is performed of the radiocapitellar dislocation. Intraoperative fluoroscopy is utilized to confirm appropriate ulnar and radiocapitellar reduction, as well as intraosseous placement of the IM device. Given the rapid healing

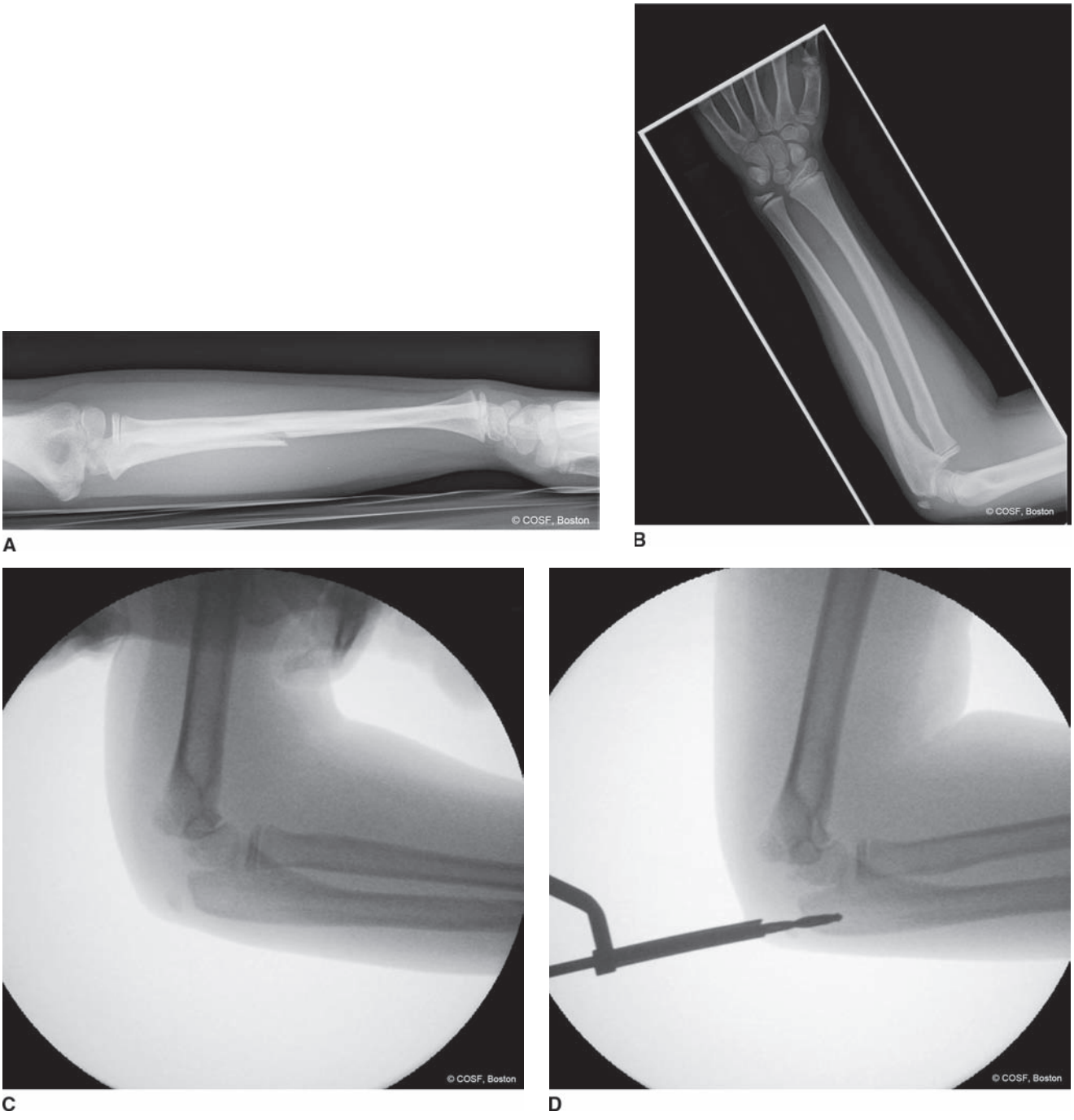


FIGURE 30-6 IM fixation of an acute Bado 1 Monteggia fracture dislocation in a 7-year-old female. **A, B:** The injury radiographs demonstrate a short oblique ulna fracture with an anteriorly dislocated radial head. **C:** Intraoperatively, closed reduction is performed. **D:** A cortical entry site is created in the olecranon.

E

F

G

FIGURE 30-6 *(continued)* **E:** A smooth K-wire is passed down the ulnar canal, stabilizing the fracture and joint reduction. **F:** Reduction is stable with elbow extension. **G:** Radiograph taken 3 months postoperatively demonstrates bony healing and anatomic joint reduction.

of the ulnar fracture, particularly with closed reduction, our preference is to bend and cut the IM nail outside the skin to facilitate subsequent removal. An above-elbow, bivalved cast is then applied with the elbow in 90 degrees flexion and the forearm in supination, which confers additional stability to the radiocapitellar articulation.

Open Reduction and Internal Fixation (ORIF)of Long Oblique or Comminuted Ulnar Fractures

Long oblique or comminuted ulnar fractures cannot be adequately stabilized with IM techniques. While passage

FIGURE 30-7 ORIF of Monteggia lesion in a 4-year-old male associated with a comminuted ulna fracture. **A, B:** Injury radiographs demonstrating the dislocated radial head and ulnar fracture pattern. **C, D:** Radiographs taken 3 months postoperatively, demonstrating a healed fracture and stable joint alignment.

of the IM rod is straightforward, the fracture pattern does not allow for adequate maintenance of alignment or length. In these cases, open reduction and internal fixation utilizing plate and screw constructs are necessary (Figure 30-7). Through a longitudinal incision based on the subcutaneous border of the ulna and centered on the fracture site, reduction is performed, and double-stacked one-third tubular or small-fragment dynamic compression plates (Synthes, West Chester, PA) are applied in the standard fashion. In our experience, four to six cortices of fixation proximal and distal to the fracture provide adequate stability in pediatric patients. Radiocapitellar joint congruity is again achieved during reduction and fixation of the ulna fracture, typically with closed manipulation alone. If closed reduction of the radiocapitellar joint is unattainable, an open reduction may be facilitated by extending the ulnar incision proximally over the posterolateral aspect of the elbow. After stable reduction of the radial head (closed or less commonly open), the periosteum is repaired over the fracture site and implant. Limited prophylactic dorsal and volar forearm fasciotomies are

performed to lessen the risk of postoperative compartment syndrome. A bivalved long-arm cast in forearm supination is applied.

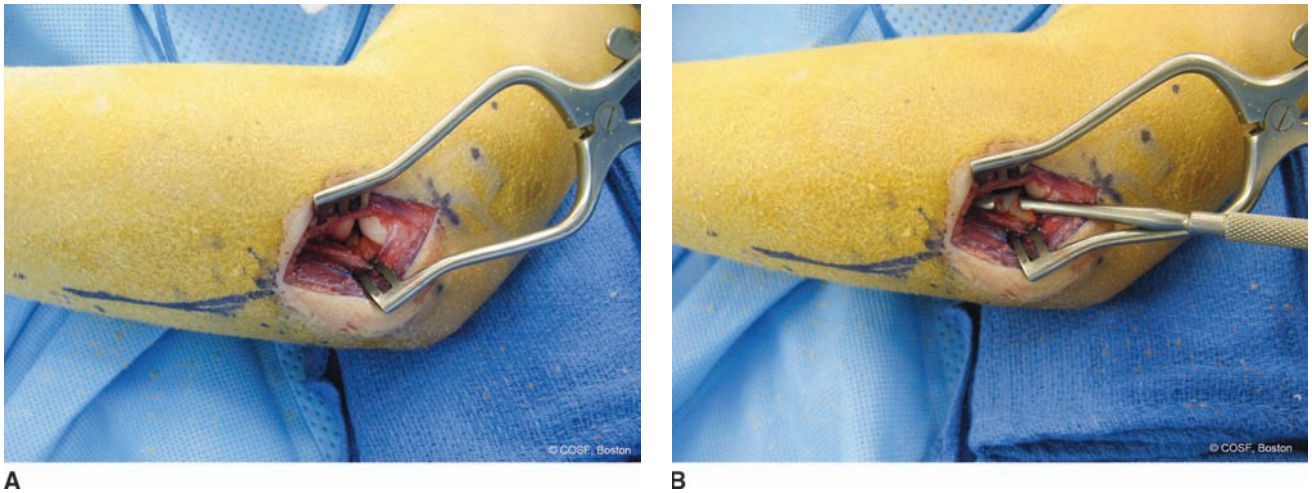
Open Reduction Annular Ligament

Close don't count in baseball. Close only counts in horseshoes and hand grenades.
—Frank Robinson

On occasion, patients presenting with acute Monteggia fracture dislocations are taken to the operating room, and closed reduction of the radiocapitellar joint cannot be achieved, even after IM or plate fixation of the ulna. In these situations, while the radial head position can be improved, there is no satisfying "clunk"; instead, the surgeon feels a soft, "rubbery" resistance during manipulation. Intraoperatively, the reduction is not perfectly congruent or is obtainable but unstable with forearm rotation.

A few critical points should be remembered in these situations. First, the temptation is great to accept a "near-perfect" reduction; even the most well-intentioned surgeons can be lured into reassuring themselves that while imperfect, the reduction will be adequate. This temptation should be avoided, as an imperfect reduction in the operating room will lead to further instability and complications postoperatively. Given the difficulty in visualizing the radiocapitellar joint while the limb is in a long-arm cast, all too often "recurrent" dislocation of the radial head is not discovered for many weeks after the initial intervention. Second, the annular ligament is almost always avulsed or interposed during the acute injury (Figure 30-8).[34] Therefore, there is a high likelihood of annular ligament or periosteal interposition blocking the reduction of the radiocapitellar joint.[30,64] Finally, in reducible but unstable cases, it is unlikely that the soft tissue impediment to reduction will "remodel" or disappear during the postoperative course. The quality of the reduction will not get any better than it is in the operating room in the acute setting.

In these cases, open reduction of the radiocapitellar joint with restoration of the normal position of the annular ligament should be performed. Do not be tempted to place a pin across the radiocapitellar joint to hold it reduced. The joint will just spring open when the pin is removed due to the soft tissue interposition. Via a posterolateral approach to the elbow, skin flaps are raised and the interval between the extensor carpi ulnaris (ECU) and anconeus developed. Capsulotomy is performed and the joint inspected. The radial neck is visualized (the radial head usually buttonholes through the anterior capsule in the irreducible Bado type I injury). Careful exploration of the joint will allow for identification of the annular ligament. Rather than being torn midsubstance, the annular ligament typically remains in continuity, tears off the ulna with a periosteal sleeve, and "slips off" the radial head and neck, similar to a loosened necktie being taken off by pulling it over the head. The opening in the annular ligament is identified, and with the use of a forceps, Freer elevator, small curette, or soft tissue probe, the ligament is reduced over the radius. In rare situations where this is not achievable, the ligament may be enlarged with partial radial incisions or incised longitudinally and repaired primarily over the radial neck with small 2-0 or 3-0 nonabsorbable sutures. Congruency of the reduction is visualized directly, and stability is confirmed with forearm rotation and fluoroscopic imaging. The wound is closed in layers and the limb placed in a bivalved long-arm cast, typically in forearm supination.



A B

FIGURE 30-8 Open reduction of the radial head. **A:** Intraoperative photograph of a left elbow, depicting a dislocated radial head identified via a posterolateral approach. **B:** A Freer elevator has been placed into the middle of the annular ligament, which can then be reduced over the radial head and neck.

◆ Chronic Monteggia Reconstruction with Open Ulnar Osteotomy with Plate Fixation, Open Reduction of the Radiocapitellar Joint, and Annular Ligament Repair or Reconstruction

It's not so important who starts the game but who finishes it.
—John Wooden

Our approach to chronic lesions is to perform an open osteotomy with rigid plate fixation of the ulna, open radiocapitellar joint reduction, and annular ligament repair or reconstruction. Based upon prior experience and to avoid potential complications of PIN injury and compartment syndrome, reconstructions are performed via an extensile posterolateral approach with identification/decompression of the PIN and forearm fasciotomies.[65]

Patients are positioned supine with the affected limb on a radiolucent hand table. Sterile tourniquets may be used, particularly in small children, to allow for more proximal exposure. A modified posterolateral approach to the elbow is utilized, with the middle of the incision curved anteromedially and the distal incision extended along the ulnar border of the forearm (Figure 30-9).[66] This extensile approach allows access to and exposure of all the necessary structures, including the radiocapitellar joint, radial nerve, and ulnar malunion site.

Subcutaneous flaps are raised, with care taken to preserve the cutaneous sensory nerves. The radial nerve is located proximally in the brachialis-brachioradialis intermuscular interval. It is followed distally as it branches into the PIN and radial sensory nerve. In chronic Bado type I reconstructions, the PIN will course immediately adjacent and be adherent to the joint capsule and displaced radial head; identifying the PIN will allow for

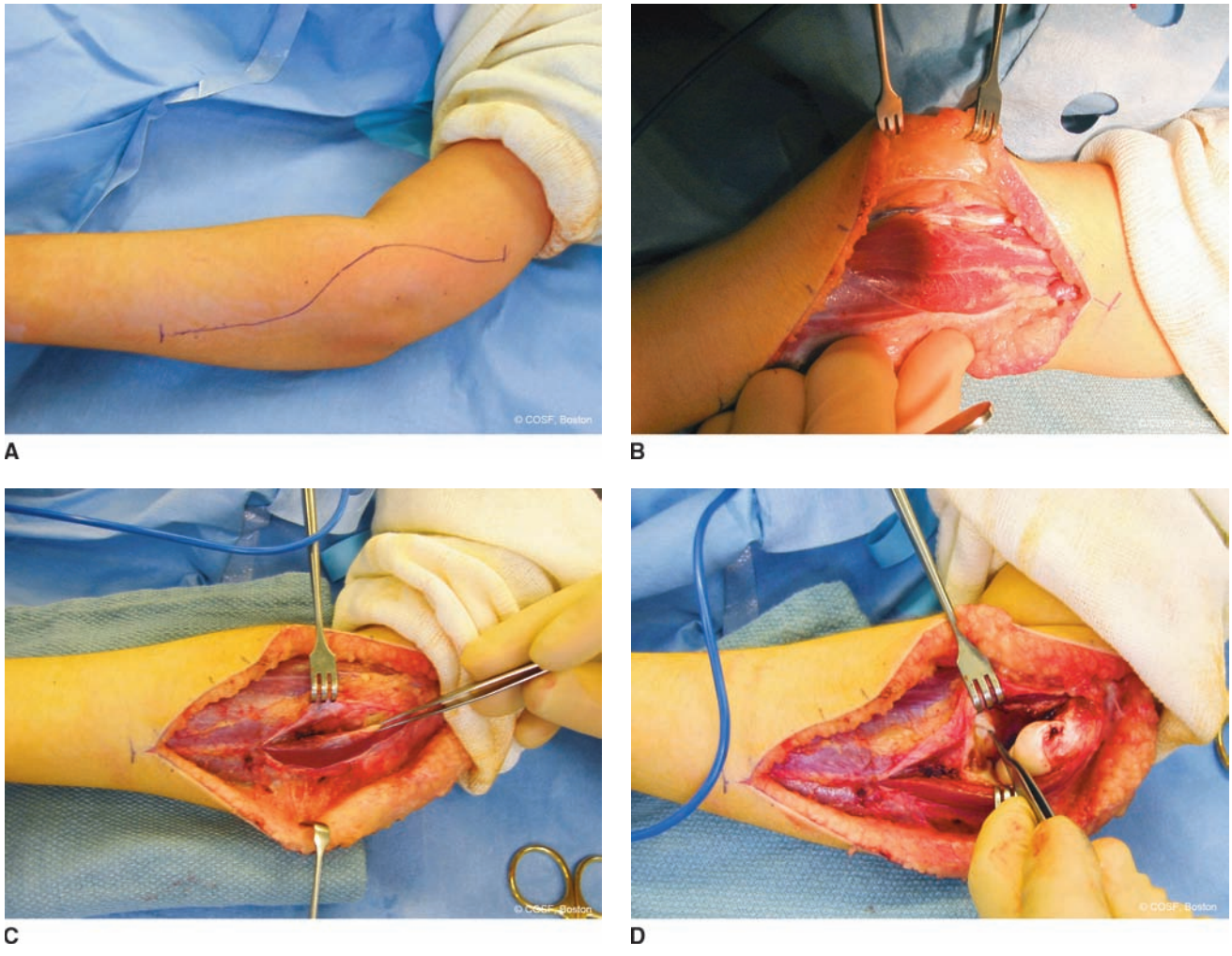
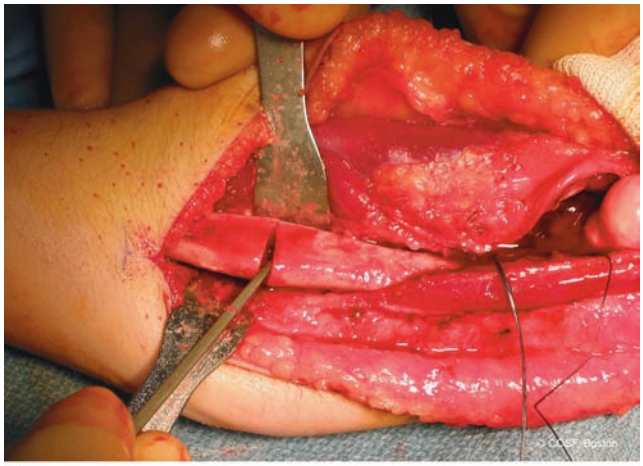


FIGURE 30-9 Chronic Monteggia reconstruction. **A:** A curvilinear posterolateral incision is utilized. **B:** The PIN can be identified and decompressed, if needed. **C:** The anconeus-ECU interval is developed to access the radiocapitellar joint. **D:** The dislocated head as well as the annular ligament are identified.



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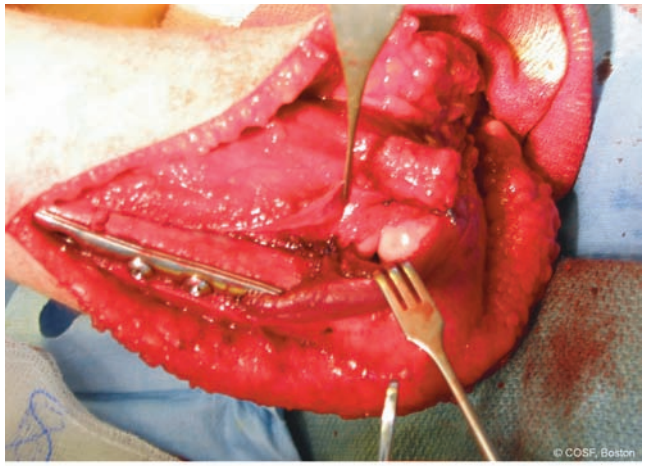

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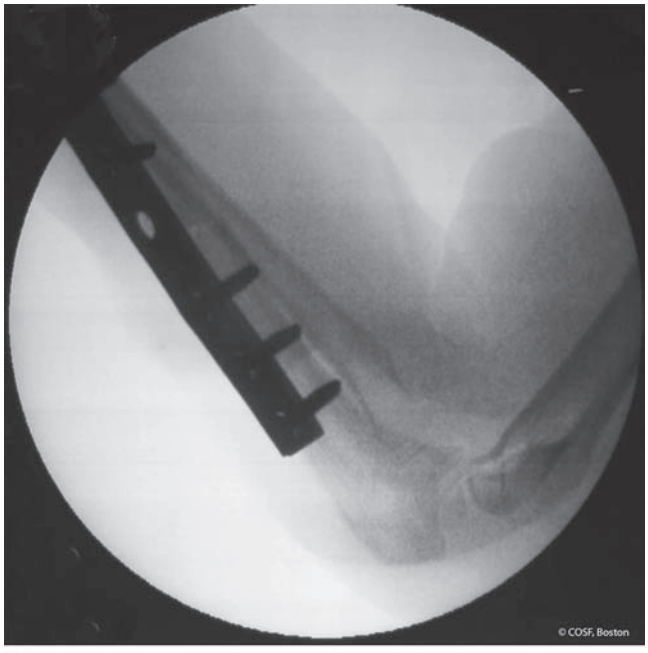

G

FIGURE 30-9 *(continued)* **E:** Sutures are placed into the annular ligament for subsequent repair. After subperiosteal dissection at the site of the ulnar malunion, an opening wedge osteotomy is created. **F:** After reduction of the radial head, the ulna is stabilized with plate and screws, and the annular ligament repaired. **G:** Intraoperative fluoroscopy is used to ascertain a stable reduction throughout a full forearm and elbow arc of motion.

its protection during reduction and joint debridement maneuvers.

Distally, the interval between the ECU and the anconeus is then developed. This interval is extended proximally, entering the radiocapitellar joint anterior to the lateral ulnar collateral ligament, thus preserving the integrity of the lateral ligament complex. If necessary for adequate visualization, the extensor-supinator mass and capsule may be elevated off the distal lateral humerus as a single soft tissue sleeve; placement of marking sutures will allow for anatomic reapproximation during closure. Initial inspection of the radiocapitellar joint typically reveals abundant intra-articular fibrous tissue and a clearly dislocated radial head, generally through the anterior capsule. The joint is carefully debrided, with care being taken to clear the radiocapitellar articulation to its most medial extent. Thorough PRUJ debridement will allow for visualization and palpation of the lesser sigmoid notch of the ulna. Locating and protecting the PIN are essential during PRUJ debridement to avoid inadvertent nerve injury.

The annular ligament is then identified. In chronic situations, the annular ligament often lies within the joint space, and its central aperture may not be immediately appreciated. Careful dissection and dilation of the central portion will allow reconstitution of the ringlike shape of the native ligament. (This is a bit like turning a disk into a ring, or a Danish into a doughnut.) If the annular ligament cannot be easily brought over the radial head and blocks the radiocapitellar joint reduction, it may be longitudinally incised along its radial border and later reapproximated. In some instances, the annular ligament has been detached at its insertion and therefore must be subsequently repaired.

Braided polyester 2-0 sutures (Ethibond, Ethicon, Inc., Somerville, NJ) are then placed into the ends of the annular ligament for future repair. Typically, a congruent and stable radiocapitellar reduction is not feasible due to the concomitant ulnar malunion. Direction is therefore turned to the ulna.

Intraoperative fluoroscopy is used to localize the site of the ulnar malunion. The posterolateral skin incision is extended along the subcutaneous border of the ulna, and subperiosteal dissection of the ulna is performed in the ECU-flexor carpi ulnaris (FCU) interval. In cases of type I Monteggia fracture dislocations, the apex of the ulnar angular malunion is volar. In these instances, an opening wedge osteotomy is created at the malunion site, with care being taken to preserve the far (volar) cortex. If an oscillating saw is utilized to create this osteotomy, copious saline irrigation is used to minimize the risk of thermal necrosis. Often, fracture callus and periosteal bone may be present at the site of the ulnar malunion; this may be used as local bone graft after completion of the osteotomy. Once the cut is created, a laminar spreader or similar instrument may be used to provide gentle and gradual opening of the osteotomy.

After the ulnar osteotomy is completed, attention is turned back to the radiocapitellar joint. The radial head is congruently reduced, and the radiocapitellar joint is provisionally pinned using a percutaneously placed posterior-to-anterior (through the triceps) 0.062″ or 0.045″ smooth K-wire. Care is taken to place this wire centrically in the proximal radius, and fluoroscopy may be used to confirm appropriate alignment. Setting the radiocapitellar reduction first is helpful, as it dictates the amount of ulnar correction needed to maintain a stable reconstruction.

The ulnar osteotomy is then stabilized with appropriately contoured plate and screws. In the younger patients, we use double-stacked one-third tubular plates (Synthes, West Chester, PA) with four to six cortices of fixation proximal and distal to the osteotomy site. Usually, we strive for a bit of overcorrection, and the plates must be prebent to fit the angle of the osteotomy. The radiocapitellar pin is removed and the elbow and forearm are ranged to assess stability, remembering that ulnar alignment determines radiocapitellar stability.

The annular ligament is repaired using the previously placed braided polyester sutures. In cases where the annular ligament cannot be identified or isolated for subsequent repair, a strip of triceps or forearm fascia may be used to perform an annular ligament reconstruction.[20,52,55] Preserving its attachment on the ulna, a central strip of triceps fascia is elevated off the muscle in a proximal-to-distal fashion, all the way to the level of the radial neck (careful distal dissection is needed to avoid inadvertently amputating the insertion of the triceps tendon onto the cartilaginous proximal ulna). This fascial strip is then passed around the radial neck, recreating the annular ligament. The reconstructed ligament may then be passed through drill holes created in the ulna or reapproximated to the ulnar periosteum using nonabsorbable sutures. Stability is then confirmed with gentle ranging of the elbow in flexion-extension and of the forearm in pronation-supination.

In rare situations when there is still radiocapitellar instability despite appropriate correction of the ulnar deformity and repair/reconstruction of the annular ligament, the radiocapitellar joint may be fixed in a reduced position with a transarticular K-wire.[41,51] Others have advocated radial shortening osteotomy to facilitate radiocapitellar reduction.[51,67] In general, these techniques are not used during typical chronic Monteggia reconstructions, but they may be of use during particularly difficult reconstructions or revision situations.

Following ulnar osteotomy, annular ligament reconstruction, and radiocapitellar reduction, the periosteum and intermuscular intervals are reapproximated and the wound is closed in layers over a drain. Prophylactic volar and dorsal forearm fasciotomies are performed to minimize risk for postoperative compartment syndrome. A bulky above-elbow bivalve cast is applied, typically with the elbow in 80 to 90 degrees of flexion and the forearm in supination.

POSTOPERATIVE

In acute fractures treated with closed reduction, cast immobilization is continued until bone and soft tissue healing at 6 weeks. With closed reduction IM fixation, the patient is followed with IM rod removal in the office or day surgery unit depending on the implant. Plates and screws are left in permanently unless symptomatic.

In chronic reconstructions, there is a slower transition from cast (6 weeks) to protective splint (an additional 3 to 4 weeks) to full rehabilitation (3 to 6 months).

ANTICIPATED RESULTS

In acute Monteggia fracture dislocations, surgical stabilization of complete ulnar fractures and reduction of the PRUJ will result in near-universal bony healing, joint stability, and restoration of elbow and forearm motion.[11,28,69]

Results of chronic reconstructions are also encouraging but imperfect. In multiple published retrospective case series, 80% or more of patients achieved bony healing and PRUJ stability.[8,20,41,45,51–62,67,70–72] Elbow flexion is commonly restored, though subtle restrictions in forearm rotation (particularly pronation) may persist.

COMPLICATIONS

The most common complications of Monteggia care involve missed diagnosis or recurrent instability following

initial nonoperative care. As discussed above, careful initial radiographic assessment and surgical treatment of potentially unstable acute injuries will minimize, if not eliminate, these adverse events. If nonoperative treatment is pursued for an acute Monteggia lesion, serial weekly radiographs should be done to rule out late displacement.

Radial/PIN injuries are relatively common with Monteggia lesions, seen in up to 20% of acute injuries.[12,26,37,52] If identified at the time of initial injury, the vast majority of PIN palsies will resolve spontaneously, and observation is warranted.[38,39,73] Serial clinical examinations will demonstrate gradual anatomically progressive return of motor function; wrist and digital extension will return prior to thumb extension. Failure of appropriate return by 6 months is a relative indication for surgical exploration and nerve care (see Chapter 37).

Rarely, intra-articular entrapment of the radial nerve may complicate the irreducible Monteggia fracture dislocation.[8,68] It is hypothesized that anterior radial head dislocation combined with a varus force imparted on the elbow will allow the radial nerve to pass posteriorly to the radial head and become incarcerated within the joint. Following the principles of the treatment of nerve injuries associated with upper extremity fractures (see Chapter 37), in suspected cases of nerve entrapment, timely surgical treatment—including identification of the radial nerve proximal and distal to the zone of injury, circumferential dissection through the zone of injury alleviating any points of constriction or compression, assessment of nerve integrity and conduction, and repair or grafting when appropriate—must accompany bone and joint reconstruction.

Radial/PIN injuries may also be seen following surgery, particularly with chronic reconstructions. Identification and protection of the PIN will help minimize these risks. In patients with new onset radial nerve deficits following surgery, early exploration should be strongly considered to confirm the nerve is in continuity.

As with other high-energy injuries of the pediatric elbow and forearm, compartment syndrome is a risk. Careful clinical observation is necessary whenever circumferential casting is applied to the acutely injured, swollen limb, particularly if immobilized in extreme positions (e.g., hyperflexion). Risk of compartment syndrome is similarly present following chronic reconstruction.[65] The use of bivalved cast immobilization and prophylactic dorsal and volar forearm fasciotomies may minimize these postoperative risks.

CASE OUTCOME

The diagnosis of an acute, Bado 1 Monteggia fracture dislocation was made. Given the complete short oblique ulnar fracture, the decision was made to proceed with closed PRUJ reduction and IM fixation of the ulna (Figure 30-10). The IM wire was removed at 4 weeks postoperatively, and cast immobilization discontinued at 6 weeks. By 3 months postoperatively, the patient had full motion and joint stability.

SUMMARY

With proper index of suspicion and radiographic evaluation, acute Monteggia fractures can be accurately diagnosed and properly treated. Given the risks of nonoperative care, surgical reduction and ulnar stabilization should be strongly considered for all patients with complete ulnar injuries, with the pattern of ulnar fracture dictating choice of fixation. Unfortunately, failure of initial diagnosis and loss of reduction following initial nonoperative care continue to occur, resulting in chronic Monteggia lesions. In symptomatic patients without secondary bone or joint changes, surgical reconstruction is safe and effective in restoring anatomy and function in the majority of patients. However, chronic Monteggia reconstruction should be performed predominately by surgeons with extensive experience.

FIGURE 30-10 Postoperative radiographs 10 weeks after closed reduction and IM fixation. The ulna is well healed, and the radiocapitellar joint remains anatomically reduced.

SIDEBAR

Calcification of the Annular Ligament

Occasionally, the delayed diagnosis of a radial head dislocation and Monteggia lesion will be made when the radiologist or surgeon sees an abnormal radiopacity on plain radiographs adjacent to the radial head (Figure 30-11). This radiographic abnormality calls to the examiner's attention the PRUJ disruption, which has been present from the initial injury. Often misinterpreted as "heterotopic ossification," this radiopacity usually represents calcification of the disrupted and displaced annular ligament and/or displaced anterior capsule and may appear within weeks of an acute injury.[74] In isolation, this mineralized tissue is not thought to cause any functional limitations, provided that an anatomic reduction of the radial head is achieved.[13,26,35,52]

FIGURE 30-11 Abnormal calcification of the annular ligament following a Bado 1 Monteggia fracture dislocation. (From Beaty JH, Kasser JR. *Rockwood & Wilkins Fractures in Children.* 7th ed. Philadelphia, PA: Lippincott Williams & Wilkins; 2010.)

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CHAPTER

31

Radial Head and Neck Fractures

CASE PRESENTATION

An 8-year-old female presents with right elbow pain after a fall from standing height. There is tenderness and swelling over the lateral elbow, and she is reluctant to flex-extend the elbow or rotate the forearm. Radiographs demonstrate a radial neck fracture (Figure 31-1).

CLINICAL QUESTIONS

- How do children with radial neck and head fractures present?
- How are radial neck and head fractures classified?
- What are the treatment principles for radial neck and head fractures?
- What are the indications for surgical reduction and fixation?
- What surgical techniques are used?
- What are the anticipated results and possible complications of surgical treatment?

THE FUNDAMENTALS

Radial neck fractures are relatively common injuries in the skeletally immature patient. While the diagnosis is often easily made, fractures of the proximal radius continue to present the pediatric hand and upper extremity surgeon with a host of clinical challenges due to (1) the controversies regarding what constitutes acceptable deformity; (2) the myriad of surgical treatment options; and (3) the propensity for these injuries to cause persistent elbow stiffness or late complications, despite seemingly acceptable radiographic alignment. In general, treatment is predicated on restoring anatomy and thus elbow/forearm motion using the least invasive means possible.

Etiology and Epidemiology

Proximal radius fractures represent approximately 1% of all childhood fractures and account for roughly 5% to 10% of all elbow injuries.[1–6] Typically affecting children between 4 and 14 years of age, the peak age for radial neck and head fractures is between 8 and 10 years.[1,3,7–11] Unlike adult proximal radius fractures, which affect the radial head and are often intra-articular, pediatric fractures typically involve the neck and traverse the proximal radial physis or metaphysis. It is believed that the cartilaginous nature of the epiphysis is more resistant to fracture and confers a relative protective effect.

Radial head and neck fractures can occur in association with other elbow region injuries. Lateral compression (radial head/neck, lateral condyle), medial tension (medial epicondyle, medial collateral ligament), anterior tension (brachialis muscle, coronoid, anterior capsule), and posterior compression (olecranon) can all occur together. These more complex injuries require treatment for each injury as a part of the care package.

Clinical Evaluation

If size is all that matters, how come the whale is endangered and the ant continues to do just fine?
—Kelly Marshall

Patients will typically present with pain, swelling, and limited elbow and forearm range of motion. Physical examination will yield tenderness with palpation over the radial neck, with resistance to passive forearm rotation in displaced injuries.

Radiographic evaluation includes standard anteroposterior (AP) and lateral plain radiographs of the elbow. As the proximal radial epiphysis does not become radiographically apparent until approximately 3 to 4 years of age, radiographic evaluation of radial neck fractures may be challenging in the very young child. Furthermore, it is important to remember that normally the proximal radius has up to 15 degrees of valgus angulation on the AP view and between 10 degrees of anterior to 5 degrees posterior angulation as seen on the lateral projection.[11] Careful inspection of the contour and alignment of the proximal radial metaphysis is needed to discern injuries in these young patients. The 45-degree oblique view may be helpful in separating the radial and ulnar structures on plain radiographs to better identify and

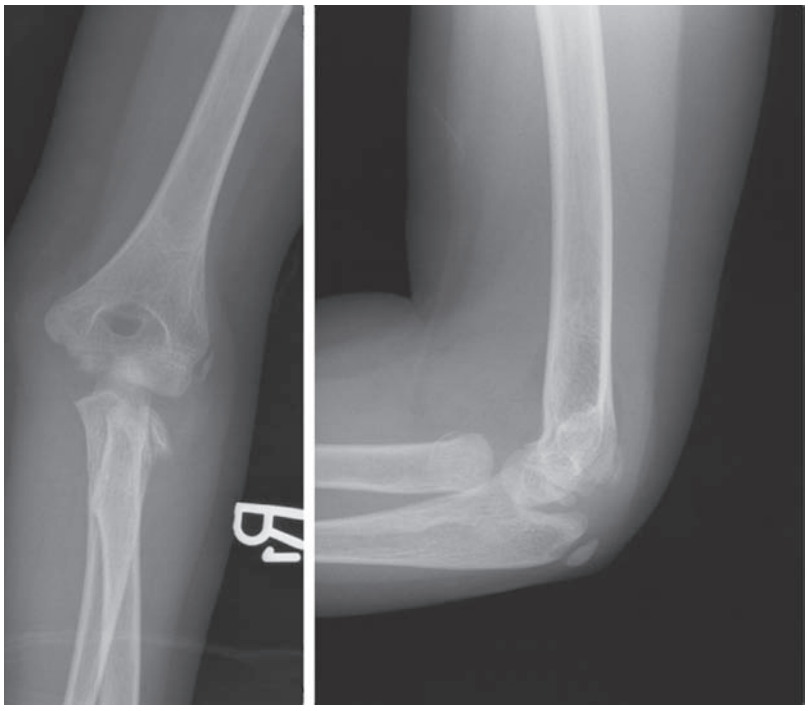

FIGURE 31-1 AP and lateral radiographs of a displaced radial neck fracture in an 8-year-old female.

characterize the radial neck fracture.[12–14] Furthermore, as radial neck fractures are frequently associated with elbow dislocations and other fractures about the elbow, systematic inspection of all the bony structures is needed to rule out concomitant skeletal injuries.

Radial neck fractures are primarily classified according to anatomic location, translation, and angulation. These fractures have been further classified according to mechanism of injury and degree of displacement.[4,8,15] Group I injuries refer to those with primarily radial head displacement. Group IA fractures include Salter-Harris type I and II fractures, group IB fractures include Salter-Harris type IV fractures, and group IC fractures involve the proximal radial metaphysis. Group ID and IE injuries refer to radial head displacement that occurs during reduction or dislocation of ulnohumeral dislocations, respectively. Group II injuries denote displacement of the radial neck, either with angular (IIA) or torsional (IIB) deformity. Finally, Group III injuries denote stress injuries of the radial head articular surface, epiphysis, or physis (see Coach's Corner).

Surgical Indications

While radial neck fractures have tremendous healing potential, excessive angulation or translation will result in loss of forearm rotation and/or elbow flexion-extension. Much of this is due to the constrained articulation of the proximal radioulnar joint (PRUJ) (Figure 31-2). With angulation or translation of the radial head on the radial shaft, cam impingement may occur, resulting in a bony block to forearm rotation.[16] Surgical procedures are therefore intended to restore more normal anatomy in hopes of preserving motion and ultimately upper limb function.

Given these considerations, intervention is recommended for excessive fracture displacement. How much angulation and/or translation constitute "too much" is difficult to answer and has not been rigorously studied. Multiple authorities and retrospective studies have suggested that <30 to 45 degrees of angulation and <3 to 4 mm of translation will allow for acceptable functional results.[5–8,10,11,17,18] While these radiographic guidelines are helpful, they can be misleading, as often the maximal

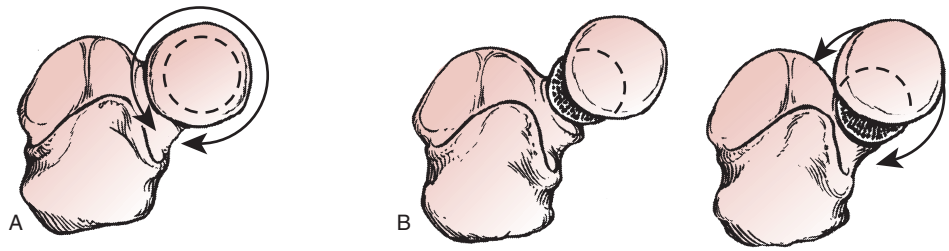

FIGURE 31-2 The effect of displaced radial neck fractures on forearm rotation. (From Beaty JH, Kasser JR. *Rockwood & Wilkins Fractures in Children*. 7th ed. Philadelphia, PA: Lippincott Williams & Wilkins; 2010.)

deformity is not appreciated on static AP and lateral radiographs of the elbow. Furthermore, radiographic remodeling of proximal radial injuries is poor, and multiple studies have demonstrated that radiographic alignment and elbow/forearm motion plateau after 6 months postinjury.[9]

We favor observation and nonoperative treatment of most of the radial neck fractures with <30-degree angulation, <4-mm translation, congruent radiocapitellar reduction, and at least 80 degrees of forearm pronation-supination. For all other injuries, the simplest and least invasive method of fracture realignment is attempted to achieve the above-stated criteria. In essence, the question is not which injuries require intervention, but rather, which fractures do *not* require further reduction.

SURGICAL PROCEDURES

Ain't no chance if you don't take it.
—Guy Clark

While a host of surgical procedures can be performed, multiple published studies highlight some common, unifying principles. First, earlier intervention is better.[19,20] Fracture reduction becomes much more difficult beyond 7 days postinjury, potentially compromising results. Second, open reduction and fracture stabilization should be deemed a last resort.[7,9,21,22] While likely due to selection bias, the literature clearly supports the notion that the need for open reduction portends a worse prognosis. Third, an imperfect but acceptable closed reduction is preferred over an anatomic reduction achieved via open means. Finally, despite surgical skill and radiographic realignment, stiffness does occur, and patients/families should be counseled about the risk of post-traumatic loss of forearm rotation.

In cases where unacceptable alignment and loss of forearm pronation-supination exist, we advocate a stepwise progression of reduction maneuvers, from simple to complex, until a satisfactory clinical and radiographic result is achieved (Table 31.1).

Table 31.1

Progression of treatment options for displaced radial neck fractures

1. Cast immobilization
2. Closed reduction (Patterson, Israeli, Esmarch bandage)
3. Percutaneous pin-assisted reduction
4. Metaizeau intramedullary (IM) reduction and fixation
5. Wallace method
6. Open reduction and internal (pin) fixation

Closed Reduction

A number of closed reduction maneuvers may be utilized for displaced and angulated radial neck fractures, and the pediatric hand and upper extremity surgeon should have experience with all techniques. Typically, these maneuvers are most successful in fractures angulated up to 60 degrees with less than complete translation. Given the sustained forces required during these maneuvers, closed reduction should be performed under general anesthesia or adequate conscious sedation with fluoroscopic assistance.

The Patterson technique is perhaps the easiest and most intuitive.[23] With the elbow extended and forearm supinated (or in a position that rotates the radial head fragment into its most lateral position), a varus moment is applied across the elbow, and direct pressure is applied to the radial head fragment to effectuate reduction. Fluoroscopic confirmation is made of bony realignment, and passive forearm rotation is assessed. This technique relies upon the intact annular ligament to confer stability to the radial head.

The Israeli technique is performed with the elbow flexed instead of extended.[24] With the elbow positioned at 90-degree flexion, the surgeon's thumb is placed over the radiocapitellar joint, applying medially directed pressure. The forearm is then pronated or supinated to rotate the radial head fragment into the surgeon's thumb, thereby achieving a congruent reduction against the capitellum and proximal lesser sigmoid notch of the ulna.

Rather than reduce the radial head to the shaft, closed reduction may also be performed by reducing the displaced radial neck and shaft to the head.[25] In this technique, the elbow is placed in extension and a varus moment applied to the elbow. The surgeon's thumbs are then used to push the proximal radial diaphysis laterally.

Finally, failing these maneuvers, an Esmarch bandage may be applied from distal to proximal in the forearm, utilizing the hydraulic effect to achieve reduction. Although not universally successful, this technique may result in surprising improvement in fracture alignment.

Percutaneous Pin-Assisted Reduction

When simple, closed reduction maneuvers fail to achieve adequate improvement in fracture alignment, percutaneous pin-assisted reduction may be used (Figure 31-3). Under general anesthesia and fluoroscopic visualization, the elbow is extended and forearm rotated until the radial head fragment is in its most lateral position. A smooth stainless steel Kirschner (K-) wire (typically 5/64″ in diameter) is percutaneously placed along the trajectory of the fracture site. If possible, the forearm is pronated to avoid iatrogenic injury to the posterior interosseous nerve (PIN), which is at risk during this procedure. Commonly, the forearm must be supinated to bring the radial head fragment into appropriate lateral position. In these cases, the pin should enter distally and posteriorly, just off the ulna.

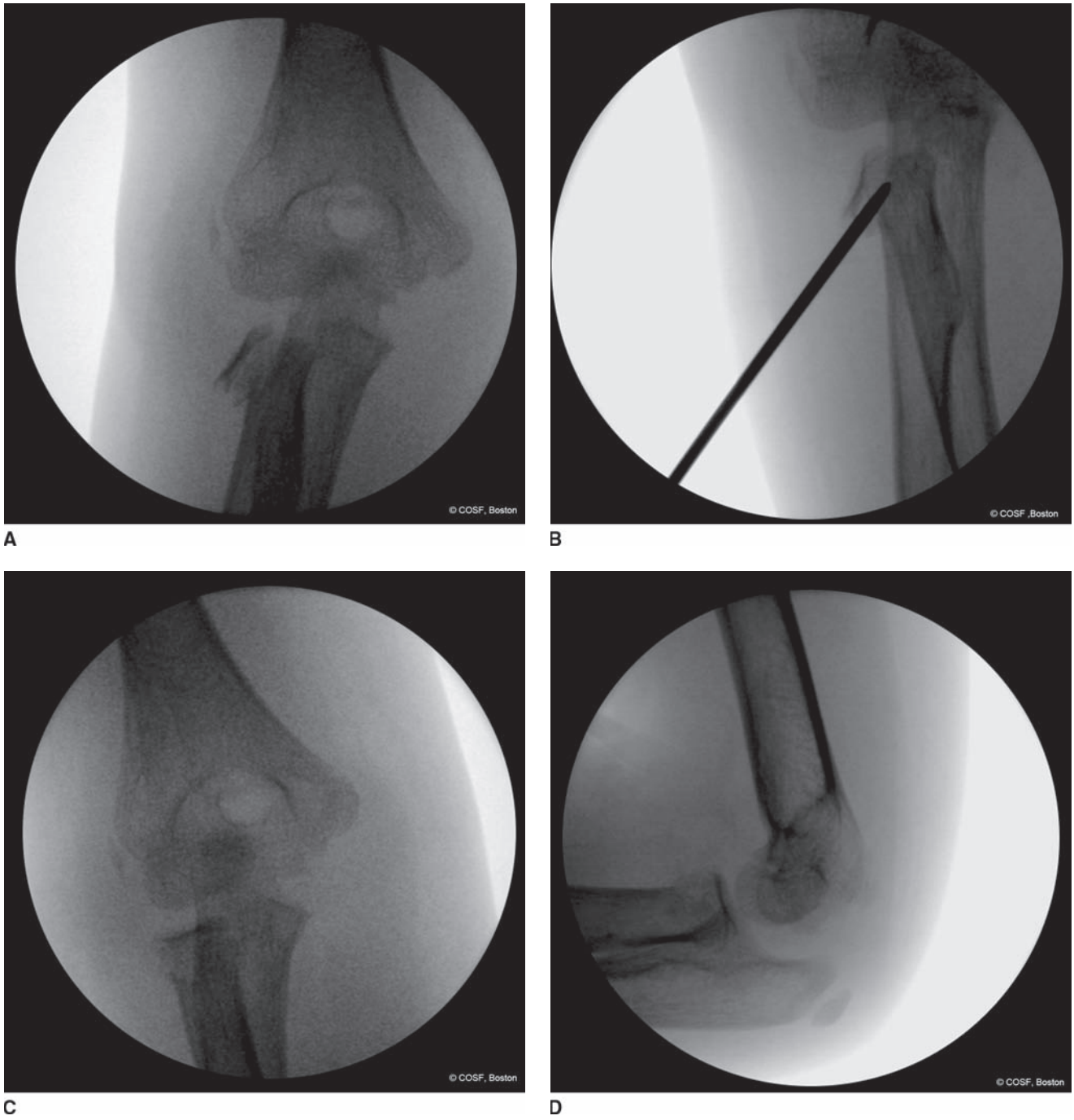

FIGURE 31-3 Percutaneous pin-assisted reduction of a displaced radial neck fracture. **A:** AP radiograph demonstrates significant angulation, and initial attempts at closed reduction were unsuccessful. **B:** A percutaneous pin is inserted and used to lever the fracture and translate the radial head fragment. **C, D:** Subsequent AP and lateral views demonstrate near anatomic reduction.

Two strategies of pin-assisted reduction have been suggested; both are useful. First, the pin may be placed into the fracture site and used to lever the angulated radial head back into position.[26,27] Care should be taken not to violate the far periosteal sleeve, for fear of causing greater fracture instability. Second, the blunt end of the pin may be inserted to push directly against the lateral aspect of the radial head fragment, correcting the translation.[28] Intraoperative fluoroscopy is used to confirm adequacy of reduction and stability with forearm rotation.

A similar percutaneous technique has been proposed by Wallace et al.[29] Again with the elbow extended and forearm positioned to maximally lateralize the radial head fragment, a dorsal incision is made just off the palpable

ulna. A small Freer or periosteal elevator is then placed into the interosseous space with care taken not to disturb the periosteum of the ulna. With direct medial pressure applied to the radial head, the elevator is used to push or lever the radial shaft laterally, achieving reduction. Additional stability may be conferred by percutaneous oblique K-wire fixation of the fracture.

Metaizeau Technique

First described by and still attributed to Metaizeau, retrograde intramedullary titanium elastic nails may be used to both facilitate reduction and provide internal fixation of displaced radial neck fractures (Figure 31-4).[28,30] Under general anesthesia, a small longitudinal incision is made

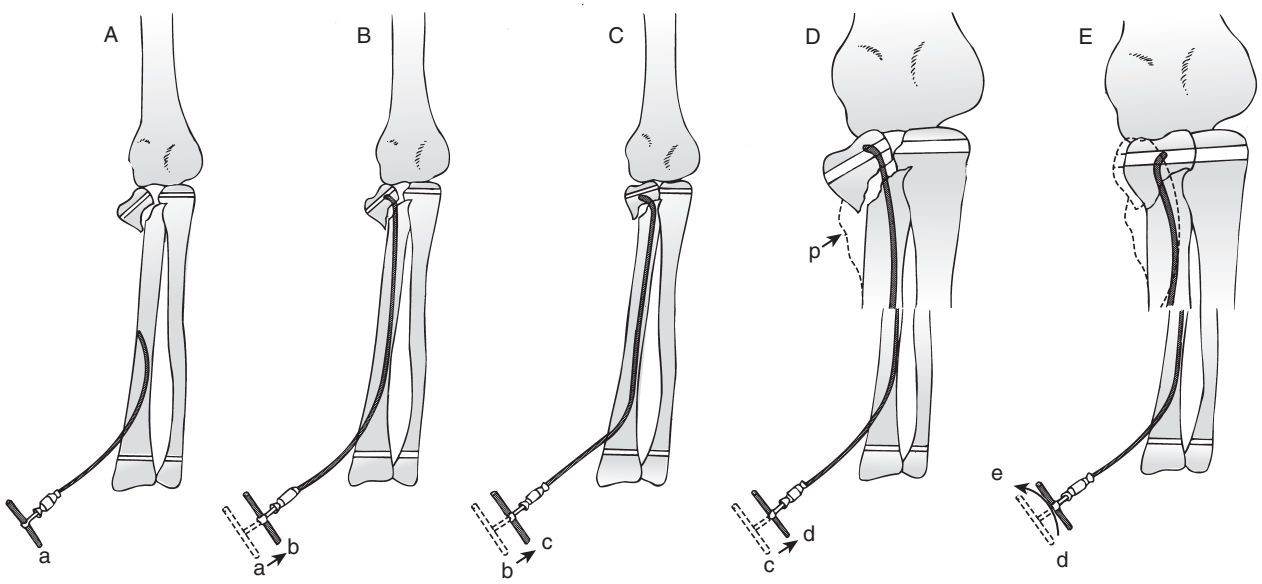

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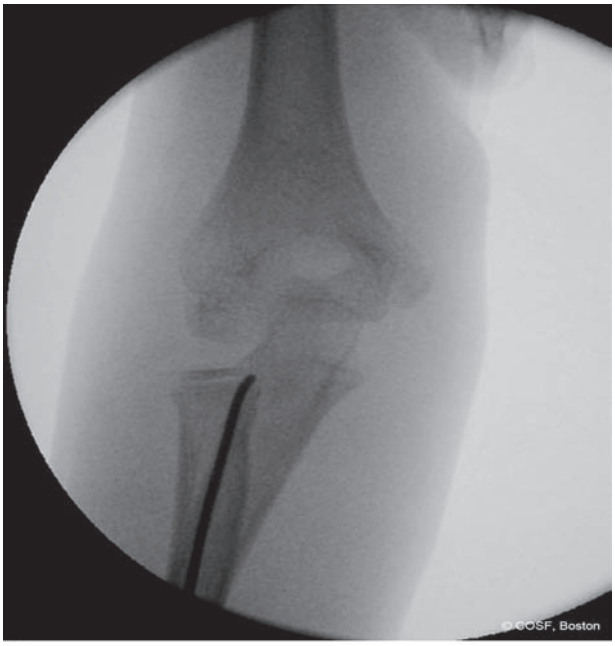
FIGURE 31-4 Reduction and stabilization using flexible elastic IM nails (Metaizeau technique). **A:** Schematic representation of the technique. **B:** Injury AP and lateral radiographs of an 8-year-old female after radial neck fracture.



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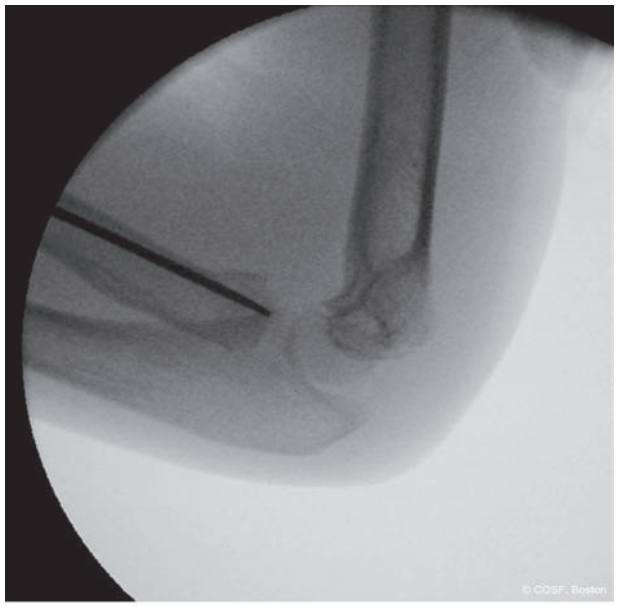

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FIGURE 31-4 *(continued)* **C:** Intraoperative appearance after IM nail passage. The eccentric position of the tip of the implant in the epiphysis is a result of nail rotation used to correct both translation and angulation. (From Beaty JH, Kasser JR. *Rockwood & Wilkins Fractures in Children*. 7th ed. Philadelphia, PA: Lippincott Williams & Wilkins; 2010, with permission.)

along the distal radial metaphysis, just proximal to the physis. Careful spreading is performed in the subcutaneous tissues to identify and retract the radial sensory nerve and adjacent extensor tendons. Periosteal elevation is performed, and a corticotomy is made with a small drill bit, angled from distal radial to proximal ulnar to facilitate subsequent IM nail passage. A small (typically 2 mm) flexible titanium elastic nail (Synthes, West Chester, PA) is then passed in a retrograde fashion within the IM canal until its tip is just distal to the fracture site. Utilizing a bend in the tip of the IM nail (either provided by the implant design or contoured by the surgeon prior to nail passage), the nail is passed across the fracture and engages the radial head fragment. Rotation of the IM nail will then allow for correction of translation and angulation. The IM nail is then briskly tapped to engage the radial head fragment with care taken not to penetrate the proximal articular surface or overdistract the fracture site. The nail is then bent and cut outside the skin, providing internal fixation while facilitating easy removal in 4 weeks.

Open Reduction Pinning

When closed and percutaneous methods fail, open reduction is required. The radial neck fracture is easily exposed via a Kocher posterolateral approach to the elbow, through the anconeus-extensor carpi ulnaris intermuscular interval. Following arthrotomy and evacuation of the hemarthrosis, the fracture is easily visualized. Reduction is performed under direct visualization with great care taken to avoid excessive stripping of the periosteum and soft tissue attachments to the radial head. After reduction is achieved, stability is assessed under direct and fluoroscopic visualization with forearm rotation and elbow flexion-extension. If there is adequate stability, no internal fixation is needed or utilized, which simplifies the procedure and obviates the need for a second procedure to remove the implants.[16] For unstable injuries, fixation can be provided with obliquely placed K-wires, entering the articular margin of the radial head and passing distally across the fracture site, engaging the distal far cortex. These pins are bent and cut beneath the skin, left just outside the joint capsule, and require removal prior to initiation of range-of-motion exercises. Alternatively, if a Metaizeau technique was attempted but failed prior to open reduction, the previously placed IM nail may be used for internal fixation.

We do not advocate the use of transarticular radiocapitellar pinning except in rare circumstances in which the entire radial shaft is displaced anteriorly due to interosseous ligament disruption. Recognition of this unusual situation of separate and unstable displacements of both the radial head and the radial shaft requires careful inspection of the injury and intraoperative fluoroscopic images. If that occurs in the young, a stout smooth pin is placed across the capitellum, anatomically reduced radial head, and into the medullary canal of the anatomically aligned proximal radius. Postoperative immobilization to protect the pin from breakage until removal is mandatory in these rare situations. The option in the older patient is an open reduction internal fixation (ORIF) with a plate and soft tissue repair.

◆ ORIF with Plate

In older patients nearing or at skeletal maturity, or in patients with intra-articular or comminuted radial head and neck fractures, formal ORIF with plate and screw constructs is performed (Figure 31-5). Advantages of plate and screw fixation include the ability to restore articular congruity and provision of rigid fixation to allow early motion.

Under general anesthesia and tourniquet control, a posterolateral approach is made to the radiocapitellar joint, pronating the forearm to avoid iatrogenic injury to the PIN. Arthrotomy is performed and extended distally, allowing for adequate access to the radial shaft while preserving the annular ligament. At times, the annular ligament may require transection for fixation and then repair during closure. Anatomic reduction is performed, and plate and screw fixation applied

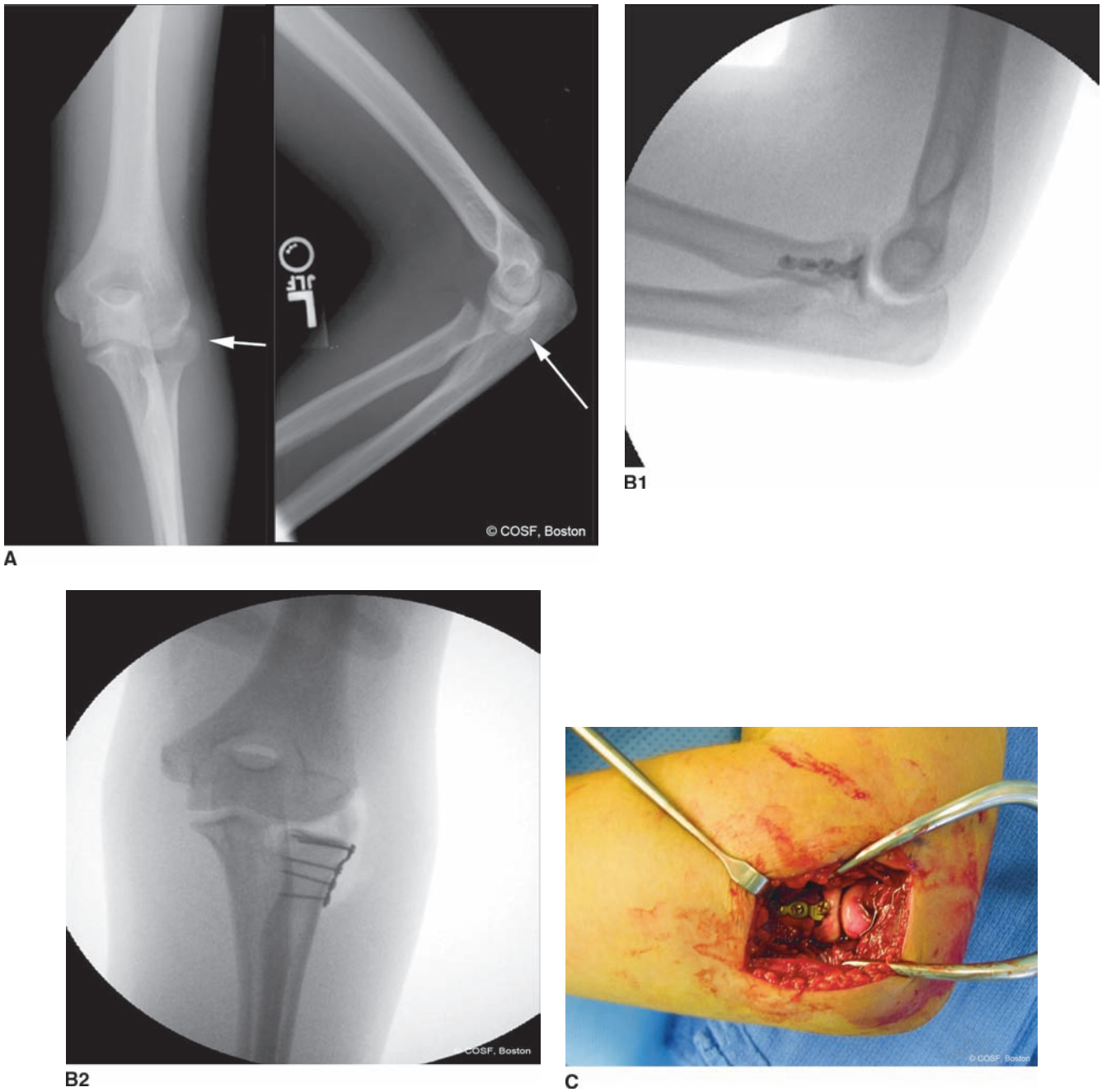


FIGURE 31-5 ORIF of a completely displaced radial neck fracture in a 13-year-old female following a fall off a horse. **A:** Injury radiographs demonstrate a radial neck fracture; the radial head fragment is completely displaced and rotated. **B:** Intraoperative fluoroscopic images depicting fracture reduction and internal fixation using plate and screw constructs. **C:** Intraoperative photograph depicting implant placement in the "safe zone."

in the anatomic "safe zone" (see Sidebar). Choice of implant will depend upon the exact fracture pattern. In general, intra-articular marginal fractures of the radial head may be stabilized using countersunk interfragmentary 2.0- or 2.4-mm screws (Synthes, West Chester, PA). For comminuted fractures of the head and neck, locking plates or mini-blade plates may be used to restore both radial head architecture and fixation of the head to the radial shaft. Following reduction and fixation, full elbow flexion-extension and forearm rotation without implant impingement or fracture instability are confirmed. The capsule and soft tissues are closed in layers, and the limb is immobilized with a long-arm bivalved cast or long posterior splint until adequate wound healing. Early range of motion with hinged elbow brace protection is desired to avoid post-traumatic stiffness.

◆◆ Osteotomy of Malunion

Radial neck malunions—regardless of etiology—may lead to loss of forearm motion, radiocapitellar and PRUJ incongruity, pain, arthrosis, and/or functional limitations. In cases of established malunion associated with functionally limiting pain, stiffness, or joint instability, osteotomy may be performed. Patients and families should be counseled at length preoperatively regarding the risks of osteotomy, including osteonecrosis, nonunion, and persistent pain and stiffness. Preoperative planning is critical, and three-dimensional imaging is helpful to characterize the deformity and determine the best means of correction.

Surgery is performed via a posterolateral approach to the radiocapitellar joint in a fashion similar to standard ORIF of acute fractures (Figure 31-6). The fracture malunion site is identified, along with the apex of angular deformity and position of maximal translation. Cartilage surfaces are identified to assess for arthrosis. Opening wedge, closing wedge, or complete transverse osteotomies may be performed depending upon the pattern of malunion. In general, emphasis is placed on achieving congruent joint reduction and restoring forearm rotation; it is better to leave the proximal radius a little short rather than too long. With effort made to preserve as much periosteum and soft tissue attachments as possible, osteotomy is performed and, when appropriate, autologous cancellous or corticocancellous bone graft placed. Internal fixation is achieved with the use of plate and screw constructs in the "safe zone," ranging in size from 1.5 to 2.4 mm (Synthes, West Chester, PA). Joint reduction and stable forearm rotation are confirmed under direct inspection and with fluoroscopic imaging on the table, prior to wound closure. Brief postoperative immobilization is provided, followed by early, protected range-of-motion exercises in a hinged brace.

◆◆ ORIF of Radial Neck Nonunion

Although rare, nonunions may occur after both nonoperative and surgical treatment of radial neck fractures. Potential contributing factors include periosteal and soft tissue disruption resulting in limited vascularity to the zone of injury, excessive fracture displacement and instability, inadvertent distraction caused by percutaneous or IM fixation, or insufficient immobilization following acute injury. A common factor in nonunions is early pin removal in unstable fractures. Prolonged cast immobilization may lead to eventual union, though the immobilization increases the risk of long-standing stiffness.[31] In patients with radiographic nonunion without pain or functional limitations, we advocate observation with serial (annual) radiographs; patients/families should be counseled regarding the risk of late joint instability and/or arthrosis requiring future intervention. In cases of radial neck nonunion associated with pain, stiffness, or functional limitations, we advocate either radial head excision or ORIF, with or without autogenous cancellous bone grafting.[32]

POSTOPERATIVE

For minimally displaced fractures or fractures treated with closed manipulation, the elbow is immobilized with a long-arm cast. The optimal position of forearm rotation in cast is controversial. We suggest that the forearm be positioned in pronation-supination, which provides the most anatomic reduction of the displaced radial head fragment. Pronation is favored, given the importance of pronation for activities of daily living, as well as the desire to avoid cam impingement in the PRUJ as the radial head is pronated into the lesser sigmoid notch.[16] Serial radiographs are obtained to confirm maintenance of reduction and rule out late fracture displacement. Given the robust healing potential and risk of post-traumatic stiffness, cast immobilization is discontinued after 4 weeks following confirmation of radiographic healing. Range-of-motion exercises are begun, followed by strengthening as tolerated.

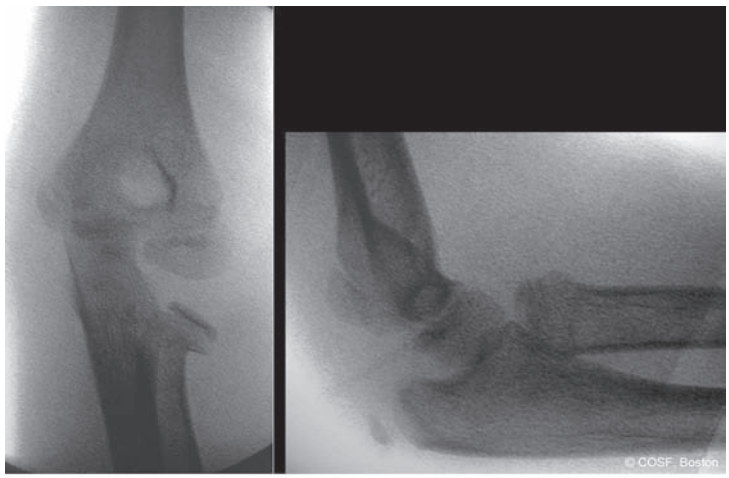
After pin or IM nail fixation, implants are removed at 4 to 6 weeks once radiographic healing is confirmed, followed by range-of-motion exercises.

In cases where rigid internal fixation is employed, early range-of-motion exercises are preferred to avoid post-traumatic stiffness in the compliant patient.

ANTICIPATED RESULTS

All great achievements require time.
—Maya Angelou

With careful preoperative clinical examination and radiographic evaluation, surgical candidates can be judiciously identified. Making every effort to perform the simplest intervention while still achieving the goal of near anatomic alignment and restored forearm rotation, bony healing and functional recovery are expected in the majority of patients. Given the nature of the traumatic injury and the anatomic constraints of the PRUJ, patients and families should be counseled regarding the risk of stiffness despite appropriate nonoperative or surgical care.



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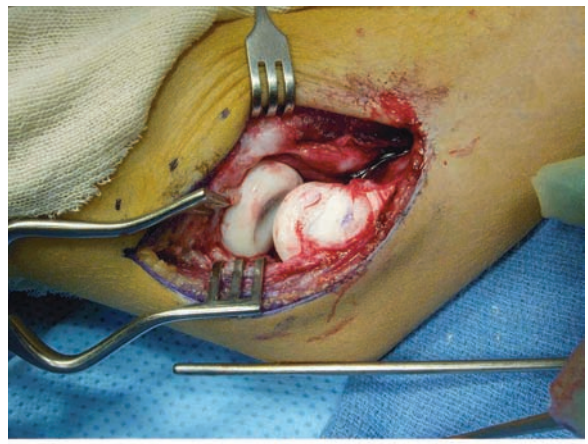

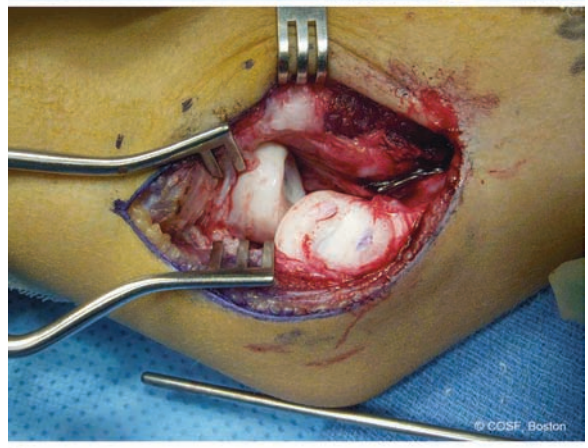

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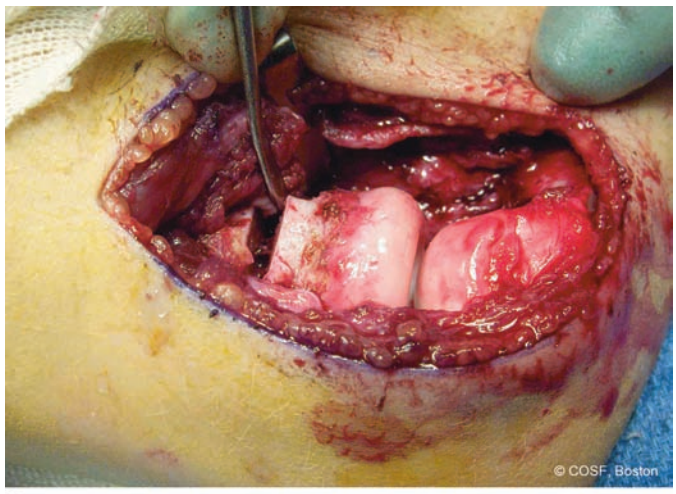

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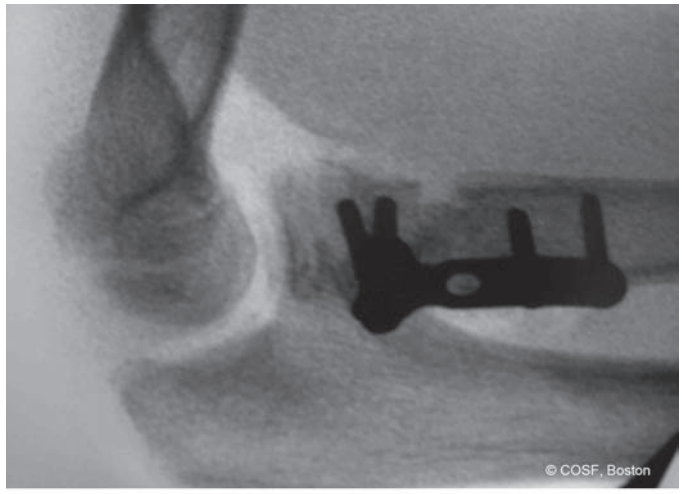

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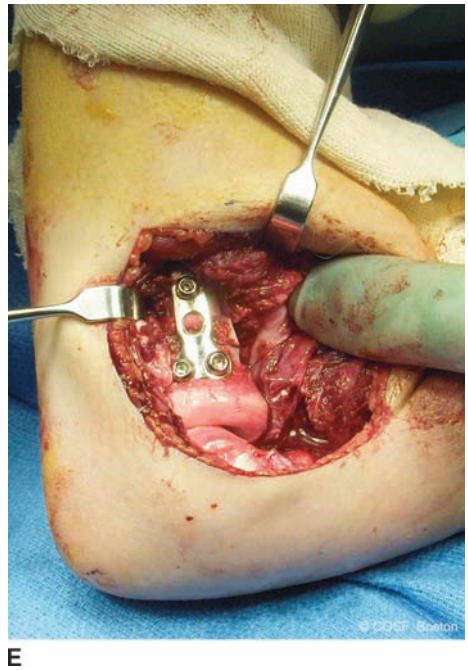

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FIGURE 31-6 Corrective osteotomy for radial neck fracture malunion. **A:** AP and lateral radiographs of a radial neck fracture malunion in a 10-year-old male. Due to fracture alignment and limitations in forearm rotation and pain, the decision was made to proceed with corrective osteotomy. **B:** Intraoperative photographs depicting rotation of the radial head out of the radiocapitellar joint with forearm rotation. **C:** Opening wedge osteotomy is performed at the apex of the deformity. **D:** The defect is bone grafted—in this case with autogenous iliac crest bone—and stability conferred by plate and screw fixation. **E:** Final intraoperative appearance, demonstrating radiocapitellar reduction and implant position.

COMPLICATIONS

Despite the seemingly innocuous nature of radial neck and head fractures, complications are relatively common. The most common complication—perhaps more an expectation than an adverse outcome—is stiffness. Loss of forearm rotation is multifactorial, and contributing factors include fracture displacement and subsequent cam impingement in the PRUJ, scar formation and arthrofibrosis, periosteal bone formation further affecting the highly constrained PRUJ, and primary or secondary radial head enlargement.

Fracture malunion or nonunion can also occur. When functionally limiting or associated with pain or joint instability, surgical reconstruction may be pursued as described above.

Complete or partial physeal arrest may occur following physeal fractures, though clinically meaningful deformity is rare due to the relatively small contribution of the proximal physis to the overall longitudinal growth of the radius.

Osteonecrosis of the radial head is thought to affect up to 20% of patients, particularly after completely displaced injuries or injuries requiring extensive open reductions.[7,8,33] While asymptomatic patients may be cautiously observed, osteonecrosis may lead to pain, collapse, arthrosis, and functional limitations.

Proximal radioulnar synostosis has similarly been reported after radial head or neck fractures. This may be due to the nature of the injury and associated periosteal and soft tissue trauma or may be secondary to excessive dissection or violation of the ulnar periosteum during percutaneous and open reduction maneuvers.

Finally, nerve injuries—most commonly of the PIN—may occur, particularly after percutaneous pin-assisted reduction.[7,34] These injuries are usually transient and resolve spontaneously, though serial clinical evaluations are required to ascertain that recovery is proceeding in a progressive and anticipated fashion.

CASE OUTCOME

Due to this patient's radiographic alignment and limited forearm rotation, the decision was made to proceed with surgical reduction. After initial attempts at closed reduction failed, the radial neck fracture was successfully reduced using percutaneous pin-assisted techniques (Figure 31-3). The elbow was cast immobilized for 4 weeks, followed by range-of-motion exercises. At 3-month follow-up, there was complete radiographic healing and return of full forearm rotation.

SUMMARY

Radial neck fractures may lead to limitations in elbow and forearm motion with excessive angulation or displacement. There is little hope for bony remodeling with continued skeletal growth. In patients with displaced radial neck fractures (over 30-degree angulation, >3- to 4-mm translation) and limited forearm rotation, surgical reduction is recommended. A stepwise progression of reduction (and fixation) maneuvers, beginning with the least invasive and advancing to the more complex, is recommended to achieve the desired clinical result and minimize complications of stiffness, neurovascular injury, or osteonecrosis.

SIDEBAR

The Safe Zone

An ORIF approach to radial head and neck fractures using plate and screw constructs provides a host of challenges to the pediatric hand and upper extremity surgeon. Adequate exposure is needed, iatrogenic injury to the PIN and soft tissue attachments to the radial head avoided, articular congruity restored, and rigid fixation applied. Additional consideration must be made of the proper placement of implants along the proximal radius.

Anatomically, the radial head is ellipsoid in cross section. The margin is covered with articular cartilage, which articulates with the lesser sigmoid notch of the ulna during forearm rotation. Prior cadaveric studies have demonstrated that the arc of articular cartilage encompasses approximately 250 degrees around the radial head.[35,36] This leaves an arc of approximately 110 degrees for placement of implants, the so-called safe zone. The marginal cartilage in this region is typically thinner and more yellow in appearance (Figure 31-7). This safe zone is most easily identified intraoperatively by the 90-degree arc that faces laterally with the forearm in neutral rotation, bordered by the axes of the radial styloid and Lister tubercle. In full supination, the safe zone moves posterolaterally. In general, with the forearm in neutral rotation, implants placed directly lateral will be located within the safe zone and will not impede or restrict forearm rotation.

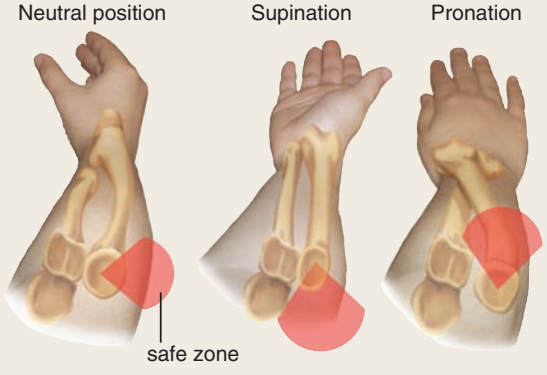
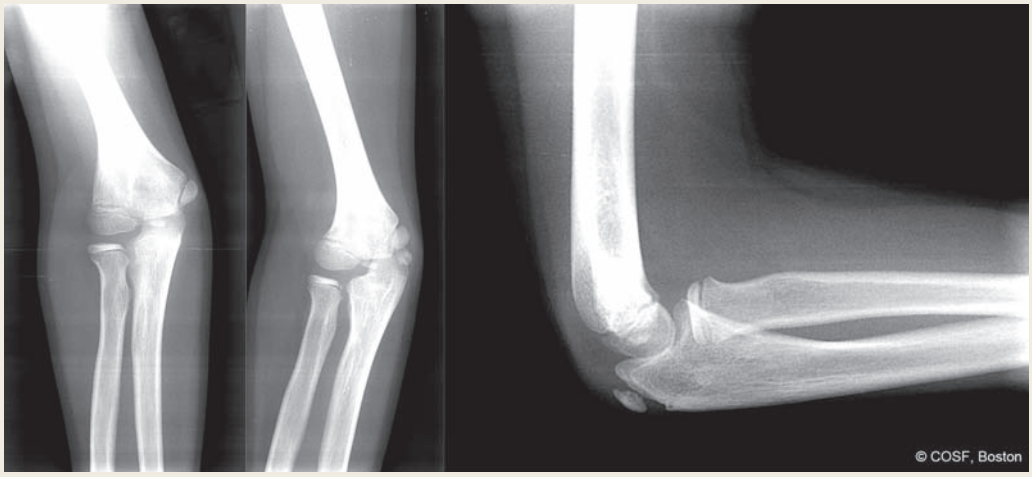


FIGURE 31-7 Schematic diagram of the anatomic "safe zone" for internal fixation of radial head and neck fractures. (From Smith GR, Hotchkiss RN. Radial head and neck fractures: anatomic guidelines for proper placement of internal fixation. *J Shoulder Elbow Surg.* 1996;5:113–117, with permission.)

COACH'S CORNER

Beware of Salter-Harris Type III and IV Fractures of the Proximal Radius

Not all radial head and neck fractures are the same, and Salter-Harris type III and IV fractures of the proximal radius have a few distinctive features that bear mention. First, these injuries are relatively uncommon in relationship to Salter-Harris type I or II fractures, though they do occur in young children and adolescents. Second, initial radiographic findings may be subtle, and it is not uncommon for an initially nondisplaced, intra-articular fracture to be missed at the time of injury. Finally and perhaps most importantly, late radial head subluxation may occur following Salter-Harris type III and IV proximal radius fractures, even in patients with initially nondisplaced injuries (Figure 31-8). While the exact etiology of this is unknown, late instability is likely due to a combination of both loss of bony constraint and concomitant soft tissue or ligamentous injury (particularly the annular ligament). For these reasons, more aggressive imaging and treatment are needed to prevent the pain, stiffness, and arthrosis that result from neglect. If nonoperative treatment is sought, serial weekly radiographs are recommended to rule out late loss of reduction. With articular step-off, joint incongruity, or progressive joint subluxation, prompt ORIF is performed. In the very young, magnetic resonance imaging (MRI) scans may be necessary to accurately make this diagnosis; surgically treat it early to prevent late collapse and joint incongruity (see Chapter 32).



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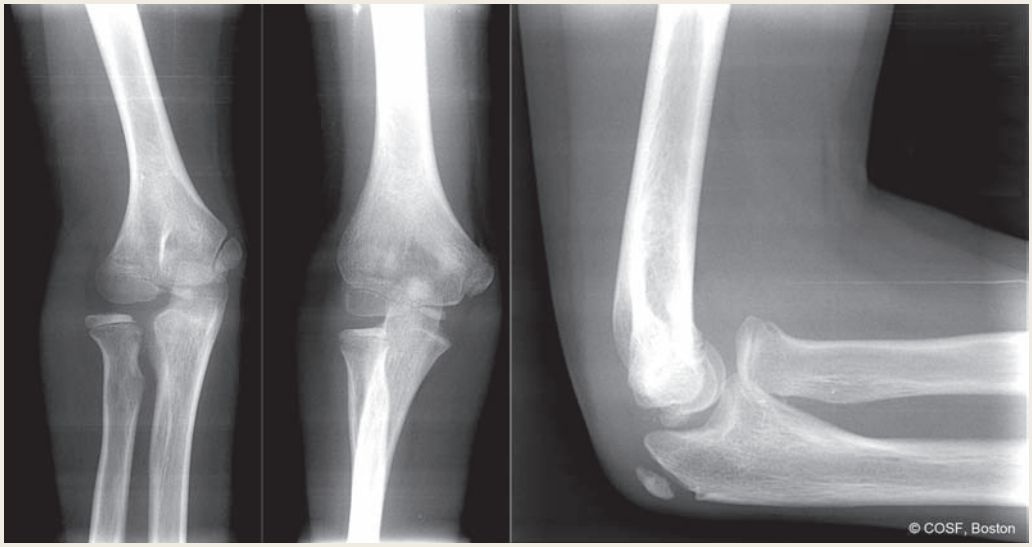
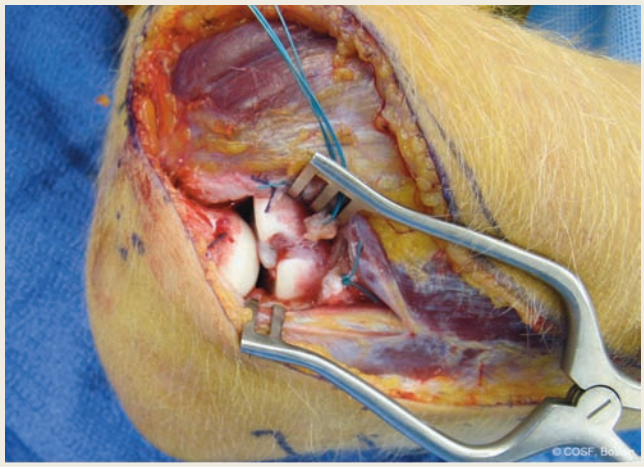


B

FIGURE 31-8 **A:** Initial AP, lateral, and oblique radiographs of an 11-year-old male with right elbow pain after a fall. Radiographs demonstrate a marginal intra-articular fracture of the radial head, well visualized only on the lateral radiograph. The radiocapitellar joint is not anatomic. **B:** Two months later, radiographs depict progressive anterior subluxation of the radius and an incongruent radiocapitellar joint.



C

FIGURE 31-8 *(continued)* **C:** Intraoperatively, findings demonstrate more extensive intra-articular injury and radiocapitellar instability than appreciated by preoperative radiographs.

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CHAPTER

32

Elbow "TRASH" Lesions

CASE PRESENTATION

A 13-year-old male suffered a right elbow fracture dislocation from a fall (Figure 32-1A). He was treated by other orthopaedic surgeons with closed reduction and splint application emergently followed by a mobilization program (Figure 32-1B). He was referred 2 months postinjury due to lack of motion and concern about treatment for a developing elbow contracture. His arc of elbow flexion-extension was 30 to 100 degrees with slight crepitus. Neurovascular status was normal.

CLINICAL QUESTIONS

- What does the acronym "TRASH" lesion mean?
- What does "muffled crepitus" on physical exam indicate?
- What is the significance of an elbow dislocation in a child less than 10 years of age?
- What is the role of ultrasound in the evaluation of elbow trauma?
- When is an MRI scan indicated with elbow trauma?
- How useful are intraoperative arthrograms?
- How aggressive should we be surgically in displaced osteochondral injuries in young children?
- What are the reconstructive options for late-presenting osteochondral malunions?

THE FUNDAMENTALS

Etiology and Epidemiology

Osteochondral fractures and subtle radiographic elbow bone and joint malalignment can be missed by the best of clinicians. The minimal bony ossification in the first 5 years of life (only the capitellum and radial head) and the vagaries and limits of ossification between years 5 and 10 of life (see Sidebar) make plain radiographic diagnosis of some elbow fracture dislocations difficult. Missing these injuries acutely can result in a disastrous elbow functional outcome. Late reconstruction offers more complex challenges yet with more limited surgical options than acute treatment. Thus, the statement, "The Radiographic Appearance Seemed Harmless" yielded the term *TRASH lesion*.[1] These lesions are mostly osteochondral fractures in children less than age 10 years.[2–6] You have to be meticulous in your clinical and radiographic analysis at all times with elbow region injuries and utilize ultrasounds, arthrograms, and magnectic resonance imaging (MRI) scans as diagnostic aids when in doubt.[7,8]

Clinical Evaluation

With TRASH lesions, the history of the trauma (fall off a second-story porch) and/or the degree of elbow region swelling often do not match the radiographic appearance. The lack of ossification in the elbow just does not give you enough information to connect all the dots in order to make the right diagnosis. It is a trap you want to avoid. So, start with the exam. Anytime you have massive swelling and what you think is a pretty normal x-ray, think again. Do not mistake a small fleck of bone as a minor injury. Do not think that a minimal joint malalignment is a minor issue. To paraphrase Dr. John Hall, "TRASH lesions are not like throwing horseshoes. Being close does not count."

If there is restricted, painful motion, or specifically "muffled crepitus" (displaced, unstable cartilage moving against cartilage or bone) with elbow motion, you have to be worried. You need more imaging to find the answer. And, if the injury story does not match the degree of swelling in a very young child, you need to be very concerned about nonaccidental trauma and obtain appropriate scanning radiographs, bone scans, and pediatric and social service consultation.

The specific injuries include (1) transphyseal fractures before capitellar ossification (Figure 32-3) (see Chapter 27); (2) anterior compression fractures of the cartilaginous radial head that lead to posterior radial head subluxation (Figure 32-4); (3) displaced medial condylar fractures before the secondary center of ossification appears (Figure 32-4) (see Chapter 29); (4) plastic deformation Monteggia lesions (see Chapter 30); (5) intra-articular osteochondral elbow fractures (olecranon, radial head, capitellum, trochlea); (6) entrapped medial

FIGURE 32-1 **A:** Radiographs of an elbow dislocation with lateral bony fragments. **B:** Closed reduction radiographs in splint. Note on the lateral view that the joint is not anatomic.

epicondylar fractures[4–6] (Figure 32-5) (see Chapter 29); (7) lateral condylar and epicondylar osteochondral avulsions that represent an unstable lateral collateral ligamentous injury (Figure 32-6); (8) complex osteochondral fracture dislocations with multiple intra-articular fractures; and (9) an elbow dislocation at <10 years of age should make you nervous for multiple sites of injury not always readily apparent on plain radiographs.

Further radiographic evaluation is warranted with these rare injuries.[7,8] You have to know that danger is lurking around the corner. Your referring team of pediatricians, emergency room caregivers, radiologists, and trainees need to be aware of the possibility of missing something important on plain radiographs of the elbow in a young child. Oblique views of the affected elbow and comparison views of the contralateral elbow might be helpful in proper diagnosis or even just increasing your suspicions that something is not right. Ultrasounds have been shown to be helpful with skilled hands (technical part) and eyes (interpretive part). For some clinicians, ultrasounds are mere confusion, and for others, they bring clarity. If you look at a lot of hip ultrasounds for dysplasia, the elbow ultrasound will make more sense to you. The use of MRI scans is extremely helpful for most surgeons, as the MRI images match the anatomy we are used to seeing and on which we base our decisions. Arthrograms are also helpful and used most often in the operating room as a part of both diagnosis and treatment (see Chapter 28, Sidebar). Very good clinicians have missed a TRASH injury and regretted it. Obtaining one or more of these additional radiographic studies acutely, or as a part of an evaluation of a chronic condition, is important for prompt, precise treatment. You

SIDEBAR

Secondary Centers of Ossification about the Elbow

In assessing traumatic injuries about the elbow, it is imperative to know the normal pattern and radiographic appearance of the secondary centers of ossification (Figure 32-2). The capitellum appears first, at 2 months to 2 years. The early appearance of the capitellum secondary center of ossification is why it is used as an indicator of fracture displacement and acceptable reduction alignment (Baumann angle, anterior humeral line, radiocapitellar line, for example). Before the appearance of the capitellum secondary ossification center, elbow bone and joint alignment can only be inferred radiographically or evaluated by ultrasounds, MRI scans, and arthrograms. The radial head appears next at 3 to 6 years of age. The medial epicondyle follows in ossification, at 3 to 7 years of age. The trochlea is next at 7 to 10 years of age, followed by the olecranon apophysis at 10 years of age and the lateral epicondyle at 12 years of age. Thus, we have the mnemonic "CRMTOL" for memorizing the sequence. Girls usually mature skeletally before boys. There are enough vagaries of the secondary ossification centers in terms of timing and appearance (especially the trochlea and olecranon) that clear understanding of the norms is essential to not mistake normal for trauma or, more importantly, assume a traumatic osteochondral lesion is "normal."

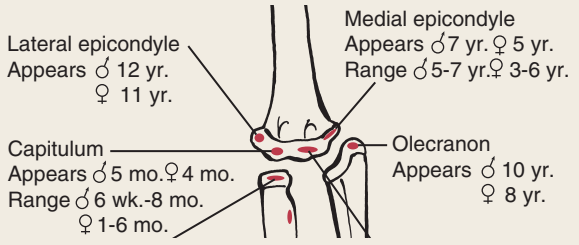

FIGURE 32-2 Secondary centers of ossification sequence of appearance by age and gender (CRMTOL). (From Beaty JH, Kasser JR. *Rockwood & Wilkins Fractures in Children*. 7th ed. Philadelphia, PA: Lippincott Williams & Wilkins, 2010.)

need to know exactly what the problem is before you can make the right decisions on fixing it.

Surgical Indications

The way to get started is to quit talking and begin doing.
—Walt Disney

Whenever the elbow joint is malaligned, anatomic reduction is required. Small osteochondral pieces that block anatomic articular reduction need to be either excised or stabilized back in place. Suture repair of articular flaps or pin or intraosseous screw (absorbable or metallic) open reduction internal fixation (ORIF) of osteochondral articular fractures is indicated and preferred if anatomic alignment and stability are to be restored. Larger intra-articular fragments, such as displaced, unossified medial condylar fractures, require arthrographically assisted, closed reduction percutaneous pinning (CRPP) or ORIF depending on the situation. Entrapped fracture fragments, such as a medial epicondyle with an elbow fracture dislocation, require extraction, anatomic reduction, and stabilization. Unstable osteochondral ligamentous injuries require protection until healed or open repair depending on the situation. Plastic deformation fractures with joint subluxation, such as a Monteggia lesion, necessitate stable fracture and joint reduction. Complex fracture dislocations may require CRPP and/or ORIF of multiple fractures in order to achieve anatomic reduction and joint stability with motion.[3] All in all, aggressive surgery is indicated in TRASH lesions. Treatment of acute Monteggia fractures, medial condylar, lateral condylar, radial neck, and olecranon fractures are covered in their respective chapters.

The most difficult cases are the late-presenting intra-articular fracture malunions (see Chapter 28), missed joint subluxations, and displaced osteochondral fractures.

SURGICAL PROCEDURES

Radiographic Interpretation

Obstacles are those frightful things you see when you take your eyes off the goal.
—Henry Ford

The theoretically simplest part, reading the radiographs properly and ordering additional images and studies, can be the hardest part. Familiarity with normal patterns and vagaries of the appearance of the secondary centers of ossification about the elbow is critical to an accurate diagnosis of each injury radiographic image in the young child (see Sidebar). We have our midlevel providers, medical students, residents, and fellows cover the patient identification information and predict the age of the child on each elbow radiograph based on the secondary centers of ossification present. We want them, and of course ourselves, to be so familiar with elbow images in the young that there is minimal chance of missing a TRASH lesion.

Lateral Collateral Ligament Osteochondral Nonunion

There are some unstable, osteochondral, lateral collateral ligament elbow injuries that are misdiagnosed either as a normal lateral epicondyle secondary center of ossification or a stable bony avulsion injury that will heal without significant intervention. Acutely these patients will be unstable to varus stress. There can be associated ligamentous

FIGURE 32-3 **A:** A 15-month-old infant presenting with marked elbow swelling, limited range of motion, and pain. Plain radiographs reveal soft tissue swelling and suggest extension and valgus malalignment. **B:** MRI confirms suspicions of transphyseal fracture. Orthopaedic treatment was CRPP with arthrogram. Medical treatment included pediatric and social service consults to evaluate for nonaccidental trauma.

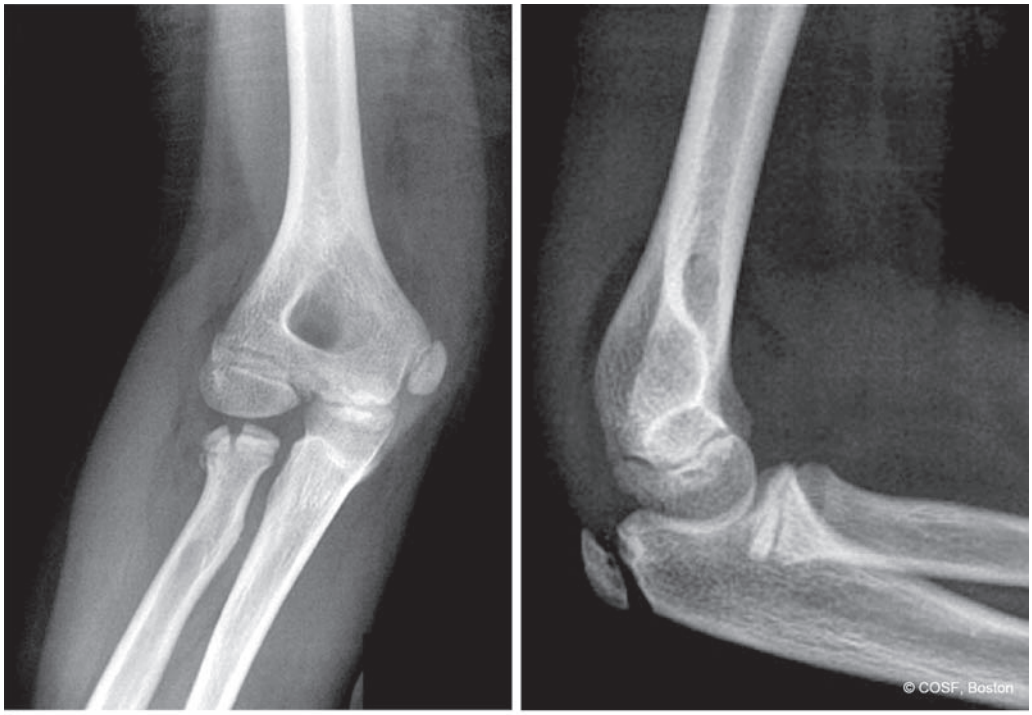

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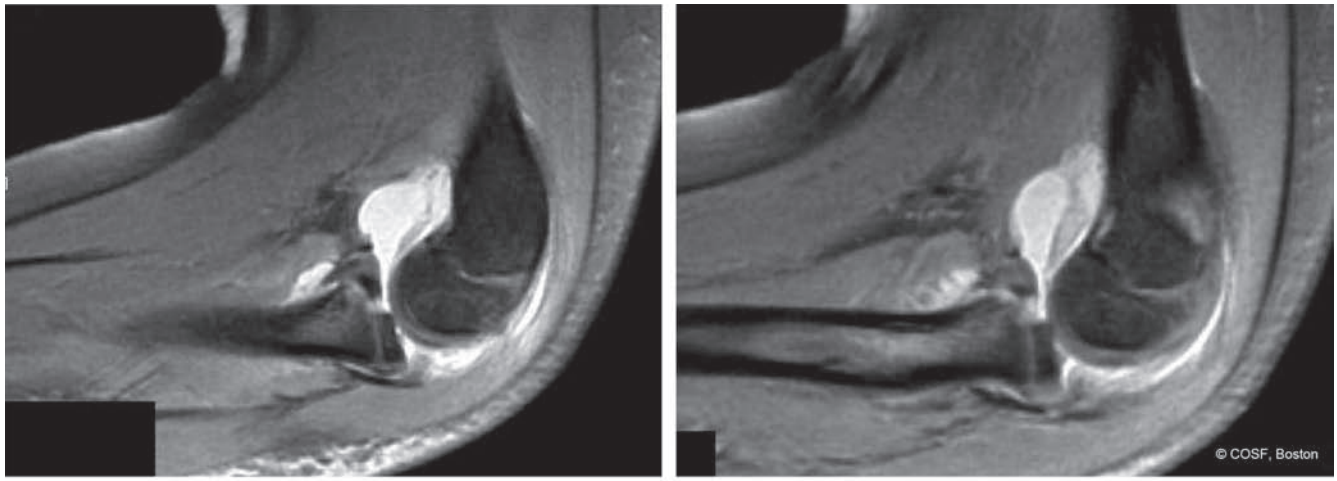
FIGURE 32-4 **A:** Plain radiographs of radial neck fracture. **B:** Initial treatment in emergency care setting was cast immobilization with the opinion that the alignment was acceptable.



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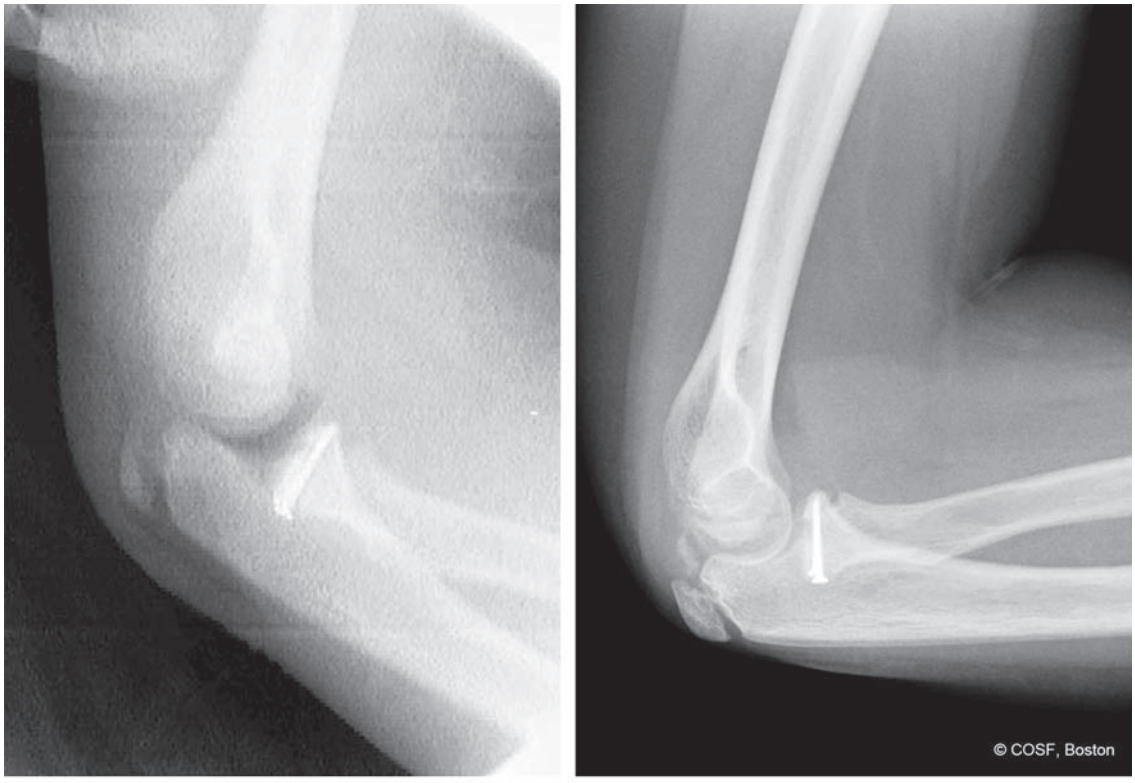


D

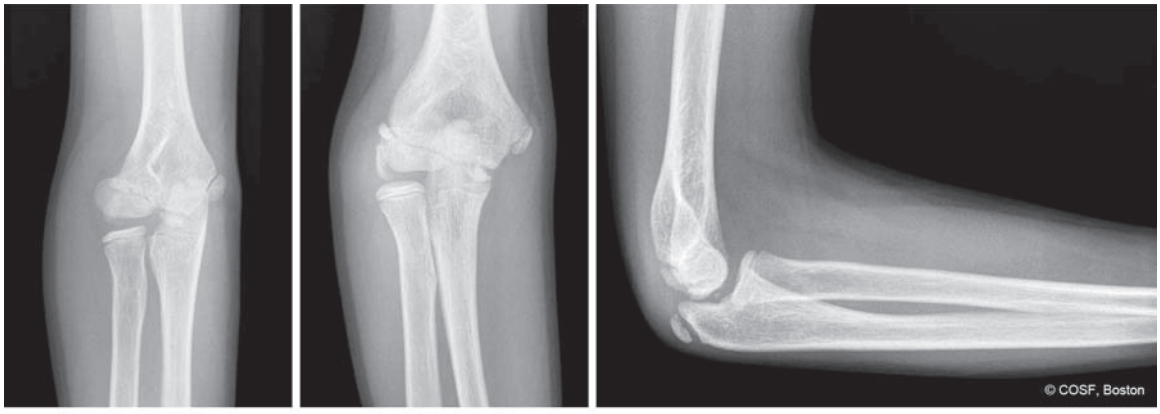
FIGURE 32-4 *(continued)* **C:** Upon referral, concern over joint malalignment with posterior radial head subluxation was confirmed by MRI scan. **D:** ORIF of the intra-articular radial head fracture was performed to anatomically align fracture and joint.

and bony injuries about the elbow. An unstable nonunion can develop if the unstable osteochondral ligamentous injury is not (1) protected until healed or (2) treated with percutaneous fixation or open repair. Physical exam, stress radiographs, and MRI scans will distinguish these injuries from normal or more benign injuries. Later, these patients present with recurrent, activity-based pain and instability. The elbow will be unstable to varus stress, which will reproduce the pain. An MRI scan will indicate the articular alignment size and vascularity of the fracture fragment and status of the lateral collateral ligamentous complex. Stable fixation and repair are required to resolve their problem.

Intraoperatively, the arm is positioned on the fluoroscopic hand table. Under tourniquet control, a straight incision is utilized directly over the lateral condyle. Valgus stress, thumb pressure, and percutaneous pin joysticking are used to reduce the osteochondral piece and displaced collateral ligament. With fluoroscopic guidance, a guide pin for the 3.5- or 4.5-mm cannulated screw system (Synthes, West Chester, PA) is placed either up the lateral column

FIGURE 32-5 Lateral radiograph of entrapped medial epicondyle after closed reduction of elbow dislocation with associated medial epicondylar humerus fracture. Surgical extraction and ORIF of medial epicondylar fracture fragment were performed after later presentation.

or across the transcondylar region (avoiding the joint and olecranon fossa) depending on which provides the most compression and secure fixation. The opposite cortex is penetrated slightly. Standard depth gauge measurement is performed, but the screw length is reduced by 1 to 2 mm to account for osteochondral fragment compression. A partially threaded, cancellous screw and washer are placed. The screw should provide anatomic alignment of the joint and compress the lateral column and collateral ligament back in place. The tip of the screw should just penetrate the opposite cortex with complete screw compression. The elbow should be stable now to varus stress. Additional suturing of the osteochondral fragment and ligament to the periosteum and lateral column soft tissues is rarely needed (Figure 32-6). Full elbow flexion-extension and forearm pronation-supination should occur with ease. The wound is closed and a bivalved long-arm cast applied.



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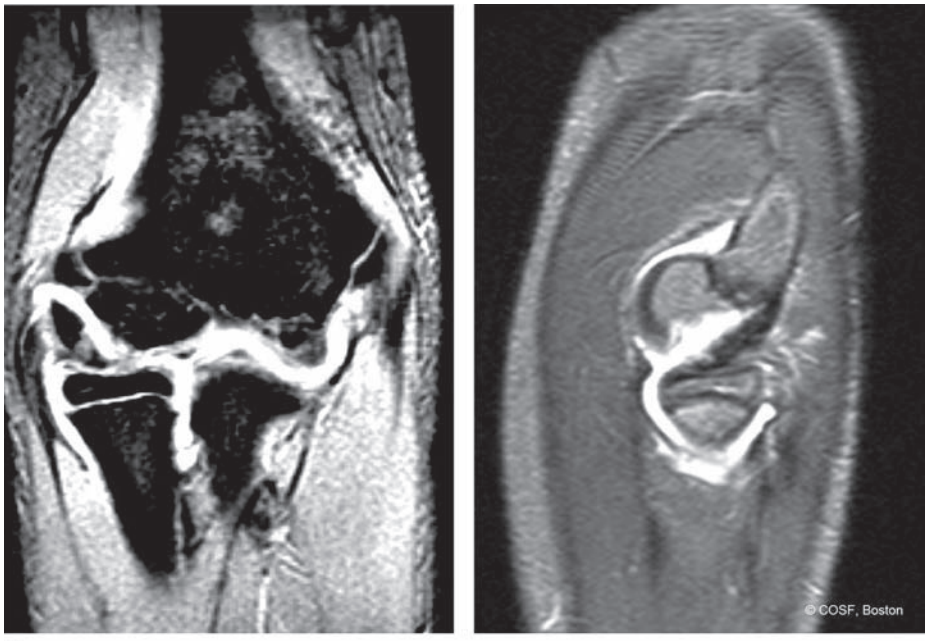
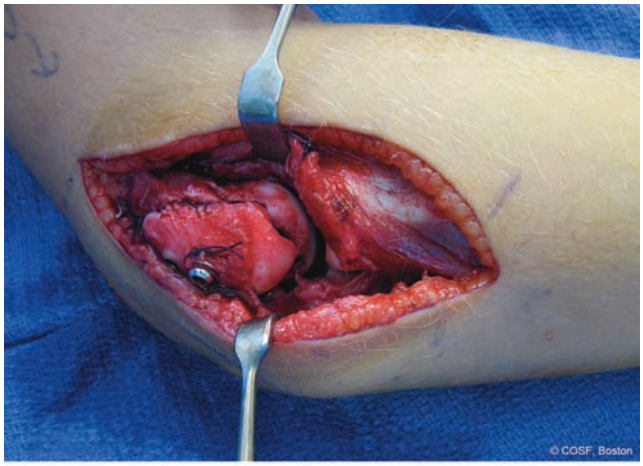


B

FIGURE 32-6 **A:** Late presentation after lateral condylar intra-articular fracture with unstable lateral collateral ligamentous complex. **B:** MRI findings confirm intra-articular derangement but indicate that ORIF with lateral repair will restore joint alignment and stability.



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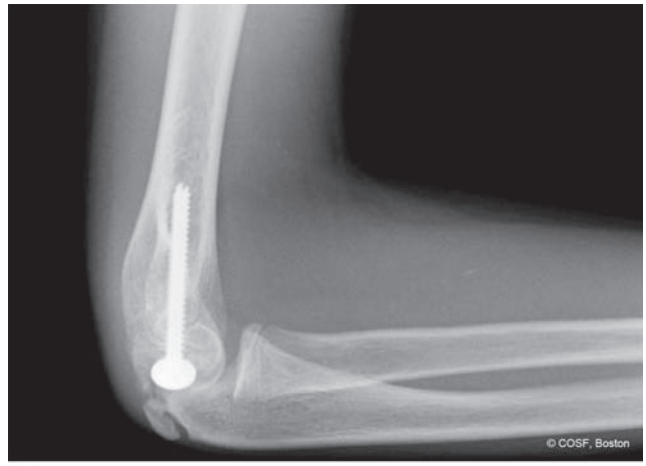

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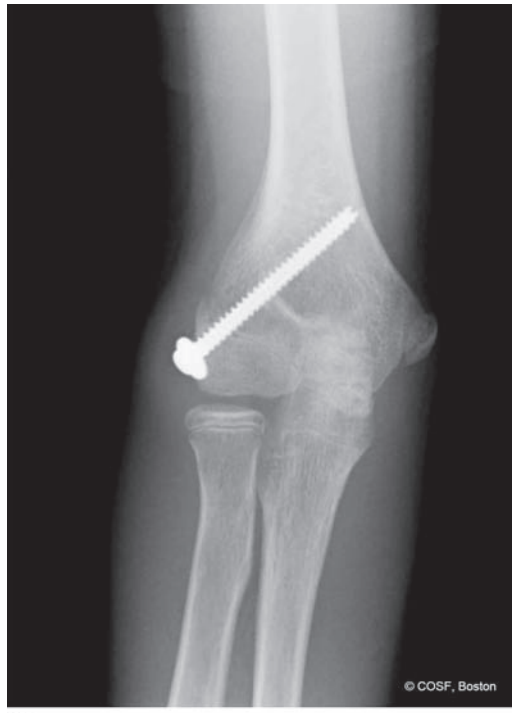


D2

FIGURE 32-6 *(continued)* **C:** Intraoperative photograph of compression screw placement before full tightening of the screw and soft tissue repair. **D:** Postoperative radiographs of repair with healed fragment and stable joint. The screw was eventually removed.

Conversion to a hinged elbow brace occurs between 2 and 6 weeks depending on the patient's age, risk of stiffness, and ability to comply with a postoperative program.

Arthroscopic Debridement of Articular Flaps and Osteochondral Loose Bodies

There are some patients with minor, symptomatic articular flaps and malunions that will respond to arthroscopic debridement. These patients are consented for a progressive ladder of surgical care (arthroscopic exam > arthroscopic debridement > open reduction osteochondral fragment > intra-articular osteotomy or radial head excision or unloading osteotomy depending on the situation). However, many respond to simple arthroscopic debridement of the synovitis, excision of loose bodies, and trimming of the articular flap back to a stable base (see Figure 28-12) (see Chapter 41 for elbow arthroscopy techniques). The technical part of debridement is not difficult. The challenge is the clinical judgment to know which situations will respond to arthroscopy versus a more complex surgery. Simply put, make the surgery fit the problem, and, when in doubt, give the easier solution a chance. (Of course you have to take on the tougher problems with bigger surgery and not waste people's time, money, and hope.) When the arthroscopic surgery is completed, we advise the family that this may not work or that it may only last for 1 or 2 years. Fortunately, with the minor articular flaps and osteochondral fragments, arthroscopic debridement can bring resolution of activity-based pain and limits.

◆◆ Late Medial Condylar Fracture Malunions

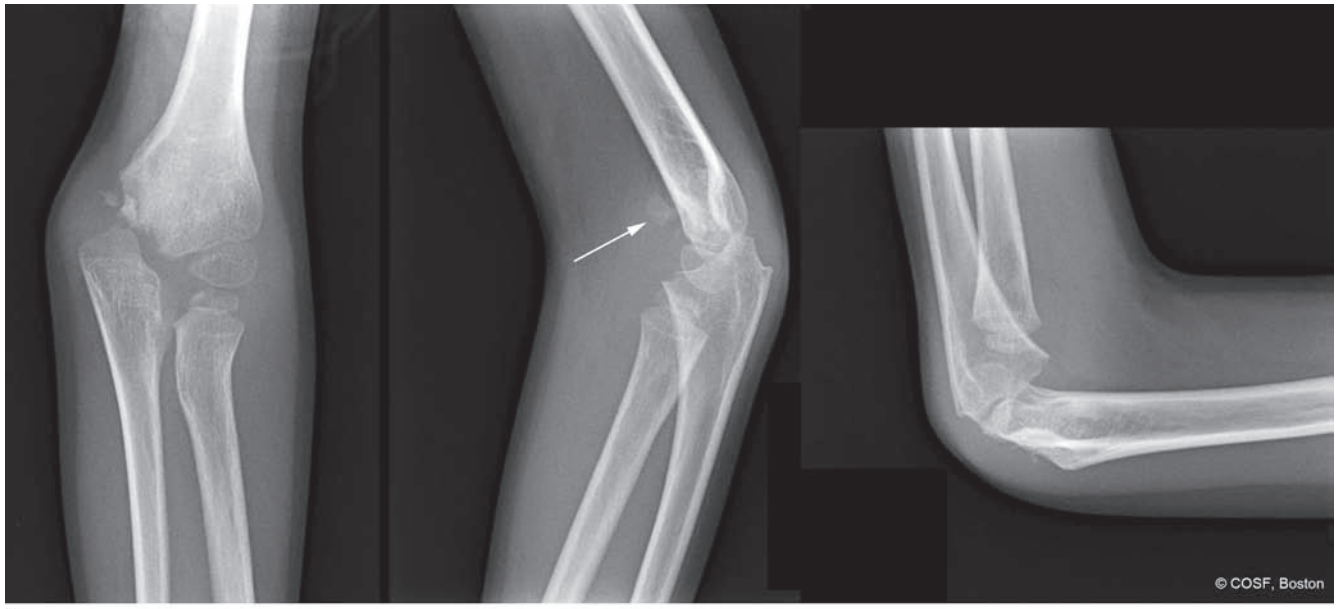
Live as if you were to die tomorrow. Learn as if you were to live forever.
—M. K. Gandhi

Missed medial condyle fractures are a major problem. The trochlea is displaced medially and anteriorly. The degree of articular incongruity is marked. The restriction of elbow motion is profound. It is amazing these children do not writhe in pain on a daily basis, particularly those who have spent hours in therapy and been judged uncooperative due to their failure to regain motion. When medial condylar fracture malunions present late, the options are (1) leave it alone because surgery can only make it worse, (2) perform a late open reduction (Figure 32-7), (3) excise the distorted fragment and perform an interposition arthroplasty, and (4) include a valgus osteotomy to unweight the medial side of the joint.

At present, there is no evidence except experience and surgical skill for the best choice. (We always hope it will come soon, but in the meantime we all have to choose.) In young children with painful restriction of motion and function, we opt for aggressive surgery if we think we can improve the situation. We know the natural history is very poor. Multiple plain film views, Computed tomography (CT) scans including three-dimensional reconstructions, and MRI scans are all necessary to determine if the fracture fragment is reducible and reconstructable. Ultimately, the decision for open reduction or distraction arthroplasty is made at the time of surgery.

An extensile anteromedial incision is utilized. Since the medial epicondyle is displaced with medial condyle, the ulnar nerve is in a distorted position. Similarly, the brachial artery and median nerve may be compressed beneath the fracture fragment. Finally, the brachial and antebrachial cutaneous nerves will be tented and displaced. After broad elevation of skin flaps, the cutaneous nerves are isolated and tagged with elastic loops. The ulnar nerve is identified proximally and carefully dissected distally. The nerve can be quite compressed and flattened. If it is not identified proximally and mobilized, there is no doubt it can be injured or even lacerated by a limited, local exposure. After the ulnar and cutaneous nerves are isolated and carefully mobilized out of harm's way, a 25-gauge needle is used with fluoroscopic guidance to find the superior edge of the medial condyle and the elbow joint. The superior-medial edge of the fracture site is entered and mobilized while preserving the flexor-pronator muscle mass and medial collateral ligament attachments to the medial condyle and epicondyle. If preoperative planning and direct and fluoroscopic visualization have indicated an open reduction is feasible, then the medial condylar fragment is mobilized from the inside out. The locations of the median nerve and brachial artery have to be accounted for during this part of the procedure. Progressively, you will get a better and better view of the joint from above. The medial condylar fracture has to be freely mobile in order to be anatomically reduced. The inside of the joint will require debridement of fibrous tissue, fracture callus, and synovitis. There may be thin articular flaps that are either debrided or preserved; the fragment will have some avascular necrosis centrally that may require debridement and potentially allo- or autografting after fragment reduction. Cannulated guide pins or smooth C-wires are placed in the medial condylar fragment in the correct orientation for anatomic joint alignment and pin and/or screw placement. The medial condylar fragment is reduced with direct and fluoroscopic visualization. Being certain that the fragment is correct in angular and rotational orientation is difficult because as you reduce the piece, you lose most of your direct view. Patience and perseverance are required. When reduced, a large compression clamp is placed from medial to lateral condyle. Joint alignment is checked and rechecked. The pins are driven across from medial to lateral. The pins should cross parallel to the joint below the olecranon fossa and up the medial column. A partially threaded compression screw of appropriate size and washer is used. Additional pin fixation is performed as necessary for stability. Full elbow motion should now be feasible. If it is not, there is a problem with the reduction, implant positioning, or both. Keep at it until you get it right. Bone grafting of any metaphyseal gap is performed. Soft tissue repair of the flexor-pronator mass and ulnar nerve transposition away from the hardware are performed to provide additional medial-sided stability, vascularity to the fracture fragment, and protection of the nerve. Again, full, stable motion should be possible at this stage as well. If not, resolve the instability or restriction of motion problem now. Sequential closure is performed after checking the safe positioning of the nerves and implants. Postoperatively, the goal of achieving anatomic bone and joint healing far outweighs the desire for early motion.

If the medial condylar fragment is too distorted and will no longer fit back in place, excision of the fragment followed by an interposition arthroplasty is performed. After indentifying and isolating the cutaneous, ulnar, and median nerves and the brachial artery, the fragment is excised subperiosteally from the inside out. The flexor-pronator origin and medial collateral ligament complex are meticulously detached by sharp Beaver blade and curved elevator dissection. The medial condylar fragment is completely excised while preserving the integrity of the soft tissue attachments. The elbow joint is opened with valgus stress; inspected for osteochondral injury; and debrided of synovitis, osteochondral flaps, and loose bodies. The flexor-pronator muscle mass is inserted into the trochlear gap and medial joint space, and the olecranon is reduced. Temporary sutures are placed, and then motion and stability are tested. If the joint drifts too much into varus, a valgus osteotomy of up to 20 degrees is necessary. The valgus osteotomy can be performed as a medial opening wedge within the same incision using the excised medial condylar fragment as a bone graft. Pin fixation is performed



A

B

C

FIGURE 32-7 **A:** AP, oblique, and lateral radiographs of chronically displaced medial condylar humerus fracture of a 6-year-old male. The arrow on the lateral view outlines a small bony fragment that represents the entire chondral joint fragment. **B:** MRI revealing entire medial condylar articular fragment is displaced superiorly and anteriorly. **C:** ORIF of chronic malunion with hybrid screw and pin fixation.

under direct and fluoroscopic visualization and palpation. Completion of the suturing of the interposition arthroplasty (with or without valgus osteotomy) is performed. Joint protection is either by crossing smooth C-wires or external fixation depending on the age of the patient. The joint is statically held reduced for approximately 4 weeks until there is sufficient soft tissue healing.

POSTOPERATIVE

Each of these operations is unique enough that the postoperative care varies widely. Restoration of motion has to be balanced with joint stability. Most straightforward pediatric elbow injuries heal quickly, and postcast treatment elbow stiffness is not a concern. More complex

intra-articular injuries are at risk for permanent contracture development, and so early motion is started if the fixation is stable. With reconstruction of misdiagnosed or mistreated elbow injuries in the young, achieving both elbow motion and stability can be difficult. In those cases, stability of the bone and joint reconstruction should be prioritized. In the end, if the joint is anatomically reduced and stable and the bone heals in proper anatomical alignment, then the lack of motion can be dealt with separately (see Chapter 29 for elbow joint contracture release).

ANTICIPATED RESULTS

What you get by achieving your goals is not as important as what you become by achieving your goals.
—Zig Ziglar

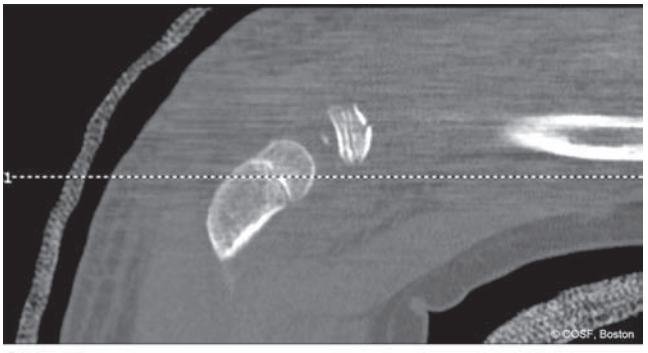
Our best anticipated results are that TRASH lesions are recognized early before they indeed become harmful. Our goal is the highest level of awareness to prevent (1) these injuries from being missed diagnostically in the acute setting and (2) complacency of thought and action ("all pediatric fractures heal well with simple care") that prevents caregivers from being appropriately aggressive in fixing all elements of a complex intra-articular injury in young children.

COMPLICATIONS

The missed or mistreated TRASH lesion is the complication. Beyond that, the complications relate to either not making a complex situation better or even making it worse, with surgical or nonsurgical care. Anything and everything bad can happen with late reconstruction of a TRASH lesion. If you and your professional colleagues start at the beginning, accurately make the diagnosis, and provide outstanding acute treatment,[9,10] then you will be less likely to have really difficult problems (that can even get more complicated) to care for.[11]

CASE OUTCOME

Review of the patient's radiographs was concerning for lack of congruent reduction of the elbow joint. (Figure 32-1). The presumption was that the joint was never fully reduced and that there were osteochondral loose bodies and soft tissue interposed. This was confirmed by CT (Figure 32-8A) and MRI scans. The osteochondral loose bodies were removed by a combined arthroscopic (Figure 32-8B) and open procedure. The joint was anatomically reduced and stable. He was restarted on therapy.



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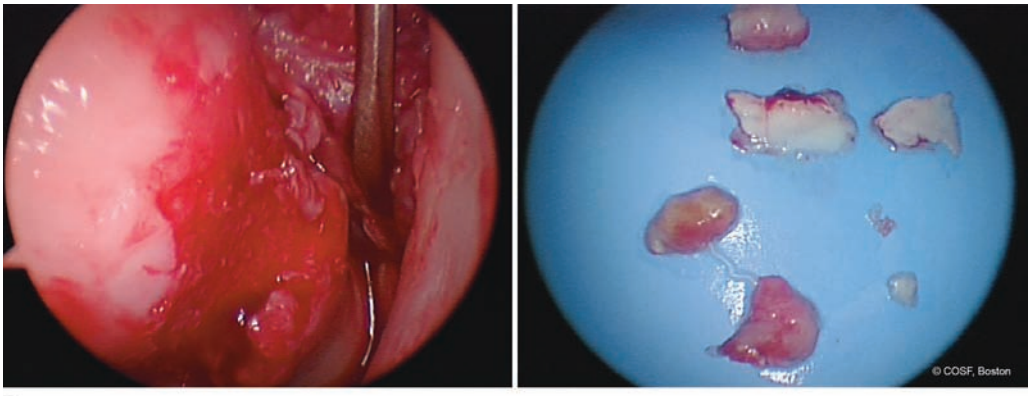

B

FIGURE 32-8 **A:** CT scan 2 months postinjury revealing an osteochondral fragment proximal to subluxed radial head. **B:** (B1)Arthroscopy of elbow joint with incongruity, hematoma, and interposed tissue. (B2)Loose osteochondral fragments that were removed allowing for anatomic joint reduction.

SUMMARY

The conditions known as TRASH lesions are major but radiographically subtle intra-articular elbow injuries usually occurring in children less than age 10 years. The lack of secondary ossification in the young can lead to misdiagnosis, mistreatment, or both, with medial condylar fractures before the secondary center of ossification appears; osteochondral fractures of the radial head, olecranon, and/or lateral condyle; joint malalignment from missed Monteggia lesions and entrapped medial epicondylar fracture dislocations; and complex, unstable elbow fracture dislocations. Comparison and stress views, ultrasounds, arthrograms, and CT and MRI scans are all helpful in prompt diagnosis and precise, anatomic treatment.

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CHAPTER

33

Forearm Fractures

CASE PRESENTATION

A 10-year-old male presents for evaluation of forearm pain after a fall off a skateboard. He denies any distal numbness, weakness, or tingling. Examination demonstrates obvious deformity of the forearm and a small volar ulnar 1-cm wound. The hand is well perfused, and grossly he is neurologically intact in the radial, ulnar, and median nerve distributions. Radiographs are shown in Figure 33-1.

CLINICAL QUESTIONS

- How common are diaphyseal forearm fractures in children and adolescents?
- How are diaphyseal forearm fractures classified?
- What are the maneuvers used for closed reduction of displaced incomplete and complete forearm fractures?
- What are the limits of radiographic deformity that will remodel over time?
- What are the indications for surgical treatment?
- What are the surgical approaches and techniques used for internal fixation of diaphyseal forearm fractures?
- What are the complications of forearm fractures and their surgical management?
- What are the indications and techniques for deformity correction in diaphyseal forearm fracture malunions?
- What are the anticipated results of surgery?

THE FUNDAMENTALS

Forearm fractures are among the most common injuries requiring surgical care in children.[1,2] Despite established treatment principles and advances in surgical techniques, forearm fractures continue to present clinical challenges, even to the pediatric hand and upper extremity surgeon. There is a wide spectrum of fracture pattern and presentation, a host of nonoperative and surgical treatment options, constant consideration of skeletal growth and remodeling potential, and ever-changing patient and family expectations. Historically, almost all pediatric forearm fractures were treated nonoperatively with closed reduction and cast immobilization. However, treatment patterns continue to evolve, perhaps due to increasing awareness of patient-derived functional outcomes; desires for more expedient return of motion, strength, and sports participation; and improvements in technical abilities. Understanding of the treatment principles and mastery of surgical techniques is essential for the pediatric hand and upper limb specialist (see Sidebar).

Etiology and Epidemiology

Forearm fractures occur in approximately 1:100 children each year.[2] When distal radius and ulna fractures are

A B

FIGURE 33-1 Anteroposterior (AP) and lateral radiographs of a grade I open forearm fracture in a 10-year-old male.

SIDEBAR

Molds and Burns: The Lost Art of Casting

Pediatric hand and upper extremity surgeons must not only possess surgical skill but also expertise in nonoperative fracture care. In the age of emerging technologies and increasing choice of surgical approaches, implants, and techniques, the merits of cast immobilization cannot and should not be forgotten. Indeed, perhaps more important than techniques of achieving reduction or methods of internal fixation is proper cast application.

In appropriate patients, successful closed treatment of diaphyseal forearm fractures involves application of a well-molded cast. As Mercer Rang and others have taught us, there are several elements to a properly molded cast (Figure 33-2). First, a three-point bending mold should be applied to maintain angular correction. Second, an interosseous mold should be applied to preserve the interosseous space, with care taken to ensure that the AP diameter is greater than the lateral. Third, a straight ulnar border should be maintained to ensure ulnar alignment and an acceptable aesthetic result. Finally, a supracondylar mold above the flexed elbow will help to prevent cast migration, particularly in the very young patient.

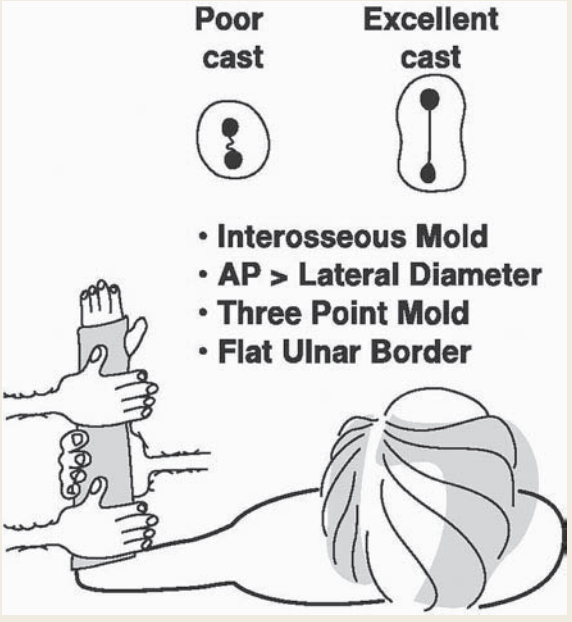


FIGURE 33-2 Schematic diagram of the elements needed for effective cast immobilization. (From Wenger DR, Pring ME. *Rang's Children's Fractures*. 3rd ed. Philadelphia, PA: Lippincott Williams & Wilkins; 2005.)

Any cast applied will eventually need to be removed, and often a cast will need to be bivalved shortly after application to accommodate soft tissue swelling. While seemingly straightforward, cast removal may result in lacerations or thermal injuries during inappropriate cast saw use.[56–59] In the pediatric population, risk is particularly high, as casts are bivalved or removed in the nonverbal, sedated, or anesthetized patient, who cannot communicate pain or discomfort. This is an entirely preventable complication and one we feel should never occur.

Both common sense and published information inform us that cast saw injuries may be avoided by a number of simple preventative interventions. Adequate cast padding of at least three to four layers should always be applied. When applying plaster casting material, excessive thickness and higher ambient dip water temperatures (>24°C) should be avoided. Sufficient time should be allotted to allow plaster material to cure and cool before fiberglass material is overwrapped. Oscillating cast saws should be kept sharp, with frequent cooling during use to avoid thermal skin injury. With these simple steps, cast saw injuries may be prevented.

considered separately, diaphyseal forearm fractures represent the third most common long bone fracture in children, following distal radius and supracondylar humerus fractures.[1] The forearm is the most common site of open fractures of the upper extremity and the most common location of refractures in the pediatric patient population.[3] Peak age of incidence is between 12 and 14 years of age, perhaps due to the combination of rapid skeletal growth and increased sporting and high-energy activities.

The mechanism of injury is usually a fall onto an outstretched upper extremity, imparting axial, rotational, and/or bending forces to the radius and ulna. The position of the forearm and the forces applied determine the fracture pattern. Bending injuries typically cause same-level radius and ulna fractures, while rotational forces result in fractures at different levels. With higher energy mechanisms of injury, greater degrees of soft tissue injury occur, leading in some cases to ligamentous disruption and open fractures.[4–6]

Clinical Evaluation

Patients will present with pain, swelling, deformity, and limited forearm motion. Circumferential inspection of the limb should be made to assess for wounds or lacerations suggestive of open fractures. Palpation and evaluation of the elbow and wrist should similarly be performed, as tenderness or deformity may indicate adjacent joint injury or concomitant fractures. The vascular and neurological status should be systematically examined to rule out associated vascular injury, nerve palsy, or impending compartment syndrome.[7–9]

Standard AP and lateral radiographs of the entire forearm are performed in all cases of suspected forearm fracture and will confirm the diagnosis. Systematic evaluation of the wrist and elbow should be performed, even in the setting of known bony injuries. Information regarding

rotational alignment of the radius and ulna can be derived from the position of bony landmarks. On AP projections, the radial styloid lies 180 degrees opposite the bicipital tuberosity; on the lateral projection, the ulnar styloid is also positioned 180 degrees from the coronoid process. Even using these radiographic landmarks, malrotation is difficult to quantify using radiographic indices and may be within 45 degrees of accuracy.[10,11]

Forearm fractures are classified according to anatomic location (proximal, middle, or distal thirds), fracture displacement and angulation, and fracture pattern. In general, three patterns occur in skeletally immature patients: plastic deformation injuries, greenstick (incomplete) fractures, and complete fractures. Each fracture pattern has its unique anatomic features and treatment considerations.

Radiographically, plastic deformation, or traumatic bowing, presents as bones that are "bent but not broken."[12] Typically affecting younger patients under 10 years of age, there is often little clinical deformity, swelling, ecchymosis, and/or tenderness. Forearm rotation, however, will be limited. Radiographic findings may be subtle, characterized by abnormal curvature of the radial and/or ulnar shafts in association with narrowing of the interosseous space. An understanding of the normal radiographic appearance of the radius and ulna, and in particular the normal radial bow, is imperative in identifying plastic deformation injuries[13] (Figure 33-3). Depending on the severity of the plastic deformation, the physical exam in patients with these injuries ranges from subtle motion and aesthetic differences, to a block to rotational motion, and an S-shaped forearm grossly. Identification of the injuries with limited motion acutely is important for a positive long-term outcome.

Greenstick, or incomplete, fractures result from torsional and bending injuries in younger children. Radiographically, one cortex is disrupted while the other cortex remains intact or is plastically deformed. Due to the inherent stability conferred by the intact cortex, closed reduction and cast immobilization remain the standard of care.

Complete fractures are those in which there is complete cortical disruption. These injuries are akin to their adult counterparts in mechanism of injury, clinical presentation, and radiographic appearance.

Because the ulna is subcutaneous in location and straight in alignment, ulnar deformity results in aesthetic differences. Conversely, radial malalignment is less visible but results in loss of forearm rotation. While loss of pronation is well compensated for by shoulder abduction, forearm supination loss is poorly tolerated due to the blocking effect of the thorax with attempted shoulder adduction to bring the palm in an upward position.[11] Multiple published series have demonstrated that diaphyseal fracture malunions contribute to loss of forearm rotation and functional impairment.[11,14–16] Cadaveric studies have demonstrated that <10 degrees of angulation results in little if any

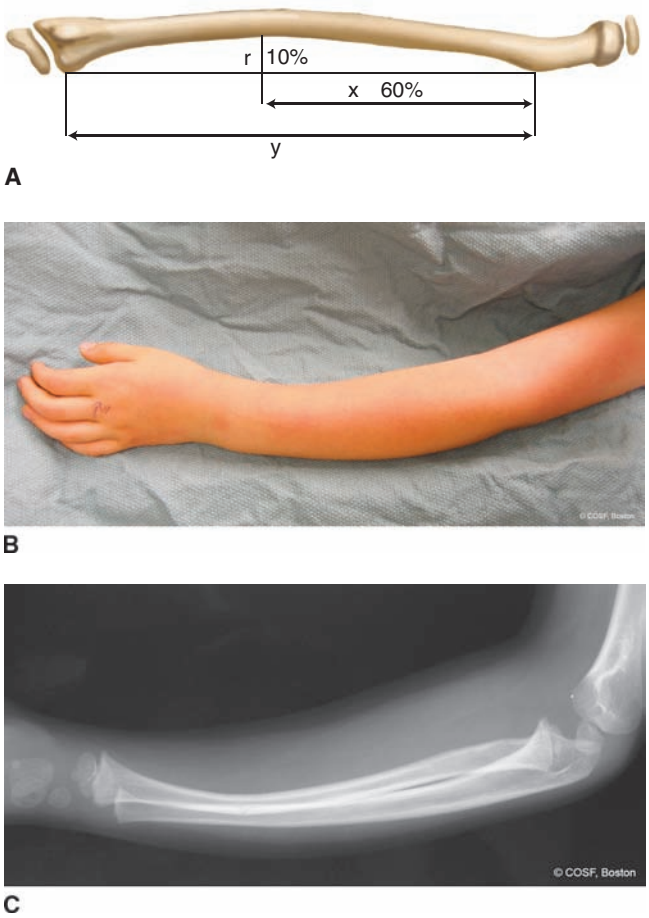


FIGURE 33-3 **A:** Schematic diagram of the normal radiographic bow of the radius. **B:** Clinical photograph of a patient with plastic deformation of the forearm. **C:** Corresponding radiograph depicting the traumatic bowing.

loss of forearm rotation. Greater than 10 degrees of angulation will proportionally impede forearm rotation. More proximal bony deformity will impart greater restrictions in forearm rotation. As a result, less angular deformity is tolerated in more proximal than more distal fractures. Malrotation, while difficult to quantify radiographically, similarly causes loss of forearm rotation.[17,18] Indeed, for every degree of rotational deformity, 1 to 2 degrees of forearm rotation may be lost. In general, ulnar malrotation does not alter the overall arc of forearm rotation but does change the "set point" of forearm motion. Radial malrotation, on the other hand, does reduce the overall arc of forearm supination-pronation. Ultimately, however, clinical forearm rotation and radiographic alignment are poorly correlated.[19]

Additional consideration must be made for bony remodeling. With fracture healing and subsequent skeletal growth, a number of bony changes occur. The adjacent physis is reoriented. The bone continues to elongate, reducing the apparent angular deformity. And finally, appositional periosteal bone formation, typically at the

concavity of the deformity, serves to "correct" angulation and displacement. Clearly, remodeling potential is greatest in younger patients, in fractures closer to the adjacent physis, and with deformity in the plane of adjacent joint motion. In general, up to 20 degrees of diaphyseal angulation may remodel in children under 8 years of age. Beyond the age of 10 years, however, more than 10 degrees of angulation is not likely to remodel spontaneously.

The available published information provides guidelines as to how much radiographic deformity can be expected to remodel with continued skeletal growth. Up to 1 cm of shortening may be accepted with little impact on forearm rotation, perhaps due to relaxation of the interosseous membrane.[11,20] Complete or 100% translation may remodel in younger patients in fractures of the middle and distal thirds.[10,11,20] Radioulnar angulation is less well tolerated, due to narrowing of the interosseous space and bony impingement during forearm rotation. Mehlman and Wall[3] have proposed the "20-15-10" rule to guide what constitutes acceptable angulation in radius and ulna fractures. Dividing the forearm into thirds, 20, 15, and 10 degrees of angulation may be accepted in the distal, middle, and proximal thirds of the forearm, respectively.

In addition to angulation, displacement, and translation, other tools have been proposed to predict the final position and ultimate outcomes of diaphyseal forearm fractures.[21,22] Younger et al. have proposed that axis deviation be utilized to predict outcomes following forearm diaphyseal fractures and thus to guide when closed reduction or surgical intervention is required (Figure 33-4). Axis deviation is defined as the distance between the fractured and anatomical axes of the bone measured at the fracture site, divided by the total length of the bone multiplied by 100. An axis deviation of >5 at the time of bony healing (i.e., cast removal) has been correlated with restricted forearm motion even after completion of skeletal growth and bony remodeling. The advantages of the axis deviation index are that it eliminates variables associated with vagaries of radiographic projection, magnification, and fracture location and does not rely strictly on radiographic angulation or translation to predict functional loss.

As clinical motion does not directly correlate with radiographic alignment, a more important question is "how much bony deformity can still allow for reasonable functional outcomes?" Historically, up to 10 degrees of angulation, complete translation, and 30 to 45 degrees of malrotation were thought to be well tolerated without functional limitations.[11] These parameters should be considered carefully, particularly given the patient and family expectations for restoration of full forearm rotation.

Surgical Indications

We make a living by what we get, but we make a life by what we give.
—Winston Churchill

The goals of diaphyseal forearm fracture treatment are to achieve bony healing, preserve forearm motion, prevent aesthetically displeasing deformity, and avoid complications.[16,19,23,24]

With this in mind, closed reduction should be considered in all acute displaced diaphyseal forearm fractures. Surgical indications include open forearm fractures, floating elbow injuries, fractures with vascular injury, fractures with soft tissue swelling precluding circumferential cast immobilization, and irreducible or unstable fractures with deformity beyond what would be anticipated to remodel, given the fracture pattern and patient age. Diaphyseal forearm refracture is considered a relative indication for surgery.

Although there are a host of surgical options, percutaneous pinning is generally insufficient, and external fixation is used most commonly in grade III open fractures and fractures with vascular impairment.[25] Currently, most forearm diaphyseal fractures are treated with intramedullary (IM) fixation or internal fixation with plate and screw constructs.

SURGICAL PROCEDURES

Closed Reduction of Incomplete Fractures

Closed reduction should be performed for all plastic deformation injuries with >20 degrees of angulation in patients over 4 years of age, given the limited remodeling potential.[12,26,27] Although seemingly straightforward, forces as high as 30 kg sustained over several minutes are required

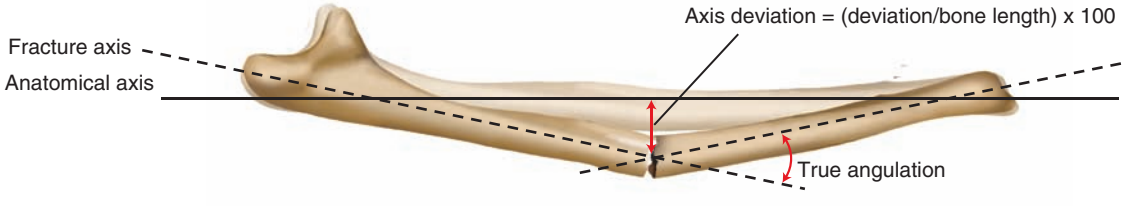


FIGURE 33-4 Schematic diagram of axis deviation.

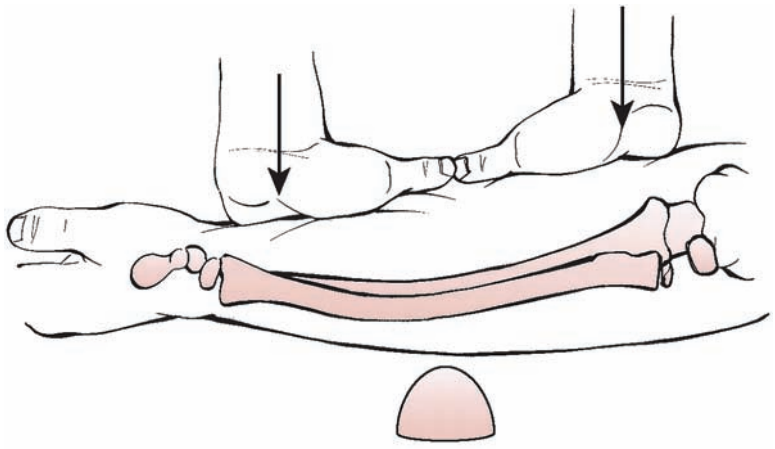


FIGURE 33-5 Schematic diagram depicting the technique of closed reduction for a plastic deformation injury.

to correct traumatic bowing.[26] As a result, controlled three-point bending over a sandbag, rolled towel, or the clinician's thigh should be performed under general anesthesia or well-administered conscious sedation (Figure 33-5). Following closed manipulation, fluoroscopy may be used to check bony alignment and restoration of passive forearm rotation. A well-molded long-arm cast is applied, which is critical for maintenance of reduction (see Sidebar). Casts should be applied with a straight ulnar border, interosseous mold, and three-point molding over the apex of the deformity.[3] Although well-molded casts may be aesthetically displeasing to the patient and family, "curved plaster is necessary in order to make a straight limb."[28] With appropriate reduction and casting, up to 85% deformity correction may be achieved.

In very rare situations, excessive plastic deformation cannot be adequately corrected despite vigorous attempts at closed reduction. If the diaphyseal bowing is excessive and impedes forearm rotation, percutaneous pin osteoclasis at the apex of the deformity may be performed, followed by correction of longitudinal alignment and appropriate cast immobilization. In essence, this technique surgically converts a plastic deformation injury into an incomplete or complete fracture to facilitate reduction.

Displaced greenstick fractures are also treated with closed reduction and cast immobilization (Figure 33-6). Closed reduction is performed by reversing the rotational deformity followed by correction of the angulation. In general, apex dorsal fractures are caused by hyperpronation and therefore are reduced with forearm supination.[3] Conversely, apex volar fractures are due to hypersupination and are best reduced with pronation. The "rule of thumbs"—in which the thumb is rotated toward the apex of the deformity—has been proposed to guide care providers about the appropriate reduction maneuver. For example, in the common apex volar angulated fracture, rotating the thumb pronates the distal fracture fragment, thus correcting the hypersupination injury. Just be certain you assess the thumb position in the adducted shoulder position to avoid misinterpreting shoulder motion for forearm rotation. In situations where the radius and ulna are fractured at the same level, pure bending is more likely to be the mechanism of injury, and reduction may thus be achieved with simple three-point molding. A well-fitting cast with appropriate interosseous and three-point mold is then applied in maintaining fracture reduction during bony healing. Controversy persists regarding whether the greenstick fracture should be completed (i.e., the

FIGURE 33-6 Radiograph depicting greenstick fractures of the radius and ulna.

intact cortex broken) during fracture manipulation. The advantages of fracture completion include greater ease of reduction and lower refracture rate due to the exuberant periosteal fracture callus formation that ensues. Disadvantages of fracture completion include greater fracture instability and difficulty in achieving and maintaining bony alignment during cast immobilization.

In patients with complete fractures of the radius and ulna diaphyses and unacceptable deformity, closed reduction is performed under conscious sedation. Fracture reduction is performed by first exaggerating the deformity to unlock and relax the intact periosteum, followed by longitudinal traction, correction of rotational malalignment, and finally reversal of the angular deformity (Figure 33-7). A long-arm cast with appropriate interosseous and three-point bending mold is then applied.

The optimal position of cast immobilization remains controversial. While the vast majority of casts are applied with the elbow flexed 90 degrees, long-arm extension casts have been used, particularly for proximal third fractures with apex posterior or apex ulnar angulation[29] (Figure 33-8). The addition of a thumb spica component and placement of a D-ring with neck strap on the extension cast help prevent the cast from sliding distally off the limb with walking and in the upright position.

The optimal position of forearm rotation is even more debatable. Theoretically, proximal one-third fractures of the radius are better immobilized in supination; this rotates the distal fragment into alignment with the proximal fragment, which is supinated by the action of the biceps and supinator muscles. Mid-diaphyseal fractures occurring proximal to the insertion of the pronator may be better immobilized with the distal segment supinated, again matching rotational alignment. Conversely, fractures distal to the pronator insertion on the radius may be best immobilized in neutral rotation or forearm pronation.

Irrigation and Debridement of Open Fractures

The forearm is among the most common sites for open fractures in children.[1] While unlikely, potentially devastating infectious complications can occur, even with seemingly innocuous grade I open fractures[25,30] (Figure 33-9). Timely irrigation and debridement in the operating room, combined with prophylactic antibiotics and fracture reduction and stabilization, is the standard of care for all open forearm fractures.[31] While there is a wealth of adult trauma literature to suggest open fractures are not a surgical emergency provided antibiotic prophylaxis is given, our preference is to treat open fractures as soon as possible after presentation. While waiting for the operating room, the wound is inspected, sterilely dressed, appropriate intravenous antibiotics and tetanus prophylaxis are given, and the limb is splinted.

Irrigation and debridement are the standard of care. This entails more than simple lavage of the superficial wound. Contaminated or nonviable skin edges from the

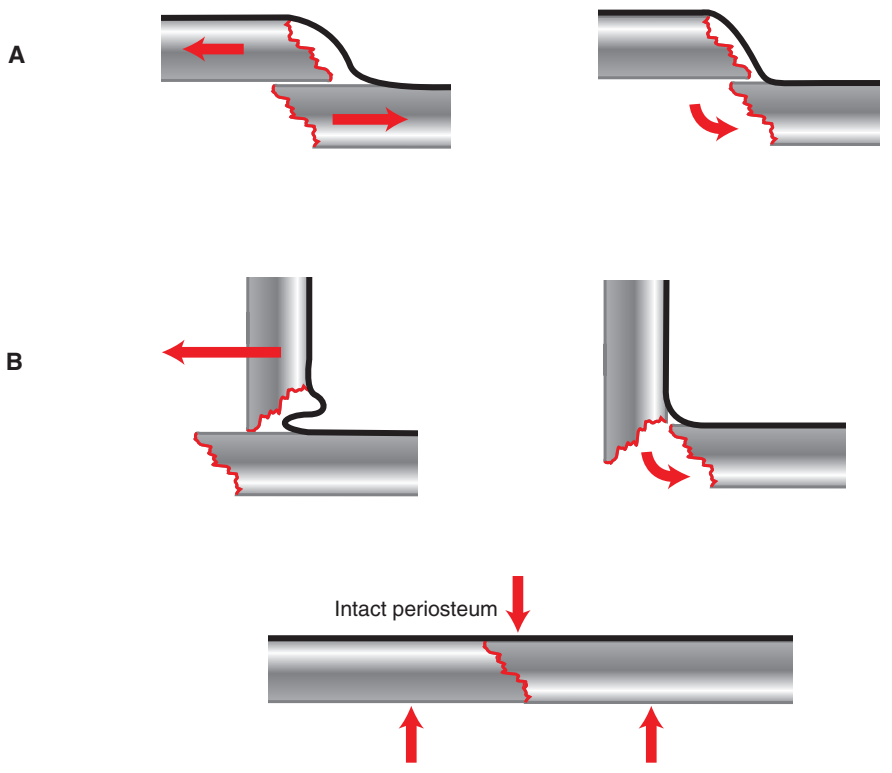


FIGURE 33-7 Schematic diagram depicting the technique of closed reduction. **A:** Although the cortical break is complete, the intact periosteum will prevent cortical apposition with straight longitudinal traction alone. **B:** To effectuate a reduction, the deformity must first be exaggerated, followed by longitudinal traction, and finally reversal of the deformity. Three-point molding may then take advantage of the stability conferred by the intact periosteum.

FIGURE 33-8 Radiograph of the forearm after long-arm extension casting for a diaphyseal ulna fracture.

traumatic wound are debrided and the surgical incision extended to allow for adequate visualization of the zone of injury and fracture fragments. Careful inspection and debridement of the bony ends are essential, as often there are contamination and foreign material within the IM canal of the fracture fragments.[32] After adequate wound care, direction may be turned to fracture management.

Internal fixation is preferred in most grade I and II open fractures for a number of reasons.[8,9,33,34] First, given the higher mechanisms of injury and soft tissue disruption, open fractures are more unstable and likely to lose reduction with external immobilization alone. The IM rodding or plate and screw fixation will provide stability and maintenance of reduction. Second, due to the soft tissue trauma and swelling, circumferential cast immobilization increases the risks of compartment syndrome and

FIGURE 33-9 Clinical photograph of a patient with gas gangrene following a grade I open fracture of the forearm. Initial treatment was an emergency room washout of the wound without an extension of the open laceration and closed reduction.

neurovascular compromise; the addition of internal fixation allows for less constrictive immobilization and ease of wound and soft tissue monitoring. The forearm fascia is always released at the conclusion of the irrigation and debridement and fracture care to lessen the risk of a postoperative compartment syndrome. The techniques of internal fixation are similar to those described below. Similar to adults, external fixation is used in the markedly contaminated wounds, fractures with segmental loss, and those with vascular impairment.

IM Rodding

They say that nobody is perfect. Then they tell you practice makes perfect. I wish they'd make up their minds.
—Winston Churchill

Use of IM fixation is now the standard technique for forearm diaphyseal fracture fixation in children and adolescents.[35–42] The IM rodding approach provides adequate restoration of length and alignment without the need for large incisions, considerable soft tissue dissection, and retention of implants. Smooth stainless steel K-wires, titanium elastic nails (Synthes, West Chester, PA), Rush rods, and Steinmann pins are all effective, emphasizing that the technique of insertion is more important than the implant used. Radial implants are prebent to facilitate restoration of normal radial bow. Rotational stability is conferred by the intact periosteum and surrounding soft tissues.

Patients are positioned supine with the affected limb supported by a radiolucent hand table. After induction of general anesthesia and provision of prophylactic antibiotics, intraoperative fluoroscopy is used to evaluate the ability to attain a closed reduction and to select the appropriate-size K-wire or titanium elastic nail. The

narrowest diameter of the IM canal is best seen on the lateral projection of the radius and ulna.

We rod the ulna first, in part due to the ease of ulnar rod placement and in part because restoration of ulnar length and alignment will often improve the alignment of the radius via soft tissue connections. In addition, there are some situations (unstable, complete fractures in 8 to 12 year olds) in which single bone fixation is adequate.[36,43] A small stab incision is created over the tip of the olecranon process, just *radial* to the center of the olecranon process to account for the apex radial bow of the proximal ulna (Figure 33-10). The triceps and underlying olecranon apophysis are incised in line with the incision, and a drill or smooth wire is used to create a corticotomy for IM rod placement. For the inexperienced surgeon, the entry point is more dorsal than anticipated. The ulnohumeral joint should not be violated during corticotomy or nail passage. The appropriately sized implant is then passed in an antegrade fashion down the canal of the ulna until it reaches the fracture site. The ulna fracture is closed reduced, and the nail is passed down the IM canal of the distal fragment until it is 5 to 10 mm proximal to the distal ulnar physis.

In selected cases[36,43] after ulnar rod placement, if the radius assumes an acceptable position with rotational reduction, consideration is made for single bone fixation. With the ulna straight and stable, the periosteum and soft tissues can stabilize the radius. In essence, the complete fracture in the young can be converted to an incomplete fracture that reduces and maintains stable alignment during healing. However, it is imperative that stability of the radial reduction be checked by fluoroscopic visualization. If the radius is unstable, nailing of both bones is performed.

Attention is then turned to the radius. We favor a radial entry site between the first and second extensor compartments. A small 2-cm incision is made over the "bare spot" of the dorsoradial metaphysis, just proximal to the distal radial physis. Careful subcutaneous dissection

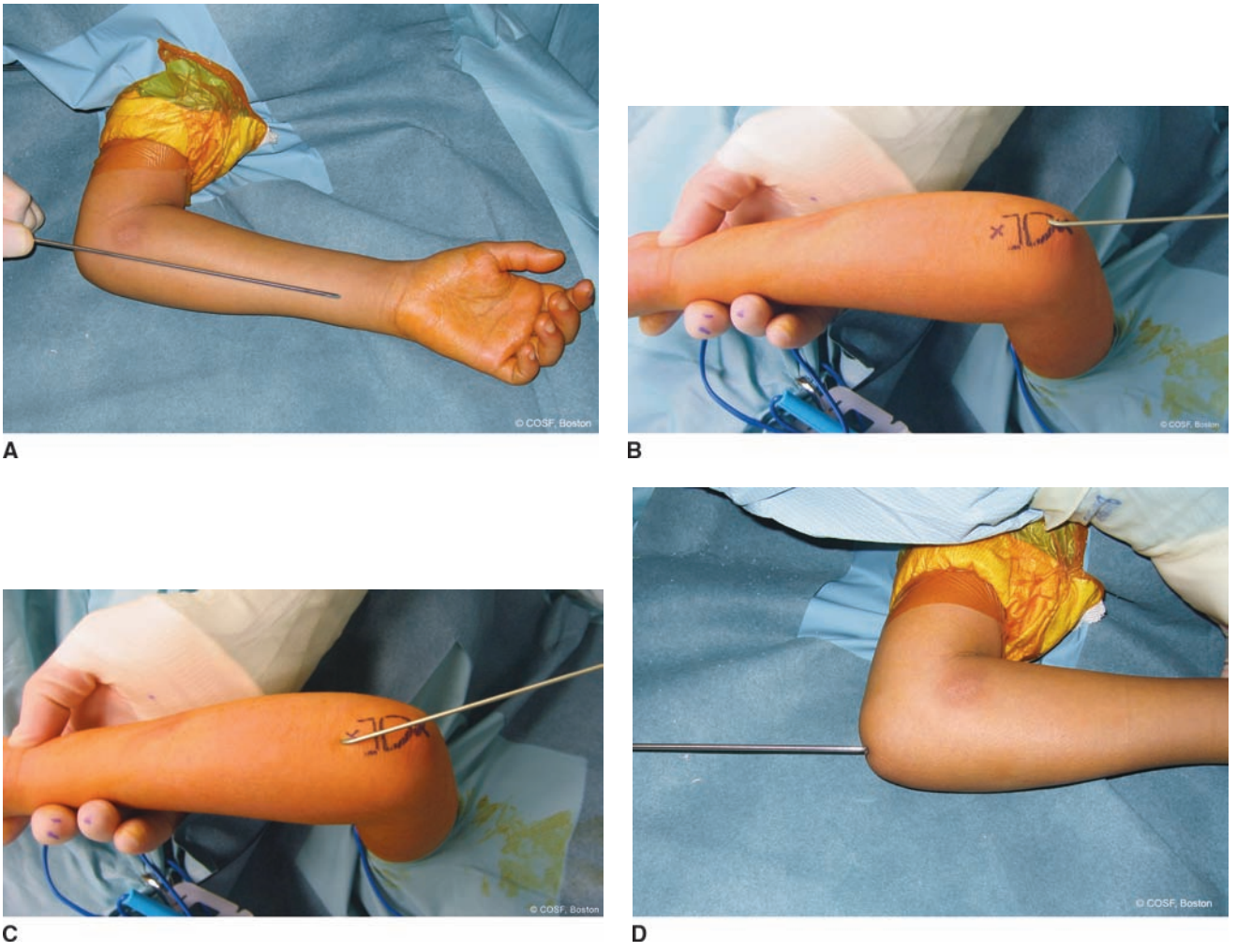
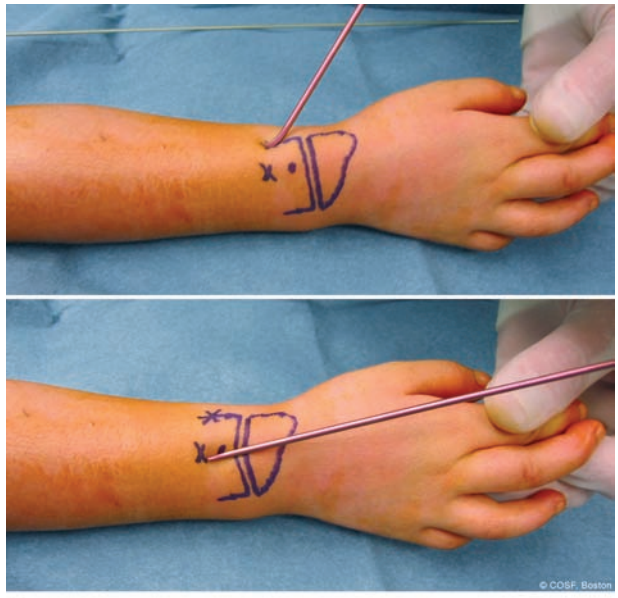


FIGURE 33-10 Technique of IM fixation. **A:** The IM rods are sized with the assistance of intraoperative fluoroscopy. **B, C:** Entry sites for the ulnar implant may be through the olecranon process or dorsally on the proximal ulnar metaphysis. **D:** After a small incision and spreading through the triceps, a corticotomy is created.

E



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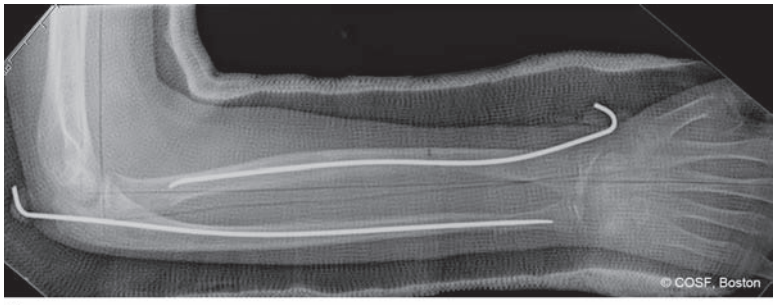

G

FIGURE 33-10 *(continued)* **E:** The ulnar rod is passed down and across the fracture site. **F:** Radial IM rod entry may be dorsal or radial. The *purple dot* marks Lister tubercle and the *X* marks metaphyseal entry sites. A small incision is made and subcutaneous spreading performed. Care should be made to protect the cutaneous nerves and extensor tendons. The radial rod should be contoured to restore the normal radial bow. **G:** Postoperative image demonstrating typical fixation and alignment achieved. In this case, the rods were left out of the skin for early removal.

is performed to identify and retract the superficial sensory branch of the radial nerve, which nearly always crosses the surgical field. The retinaculum overlying the first dorsal compartment is indentified and incised. After subperiosteal elevation, a drill is utilized to create a cortical opening for nail placement. Creation of an oblique path (from distal radial to proximal ulnar) will greatly facilitate nail placement. The appropriately sized nail is placed into the IM canal of the distal radial fracture fragment. Closed reduction of the radius is performed, and the nail is passed into the canal of the proximal radial fracture fragment until the tip lies at the level of the bicipital tuberosity. Multiplanar fluoroscopic images are obtained to confirm adequacy of reduction, stability, and implant placement. Sterile bandages and a long-arm bivalved cast are then applied.

Repeated forceful attempts at closed reduction and nail passage are discouraged, owing to the risk of increased soft tissue swelling and subsequent compartment syndrome.[39,44] If closed reduction and IM nail passage cannot be achieved easily with limited attempts, open reduction is performed. A small incision centered over the radius fracture, utilizing the brachioradialis (BR)-flexor carpi radialis (FCR) or BR-pronator teres (PT) interval distally and proximally, is used. Surrounding soft tissues and neurovascular structures are protected and entrapment in the fracture site is avoided. If the reduction is performed open, the forearm fascia is prophylactically released before closure.

Most pediatric orthopaedic surgeons cut the nails beneath the skin and plan for staged, elective implant removal 6 to 12 months postoperatively. Our preference, however, is to bend, cut, and leave the rods out of the skin. We remove the IM nails with bony healing, usually in the first 6 to 8 weeks. Although there is a theoretical risk of soft tissue irritation and infection with external rod tips, this has not been a significant problem with sterile dressing application and long-arm cast immobilization.

The benefit to early rod removal is avoidance of soft tissue and implant-related problems. The risk is refracture. Buried nails do result in a small incidence of soft tissue irritation and tendon disruption, particularly if a dorsal entry site is utilized for the radius where the extensor tendons are more at risk for implant-related rupture. Furthermore, removal of buried rods may not be trivial later on.

Open Reduction and Internal Fixation

Formal open reduction and internal fixation (ORIF) using plate and screw constructs may be used in patients of any age, though it is typically reserved for older adolescents with <2 years of remaining skeletal growth (i.e., males over 14 and females over 12). Surgical technique is similar as in adults, with several modifications. First, adequate stability may be achieved with four cortices of fixation proximal and distal to the fracture site, particularly if supplemented by postoperative cast immobilization. In addition, due to the smaller size of the radius and ulna in children and adolescents, size-appropriate implants (2.4- or 2.7-mm compression plates, double-stacked one-third tubular plates) should be used. Our preference is to use double-stacked one-third tubular plates, which have greater bending rigidity but are still narrower and have lower profile. Theoretical advantages of plate and screw fixation include the ability to achieve anatomic reduction and maximize return of full forearm rotation, particularly in older adolescents who lack great remodeling potential. Furthermore, early motion may be initiated given the rigid internal fixation, perhaps diminishing the likelihood of functionally limiting loss of motion. The disadvantages of plate fixation include the need for more extensive dissection, slower bony healing, aesthetically displeasing superficial scars, and more extensive surgery for implant removal, if necessary.

As with adults, ORIF is performed in the supine position with the limb supported by a radiolucent hand table. After the tourniquet is inflated, attention is first turned to the ulna. A subcutaneous longitudinal incision along the ulnar border of the forearm is created, centered on the fracture site. The extensor carpi ulnaris and flexor carpi ulnaris interval is identified and incised. Subperiosteal elevation is performed and the fracture exposed. Under direct visualization, the ulna is reduced, and the appropriate-size plate is applied, allowing for four to six cortices of fixation proximal and distal to the injury. The ulna may be definitively fixed or provisionally fixed with a single screw proximal and distal to the ulna fracture. Provisional fixation will allow for maintenance of alignment and length, while still allowing for some mobility, which may facilitate reduction of the radius. A volar (Henry) approach to the radius is then performed. Proximally the PT-BR interval is developed, whereas distally the BR and FCR interval is used. The radial artery is typically retracted radially in the distal third and ulnarly in the middle and proximal thirds of the forearm. Deep dissection will require elevation of the pronator quadratus and flexor pollicis longus, PT, and supinator off the distal, middle, and proximal third of the radius, respectively. The radius fracture is exposed and anatomically reduced. Fixation again is provided by placing the plate and obtaining four to six cortices on either side of the fracture. Care is taken to restore the normal radial bow and avoid the temptation of straightening the radius by plate placement. Prebending the plate before fixation is required. Fluoroscopic imaging will confirm anatomic alignment, fracture stability, and implant position. Range of forearm motion is assessed, with confirmation of distal radioulnar joint (DRUJ) stability. The periosteum is reapproximated over the radius and ulna. We routinely perform limited subcutaneous fasciotomies under direct visualization to minimize the risk of postoperative compartment syndrome. Soft tissues are closed in layers, and a bivalved cast is applied.

Osteotomy for Malunion

Wanting to work is so rare a merit that it should be encouraged.
—Abraham Lincoln

Patients with diaphyseal forearm fracture malunions and functionally limiting loss of forearm motion are candidates for corrective osteotomy (Figure 33-11). Careful preoperative evaluation is necessary to ascertain the true functional impact of any bony malalignment and to determine whether the bony deformity has the potential to remodel with observation alone.[10,14,45] Radiographs should be evaluated to assess angular deformity, malrotation, and length; careful inspection of all available radiographs, particularly from the time of original injury, is helpful, as often the location and pattern of the original fracture are difficult to identify on the most recent x-rays. Proper patient selection is critical, as this procedure can be difficult with no guarantees that full forearm rotation will be restored. As always, it is important to treat the patient, not the pictures.

Although a host of surgical strategies are available, we advocate a simple approach to corrective osteotomy.[46] Either a closing wedge osteotomy or oblique osteotomy is performed at the apex of angular deformity, followed by rotational correction after the coronal and sagittal plane alignment is restored. Closing wedge osteotomies are preferred for a number of reasons: (1) they are technically more reproducible than single-cut, oblique osteotomies; (2) they avoid obligate lengthening, which may cause difficulties with internal fixation and alter the proximal radioulnar joint and DRUJ; and (3) they alleviate tension on the surrounding soft tissues, minimizing risks of neurovascular compromise and compartment syndrome. However, there are some situations that are just perfect for an oblique osteotomy (Figure 33-12).

Surgery to the radius and ulna is performed via standard Henry volar and ulnar approaches. Attention is first

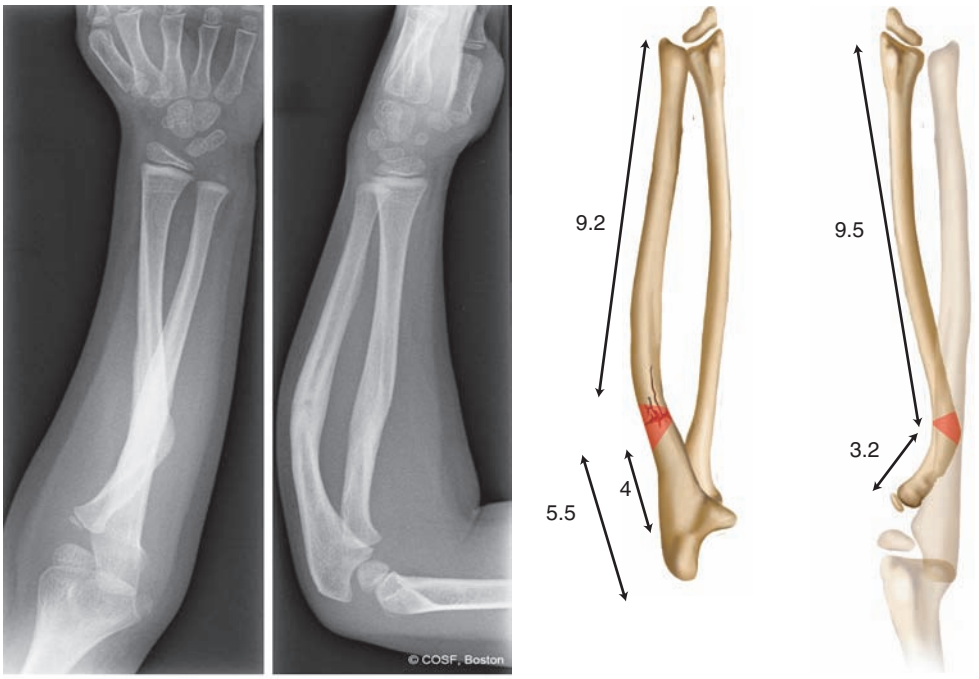

FIGURE 33-11 Corrective osteotomy for forearm fracture malunion. **A:** Preoperative AP and lateral radiographs of a 7-year-old female with a diaphyseal malunion and functionally limiting loss of forearm rotation. **B:** Preoperative plan depicting closing wedge osteotomies for deformity correction. **C:** Postoperative radiographs after corrective osteotomy and plate and screw fixation.

turned to the radius. After the apex of the deformity is confirmed on intraoperative fluoroscopy, a closing wedge osteotomy is performed using a microsagittal saw with copious saline irrigation to avoid thermal necrosis. Proximal and distal cuts are made perpendicular to the longitudinal axis of the radius, allowing for subsequent rotational correction once the osteotomy is reapproximated. The ulna is similarly exposed and osteotomized. Plate and screw fixation is performed using size-appropriate implants, obtaining four to six cortices of fixation proximal and distal to the osteotomy. Rotational alignment is confirmed by the radiographic orientation of the radial styloid and bicipital tuberosity and the ulnar styloid and coronoid process, which should be directed 180 degrees apart. Full-motion and DRUJ alignment and stability are confirmed. Prophylactic forearm fasciotomies are performed, and, after wound closure, a well-padded bivalved long-arm cast is applied.[46]

◆ Extraction of Entrapped Flexor Tendons

On occasion, the pediatric hand and upper extremity surgeon will encounter a patient with tendon entrapment

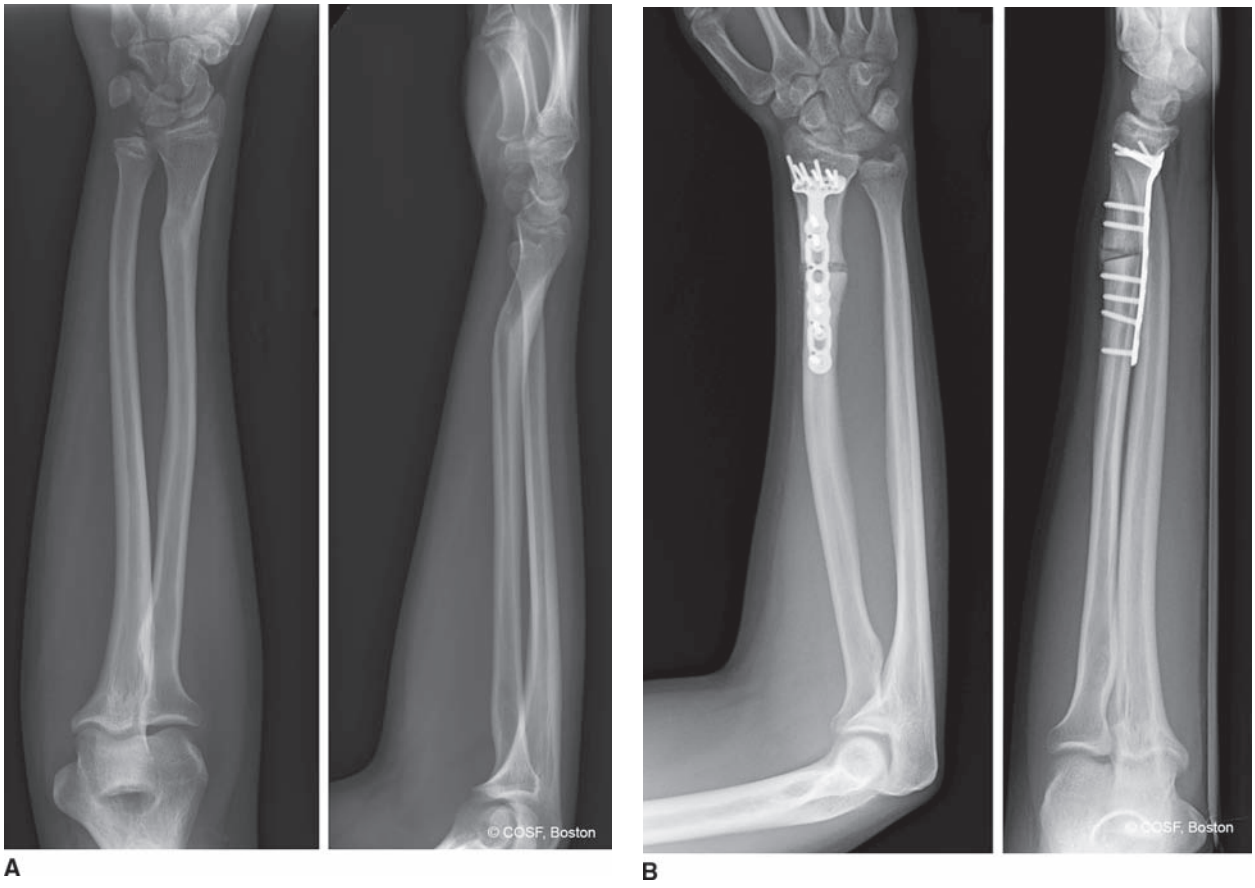

FIGURE 33-12 **A:** Forearm fracture malunion AP and lateral radiographs. **B:** AP and lateral radiographs of corrective radial osteotomy with bone graft.

at the site of a diaphyseal forearm fracture. It is usually with a displaced ulnar shaft fracture that the long and/or ring flexor digitorum profundus muscle will be incarcerated within the fracture with or without ulnar nerve entrapment (see Chapter 37). The entrapment is immediate but may not be recognized for a while. The patients with entrapment lack both passive and active digital extension. There is a true block to extension that has to either be a missed compartment syndrome or entrapped tendon-muscle unit. Assessment of passive digital motion, evaluation of sensibility, and careful testing of extrinsic or intrinsic motor function will help distinguish nerve from muscle injury. Finally, serial examinations are essential. The absence of an advancing Tinel sign, persistent motor and sensory loss, and radiographic findings indicative of soft tissue incarceration within the fracture site or callus should raise suspicion for nerve entrapment. In patients with muscle-tendon entrapment, their sensibility and active motion within the limits of entrapment will be normal. Florid compartment syndrome patients will have profound motor-sensory loss.

In patients with tendon entrapment, early exploration is warranted. An extensile approach is preferred, and the tendons, nerves, and arteries are isolated proximal and distal to the zone of injury. The muscle-tendon unit is then decompressed through the region of the fracture. Passive digital and wrist motions are restored with intraoperative stretching. Associated incarcerated nerves must be simultaneously liberated from the fracture site and surgically reconstructed (see Chapter 37). Postoperatively, providing skeletal stability is not compromised and there is no nerve reconstruction, aggressive therapy for range of motion is pursued.

POSTOPERATIVE

Following closed reduction of displaced diaphyseal forearm fractures, patients are placed in appropriate long-arm cast immobilization. Radiographs are checked at 1 and 2 weeks postinjury to rule out loss of reduction requiring repeated manipulation or surgery. For distal and middle third fractures, we typically transition patients to short-arm casts at 4 weeks postinjury, provided there is adequate clinical and radiographic healing. Cast immobilization is discontinued after a total of 6 to 8 weeks with bony healing, followed by range-of-motion exercises and strengthening.

Immediately after IM fixation of forearm diaphyseal fractures, the cast is bivalved to allow for postoperative swelling. The IM nails are removed at 4 to 8 weeks in the office (stainless steel wires) or in the operating theater

with sedation or brief general anesthesia (titanium rods), followed by an additional 2 weeks of cast immobilization. Although early rod removal theoretically increases the risk of refracture, this has not been a common occurrence, and families are counseled about appropriate refracture risk and activity modification. If the IM nails are buried beneath the skin, elective implant removal may be performed at 6 to 12 months postoperatively. Long-standing buried ulna IM rods are less likely to have problems with a metaphyseal proximal entry site that allows deep placement of the tip.

As ORIF with plate and screw constructs imparts rigid stability, early range-of-motion exercises may be initiated; strengthening is started once there is clinical and radiographic evidence of healing. In the very young or noncompliant patient, cast immobilization for 4 to 6 weeks may be used. At present, we do not routinely remove buried plates or screws unless patients are symptomatic.

ANTICIPATED RESULTS

Adherence to the above-stated principles and techniques should result in bony healing and restoration of motion in the majority of patients. If carefully inspected, some loss of forearm rotation may occur, even in surgical patients in whom radiographs demonstrate anatomic bony alignment.[11,19,21,24,35] Typically, these differences are subtle and not associated with any complaints or functional limitations.[14,19]

COMPLICATIONS

Success is not final, failure is not fatal: it is the courage to continue that counts.
—Winston Churchill

In cases in which the above principles are not followed, fracture malunions may result (Figure 33-11). Price et al.[11] previously reported on a series of 39 children with malunions following closed treatment of displaced forearm fractures. The average patient age at the time of injury was 9.3 years. Malunion was defined as radiographic angulation >10 degrees, >50% displacement, malrotation, and/or encroachment of the interosseous space. Overall, 82% of patients had excellent and 10% good results; there were only 8% fair results, and no poor outcomes. All patients were reportedly "satisfied" with aesthetics and function regardless of age or radiographic findings, which did not correlate with final clinical motion. Based on their observations, the authors conclude that up to 10 degrees of angulation, complete translation, complete loss of radial bow, and 45 degrees of malrotation may be well tolerated with minimal aesthetic or functional consequences. Similar findings have been reported by Creasman et al.,[10] Daruwalla,[14] and Fuller and McCullough.[45] In cases of functionally limiting loss of forearm motion and excessive deformity unlikely to remodel, corrective osteotomies may be considered as described above.

Refracture of diaphyseal fractures of the forearm occurs in 4% to 8% of patients.[47–49] Refracture occurs more commonly in males than females, with peak incidence at 6 months after index injury. Proximal radius fractures in which the fracture line is still visible at the time of cast removal or follow-up radiographs may be most prone to refracture.[50] Patients and families should be counseled about the refracture risk at the time of cast and/or implant removal, and a transitional period of splint immobilization should be considered to minimize refracture risk.

Compartment syndrome is a potentially devastating complication of both nonoperative and surgically treated diaphyseal forearm fractures.[8,44,51] In cases of open fracture, the prevalence of compartment syndrome may be as high as 10% in surgically treated patients. Diagnosis may be difficult, particularly in the young, agitated, and/or nonverbal child. In addition to the traditional signs of compartment syndrome, a rising analgesic requirement and increasing agitation may be evidence of an impending compartment syndrome in children.[52] In children, the three A's are used for clinical compartment syndrome diagnosis: Agitation, Anxiety, and increasing Analgesic requirement. Early recognition and prompt treatment with open forearm fasciotomies are critical to avoid permanent sequelae.

The need for implant removal after bony healing remains controversial.[48,53–55] Some have advocated for routine removal of plate and screw constructs after bony healing of forearm fractures, citing risks of refracture, growth alteration, metallic allergies, and adverse effects on bone density due to mechanical stress shielding. Others have cited the low frequency of symptomatic implants and complication rates of up to 40% as arguments against implant removal from the upper extremity in children. At present, we do not routinely remove deep implants unless they are symptomatic.

CASE OUTCOME

After unsuccessful closed reduction, this patient was treated with closed reduction and IM nailing (Figure 33-10). Implants were removed at 6 weeks, followed by gradual range-of-motion exercises. At most recent follow-up, there was appropriate bony healing and full return of forearm rotation without functional limitations.

SUMMARY

Diaphyseal forearm fractures are common. While most do well with nonoperative care, surgical treatment is indicated in cases of open fractures, refractures, floating elbow injuries, fractures with vascular compromise, fractures with soft tissue swelling precluding circumferential cast immobilization, and unstable/irreducible fractures. Full

understanding of the anatomy, remodeling potential with continued skeletal growth, surgical techniques of both IM fixation and ORIF, and the potential complications are essential for the pediatric hand and upper extremity surgeon.

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CHAPTER

34

Distal Radius and Carpal Fractures

CASE PRESENTATION

A 17-year-old male suffered a fall onto his extended wrist while playing basketball 2 months ago at boarding school. His wrist has hurt intermittently with sports, push-ups, and some activities of daily living with his wrist extended. He never sought medical attention while at school. He is home for the winter holidays, and his mother decided to bring him in for an evaluation. He has snuffbox, scaphoid tubercle, and thumb axial compression pain. His wrist extension is limited compared to the opposite side. His radiographs 2 months postinjury are seen in Figure 34-1A. His computated tomography (CT) scan is seen in Figure 34-1B.

CLINICAL QUESTIONS

- Do nondisplaced distal radial metaphyseal buckle fractures require cast treatment?
- Is there an outcome difference between long-arm and short-arm cast immobilization for distal radius fractures treated with CR?
- How much and over what time can a distal radius fracture remodel?
- What are the indications for CRPP of distal radius fractures?
- What are the indications for ORIF of distal radius fractures?
- When should ulnar styloid fractures be acutely fixed?
- What is the risk of growth arrest in a distal radius physeal fracture?
- What are the indications for an ulnar shortening osteotomy?
- Which scaphoid fractures should be treated with cast immobilization in children and adolescents?
- What are the indications for percutaneous scaphoid screw fixation?
- Should every scaphoid nonunion in the pediatric age group be treated surgically?
- What is the surgical approach for an acute transscaphoid perilunate dislocation?

THE FUNDAMENTALS

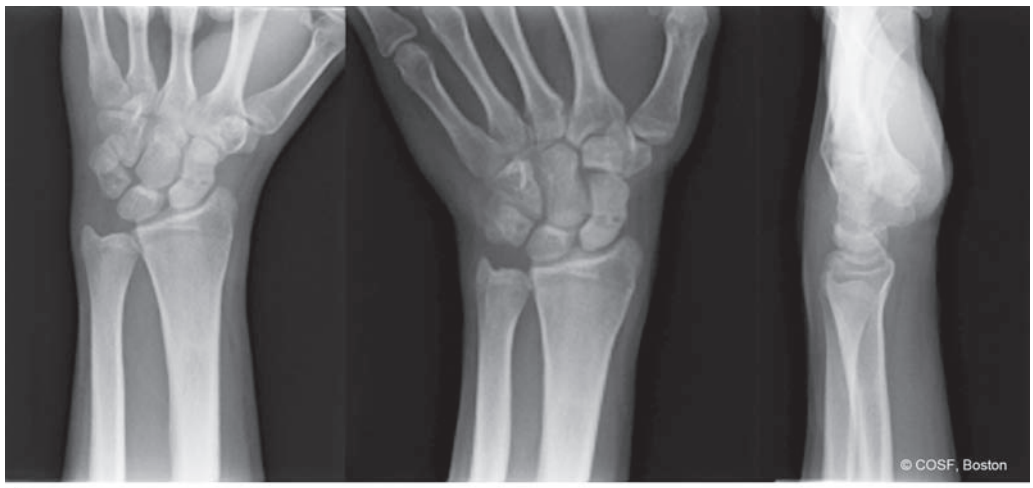
Etiology and Epidemiology

The distal radius (in isolation or with a distal ulna fracture) is the most common site of a pediatric fracture.[1–4] Distal radius fractures occur most commonly in adolescent patients, almost exclusively secondary to a fall. A fracture during a sporting event is a common occurrence, in particular skateboarding, snowboarding, and soccer goalkeeping, among others.[5–7] Protective wrist guards are of benefit in reducing fracture risk in these sports.[8] Children with obesity and poor bone mineralization are at more risk for a fracture with a routine fall.[9–12] Repetitive stress loading of the wrist, such as with gymnastics, can lead to a distal radial physeal stress fracture (see Chapter 39).[13–16] Triangular fibrocartilage complex (TFCC) tears (see Chapter 42) are more common with positive ulnar variance, and Kienbock disease (avascular necrosis [AVN] of the lunate) (Figure 34-2) is more common with negative ulnar variance.

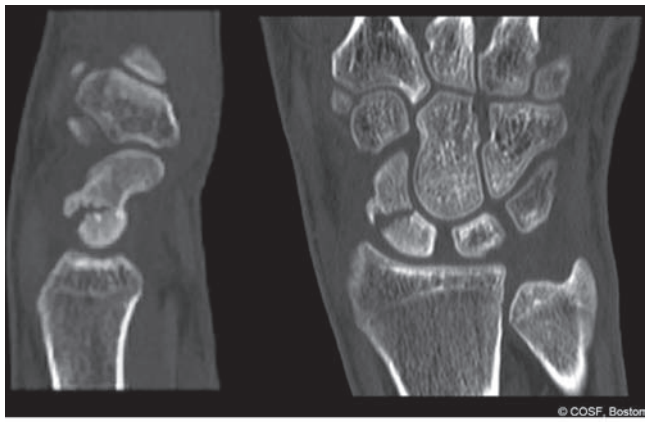
Clinical Evaluation

Children and adolescents with a distal radius fracture will present with localized pain and restricted motion. Nondisplaced fractures in the young may have minimal pain or restrictions due to periosteal stabilization. Displaced fractures of the distal radius and ulna will have obvious deformity. With markedly displaced fractures, neurovascular (NV) compromise can occur. Open fractures do occur and are more at risk for NV impairment.

Distal forearm fractures are classified radiographically by location of fracture (metaphyseal or physeal), direction (volar or dorsal) and degree of displacement, and bone involved (radius, ulna, or both). Metaphyseal fractures are further defined as torus/buckle (one cortex and therefore stable), both cortices (potentially unstable), and complete, displaced fractures. Most distal forearm fractures extend due to the fall on an outstretched wrist mechanism of injury. A variant is the pediatric Galeazzi fracture dislocation: a displaced distal radial metaphyseal fracture with either a distal ulnar physeal fracture or distal radioulnar joint (DRUJ) dislocation. Transphyseal fractures are less common than



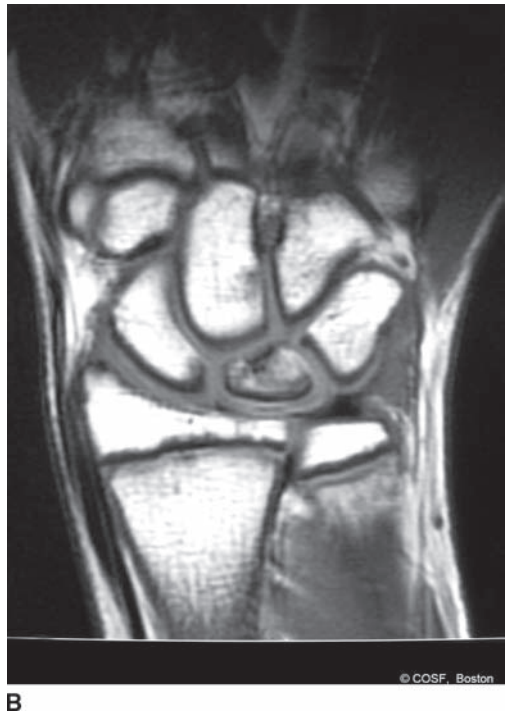
A



B

FIGURE 34-1 **A:** Radiographs of mildly displaced scaphoid fracture that occurred 2 months before. **B:** CT scan confirms mild humpback deformity, fracture with minor cystic changes.

A



B

FIGURE 34-2 **A:** Mild Kienbock disease anteroposterior (AP) radiograph and (**B**) confirmed on magnetic resonance imaging (MRI) scan.

metaphyseal fractures and are defined by standard Salter-Harris classification.[17] Salter-Harris type II, followed by Salter-Harris type I, injuries are the most common displaced distal radial physeal fractures. Intra-articular fractures are uncommon with an open physis (Salter-Harris type III) but are more and more common with skeletally mature adolescents during their highly competitive sports participation. Classification of intra-articular distal radius fractures is similar to adults. The use of CT scans is necessary to define displacement, number of fracture fragments, and operative indications.

Scaphoid fractures are more subtle than distal radius and ulna fractures by history and exam.[18,19] Snuffbox tenderness, scaphoid tubercle tenderness, and axial compression of the thumb are all sensitive physical exam findings for an acute scaphoid fracture or chronic nonunion, but axial compression is the most specific. Plain radiographs need to include a 30-degree ulnar deviation AP view (scaphoid view). Scaphoid fractures are defined by location of the fracture (waist, proximal, or distal pole) and displacement (nondisplaced, <2 mm, >2 mm). Proximal pole fractures have the highest risk of AVN. The use of CT scans is often necessary to define operative indications (displaced fractures >2 mm) but need to be taken in the longitudinal plane of the scaphoid to be accurate.[20,21] The use of MRI scans is appropriate for patients with snuffbox tenderness, scaphoid tubercle tenderness, and/or thumb axial compression pain but normal plain radiographs[22–25] (Figure 34-3). Scaphoid nonunions usually present long after the fracture and often

A

B

C

FIGURE 34-3 **A:** Original radiographs of the scaphoid were interpreted as negative for fracture. **B:** MRI 3 weeks later reveals scaphoid fracture. **C:** Percutaneous scaphoid screw fixation was the treatment of choice for this patient with radiographic healing noted.

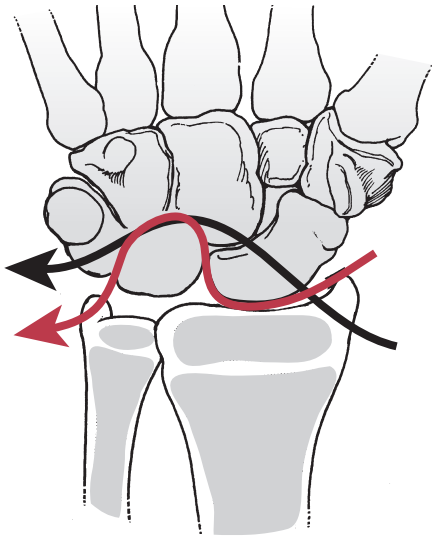


FIGURE 34-4 Disruption pattern of a trans-scaphoid perilunate dislocation (black line) or pure perilunate dislocation (red line) noted by illustration. (From Beaty JH, Kasser JR. *Rockwood & Wilkins Fractures in Children*. 7th ed. Philadelphia, PA: Lippincott Williams & Wilkins, 2010.)

with lack of treatment since the time of injury. The pain is usually mild, worse with wrist extension and axial loading activities, and often not debilitating. There is generally limited wrist extension and scaphoid-specific pain on physical exam. X-rays will reveal the nonunion and possible AVN of the proximal pole with scaphoid collapse (dorsal intercalary segment instability [DISI] pattern with the distal pole of the scaphoid flexed and lunate extended on the lateral radiographic image).

Trans-scaphoid perilunate dissociations are the most common type of acute perilunate carpal dislocations. These dislocations are rare and secondary to a high-velocity injury in extreme wrist dorsiflexion. An acute median neuropathy is common with a complete perilunate dislocation. There is usually marked swelling, deformity, and pain. Inexplicably, some of these patients present days after injury, which heightens the risk of AVN of the scaphoid proximal pole and/or dislocated lunate. The force of a perilunate dislocation starts radially either through the scaphoid as a fracture or through the scapholunate ligament; it then extends between the lunate and capitate dissociating the proximal and distal carpal rows; and finally it returns to the ulnocarpal joint in a clockwise fashion through the lunotriquetral joint (Figure 34-4). In a complete injury, the lunate usually ends up volar in the carpal canal, and the radius and capitate become colinear.

Surgical Indications

All displaced fractures and dislocations of the distal forearm and wrist require treatment. The major defining factors for treatment type closed reduction (CR), closed reduction percutaneous pinning (CRPP), or open reduction and internal fixation (ORIF) for distal radius and/or ulna fractures is the age of the patient, degree and direction of displacement, and any articular involvement. If the child is young (>2 years of growth remaining), the fracture is extra-articular and displaced in the plane of motion of the joint and has <20 degrees of malangulation without malrotation, then the bone will eventually remodel. Using CR and cast treatment is appropriate with close follow-up.[26–28] Some fractures treated with CR will redisplace and require either repeat CR or CRPP (Figure 34-5).

A1

A2

FIGURE 34-5 **A:** Injury films of displaced distal radius and ulna fractures.

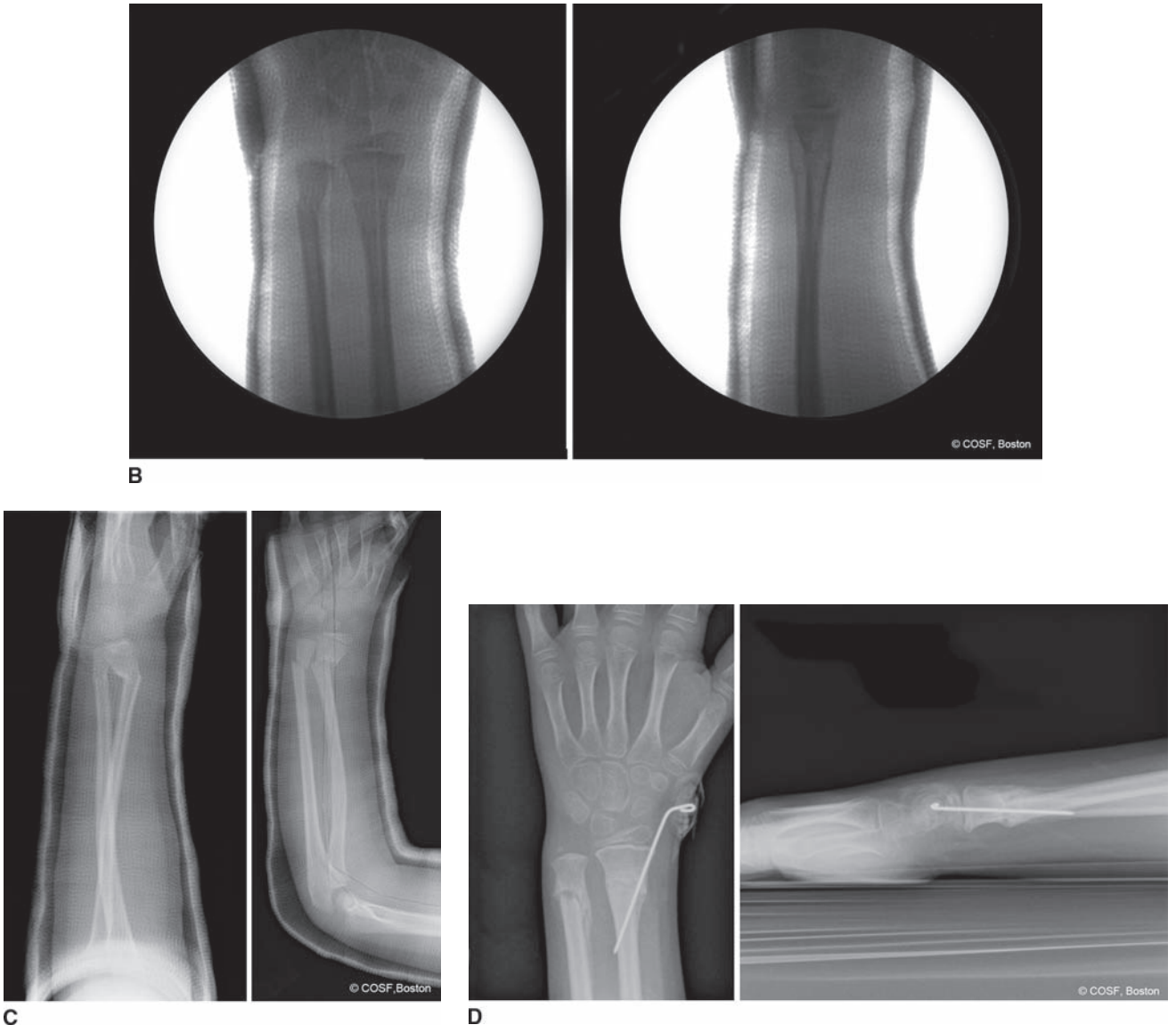


FIGURE 34-5 *(continued)* **B:** Conscious sedation reduction in emergency department is near-anatomic reduction. **C:** Loss of reduction in cast is noted on radiographs 13 days later. **D:** CRPP to anatomic alignment and healed fractures just before pin removal in office.

In skeletally mature adolescent patients, CRPP or ORIF is indicated for displaced fractures to restore radial inclination, physiologic ulnar variance, and DRUJ alignment. All displaced intra-articular fractures require anatomic reduction and rigid fixation.

Displaced scaphoid fractures[29] and scaphoid nonunions require anatomic reduction and fixation. Nondisplaced, acute fractures without bone loss, and proximal pole scaphoid fractures, can be treated with percutaneous screw fixation.[30] Acute fractures and chronic nonunions with bone loss require ORIF with bone graft to restore carpal alignment and expedite healing.[31–34]

All displaced perilunate dislocations require operative reduction and stabilization. Although there is debate about the method of treatment (CRPP or ORIF) and surgical approach with open reduction (volar, dorsal, or combined), there is no debate about the need for reduction and stabilization for the best results.

SURGICAL PROCEDURES

Closed Treatment of Stable Fractures

Nondisplaced unicortical fractures of the distal radius and/or ulna metaphysis are stable injuries. A removable Velcro splint, posterior plaster or fiberglass splint, or bivalve cast immobilization have all been successful forms of treatment.[35,36] There is some evidence that these patients may not need to return for follow-up appointments and still have uncomplicated outcomes.[37] The only potential

problem is mistaking a bicortical, unstable fracture for a stable injury. The bicortical fractures may have been more displaced at the time of injury and can redisplace in nonrestrictive immobilization. Nondisplaced metaphyseal distal radius and/or ulna fractures are usually clinically healed by 3 to 4 weeks, at which time the immobilization can either be discontinued at home by patient and family or in the office by medical personnel. Repeat radiographs are often not obtained.

CR of Distal Radius and Ulna Fractures

Displaced distal radius and/or ulna fractures usually require reduction to realign the bones and joints and lessen the risk of further displacement over the next 3 weeks of healing. The reductions are generally performed in the emergency room with conscious sedation. Conscious sedation is performed by the emergency room attending staff with in-hospital anesthesia attending as backup. Once the patient is adequately sedated, the CR is achieved in a series of steps. For metaphyseal fractures with bayonet apposition, the deformity is initially accentuated (Figure 34-6A). The degree of deformity accentuation needed to unhinge a bayonet apposition fracture can be extreme, to the point of instilling nausea in the observing health care personnel. Once the fracture is unhinged and the dorsal periosteum is relaxed, the fracture fragment is "walked" distally with the extension deformity maintained. This maneuver will get the fracture out to length, but it takes very strong intrinsics and thumbs for most fractures. Many fall short with these first two maneuvers. Then the distal fracture fragment is reduced onto the proximal fragment metaphysis (Figure 34-6B) with dorsal to volar thumb pressure. Complete reduction may

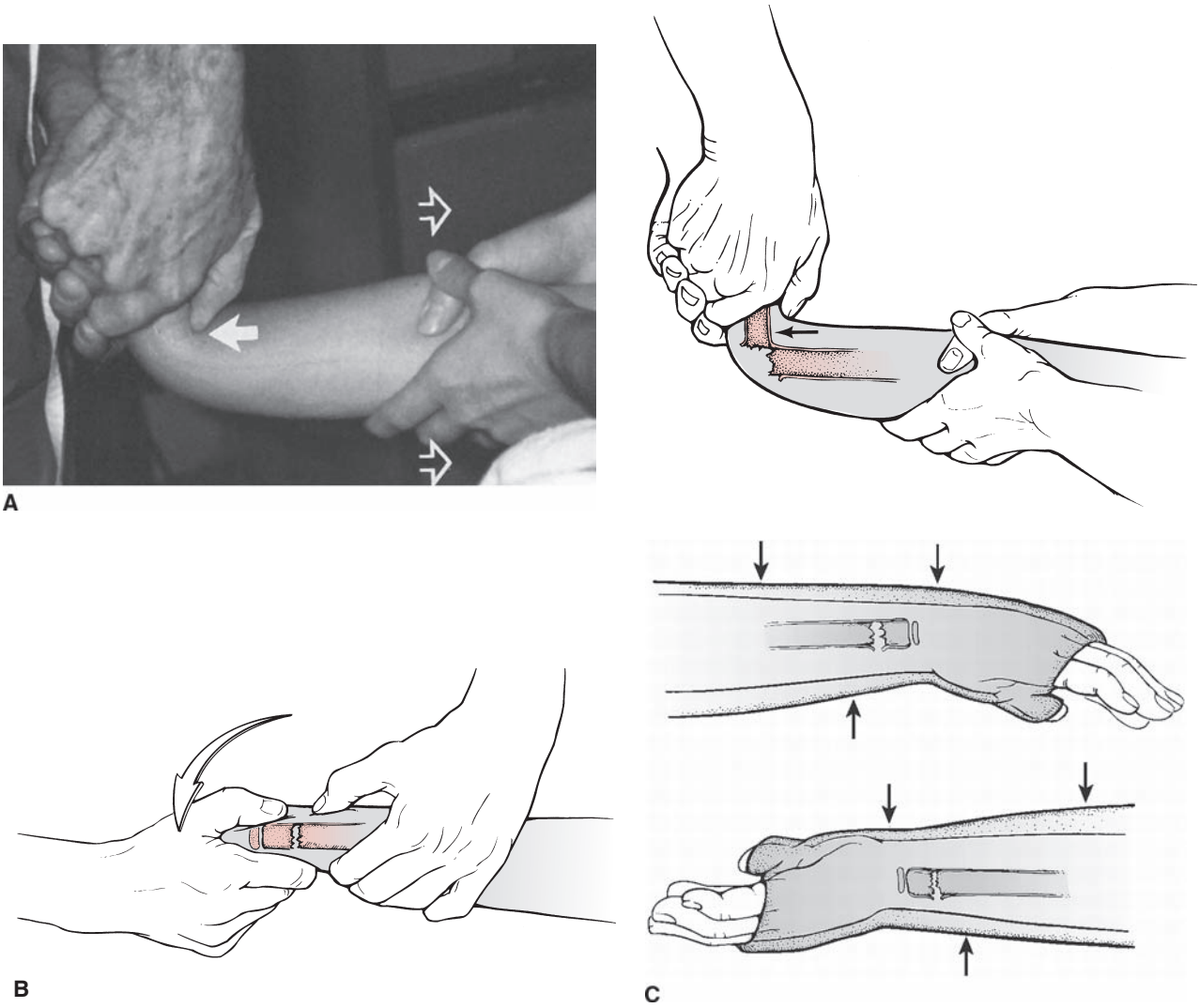


FIGURE 34-6 Illustrations of CR of distal radial metaphyseal fracture note the accentuation of the deformity (**A**) followed by reduction of the fracture by bringing the dorsal, distal fragment over the top of the volar, proximal fragment. **B, C:** Three-point molding is performed with cast application. (From Beaty JH, Kasser JR. *Rockwood & Wilkins Fractures in Children*. 7th ed. Philadelphia, PA: Lippincott Williams & Wilkins, 2010.)

take several back and forth maneuvers until the fracture is anatomic. Anything less than anatomic will have a higher risk of redisplacement over the next 3 weeks. Anatomic reduction can be felt by dorsal bony alignment, seen by loss of obvious deformity, and confirmed by fluoroscopy. Following anatomic reduction, the choice is well-molded cast immobilization or CRPP. Irreducible fractures require an open reduction by volar approach to extract interposed periosteum and/or pronator quadratus (PQ).[38–40]

Displaced physeal fractures require a gentler reduction. This can usually be performed with finger trap distraction and dorsal to volar finger reduction (Figure 34-7). The reduction is again performed under conscious sedation. Avoiding additional injury to the distal radius physis with reduction is imperative. This is usually not a difficult reduction. The reduction can also be done under hematoma block but does require a noncombative patient to prevent shear and compression stress injury to the physis. Anatomic reduction is confirmed by fluoroscopic images.

In both metaphyseal and physeal fractures, the dorsal periosteum acts as a tension band in helping maintain reduction. The wrist is positioned in slight (~20 degrees) palmar flexion to provide dorsal periosteal tension. Cast padding and molding are key to providing external support for maintaining reduction. A dorsal mold directly over the fracture and a more proximal volar mold provide three-point fixation (Figure 34-6C). The dorsal mold cannot be too distal, or it will lead to venous congestion due to outflow obstruction on the dorsum of the hand. A straight ulna border and anatomic radial bow mold of the forearm are required. The results of long-arm and short-arm cast immobilization are equivalent,[26,28] including prospective randomized studies.[41,42] The most important factor is the quality, not the length, of the cast. The quality of the cast molding can be measured by the cast index, which is the sagittal diameter divided by the coronal diameter at the fracture site. A value of 0.7 or less defines a well-molded cast and carries less risk of loss of reduction (Figure 34-8A).

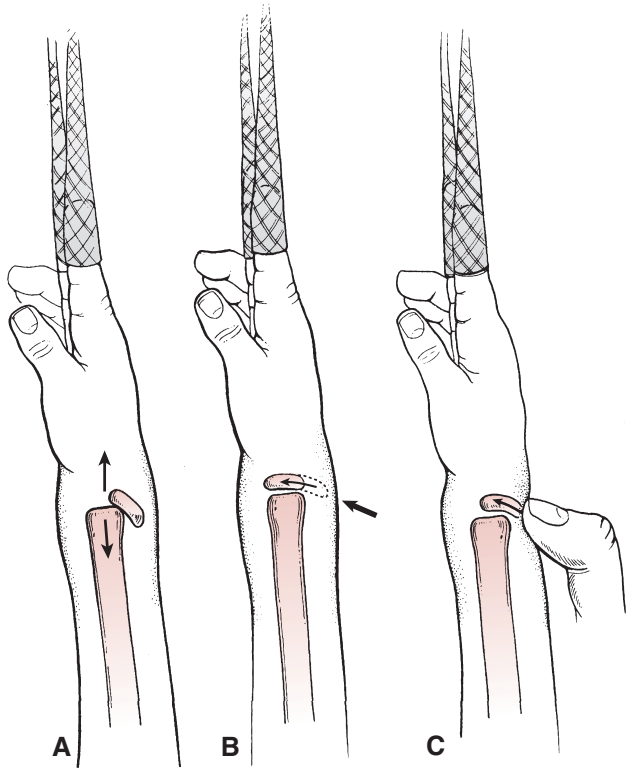


FIGURE 34-7 Illustration of distal radial physeal fracture reduction. Longitudinal traction (**A**) is followed by gentle dorsal-to-volar pressure on the distal epiphysis (**B**), usually preformed by the surgeon's thumb (**C**). The reduction should be atraumatic to lessen the risk of growth arrest. Finger trap distraction and stabilization with a few pounds can help. (From Beaty JH, Kasser JR. *Rockwood & Wilkins Fractures in Children*. 7th ed. Philadelphia, PA: Lippincott Williams & Wilkins, 2010.)

Even with acceptable reductions and casts, there is a high rate of loss of reduction in distal radial metaphyseal fractures.[43–49] On average, the incidence of loss of reduction is 20% to 30%. Higher rates of fracture instability occur with isolated distal radial metaphyseal fractures,[49] incomplete fracture reduction,[44,45] and initial displacement >30 degrees, and the highest rates occur with complete displacement.[50] The decision for the surgeon then is to allow the fracture to remodel; do a repeat CR and new cast application; or perform a CRPP. Ultimately, the choice among these options is dependent on the age of patient; degree of deformity; amount of fracture healing; and patient, parent, and surgeon preferences. Physeal fractures will remodel remarkably and are at risk for growth arrest if a repeat reduction is performed after 5 days from injury.[51]

CRPP of Distal Radius Fractures

Due to the high rate of loss of reduction for distal radius metaphyseal fractures treated with CR cast immobilization, many centers perform CRPP as the primary approach for the fractures with complete displacement.[52] Evidence by prospective study of distal radial metaphyseal fractures[47,48] reveals that the results of CRPP and CR cast immobilization are equivalent at 2 years postinjury if (1) there is sufficient growth remaining for remodeling and (2) repeat reductions are performed when the fracture redisplaces in a cast. The surgeon, patient, and family can choose what is the best treatment for the patient (i.e., there is clinical equipoise). In older patients, there is not sufficient time for remodeling, so CRPP or ORIF is indicated in the skeletally mature or near skeletally mature patient with an unstable, displaced fracture (Figure 34-9).

In addition, distal radial physeal fractures with median neuropathy are candidates for CRPP to avoid NV compromise and/or unacceptable loss of reduction.[53,54] Loss of reduction after initial CR cast immobilization of metaphyseal fractures can be treated with CRPP, but be careful about late reduction (more than 5 days postfracture) in physeal fractures due to risk of growth arrest. Finally, open fractures are candidates for CRPP, external fixation, or ORIF after operative washout of the contaminated bone and soft tissues.

FIGURE 34-8 **A:** Markedly displaced distal radial physeal fracture treated with CR cast immobilization with excessive wrist flexion mold on lateral radiograph. **B:** CR of radius and ulna metaphyseal fractures with a poor cast index noted. The obvious loss of reduction is evident.

The technique for the CR in the operating room under general anesthesia is the same as described by CR under conscious sedation in the emergency room. Once the fracture is aligned in the AP and lateral planes, sterile prepping and draping are performed. The arm is abducted onto a fluoroscopic arm table. Confirmation of the anatomic reduction on the fluoroscopic images is again obtained prior to pinning. Single or double pin techniques are used depending on the age of the patient and stability of the fracture. Blind pinning is avoided to prevent injury to the radial sensory nerve and/or extensor tendons. The first, and sometimes only, pin is placed obliquely from distal to proximal and radial to ulnar. Outlining the desired trajectory of the pin with a skin marker is helpful. A small incision is made distal to the radial styloid if the epiphysis is the entry site (distal physeal fractures and metaphyseal fractures

FIGURE 34-9 **A:** Injury films reveal markedly displaced distal radial physeal and ulnar metaphyseal fractures. **B:** The radial physeal fracture was treated with CRPP and the ulna fracture with CR. **C:** Healed fractures at 2 months post-CRPP. Epiphyseal and metaphyseal pin tracks still evident, but no physeal arrest is present.

with a short distal metaphyseal segment). The incision is more proximal with a larger distal metaphyseal segment, so the pin can avoid the physis and pass exclusively in the metaphysis. Skin and subcutaneous dissection down to the bone is performed, and retractors are placed to protect the neighboring extensor tendons and radial sensory nerve. The pin is placed against the bone to match the planned trajectory marked on the skin. Fluoroscopic images are used to confirm the pin entry site, projected path, and to avoid false entry into the joint or surrounding important soft tissues. The pin is passed on oscillation with power to prevent entanglement of the soft tissues on the pin. The proximal ulnar cortex is penetrated proximal to the fracture site. The stability of the fracture is tested manually and with fluoroscopy. If the single pin is sufficient, then the CRPP is complete. If there are instability concerns, then a second parallel radial pin or a crossed pin is placed.

An additional crossed pin may be placed from distal ulnar to proximal radial with the entry point between the fourth (extensor digitorum communis) and fifth (extensor digiti quinti) dorsal wrist compartments. The pin(s) is(are) left out of the skin, bent and cut, and dressed sterilely in a bulking fashion to prevent irritation, infection, or migration (Figure 34-10). Even some intra-articular fractures can be treated with CRPP (Figure 34-11).

ORIF of Distal Radius Fractures

If winning isn't everything, why do they keep score?
—Vince Lombardi

There are many different techniques for ORIF of an adolescent distal radial fracture. Volar and dorsal plating; locked, neutralization, and compression plating;

FIGURE 34-10 Small incision noted with pins left out of skin for removal at 4 weeks.

segmental fixation systems; and pin fixation have all been used successfully.[55,56]

The choice of surgical approach and instrumentation is often fracture and patient specific (Figure 34-12). The goals are the same regardless of implant choice: anatomic, stable reduction of both the extra-articular and intra-articular fracture fragments that allows for full rehabilitation. That said, like the adult, the present volar distal radius locked, segmental fixation systems are effective for the adolescent displaced, unstable fracture that requires ORIF (Figure 34-13).

A volar approach to the distal radius is used.[57,58] The flexor carpi radialis (FCR) tendon sheath is incised and the radial artery protected. The FCR tendon is mobilized. The digital flexors are swept ulnarly off the PQ. A moist sponge followed by a deep retractor is very effective. Crossing vascular channels are cauterized. The PQ is elevated off the radius with a deep linear incision to bone. If there is intra-articular involvement, the pronator is elevated with an upside-down "L" incision all the way to the ulnar side of the radius. Subperiosteal retractors are placed radially and ulnarly after full subperiosteal exposure is performed of the bone and fracture site. This approach and technique are now commonplace for the modern-day orthopaedic trainee, as so many of the adult distal radius fractures are now plated volarly.

The fracture is cleansed of hematoma and reduced using saline irrigation, suction, dental picks, and elevators. Temporary small, smooth wire fixation is used to align the extra-articular and, if present, intra-articular fracture fragments. Often these wires can be placed through the designated holes in the plate. Confirmation of the reduction is obtained with fluoroscopic imaging. A plate with appropriate side (left or right) and size (length and width) is chosen and fixed to the bone with smooth wires through the guide holes proximal and distal to the fracture site. Final confirmation of proper positioning on the radius in terms of proximal-distal, radial-ulnar, and plate angle orientation is obtained with direct and fluoroscopic visualization. The proximal slotted screw is placed first. Finally, tinkering of the distal alignment is performed if necessary, and then the distal pegs or screws are placed. In most adolescent fractures, nonlocking screws are appropriate, though pegs and locking screws can clearly be used as needed. Anatomic reduction and rigid internal fixation are obtained, which allows for early motion and protected rehabilitation while the bone and soft tissues are healing.

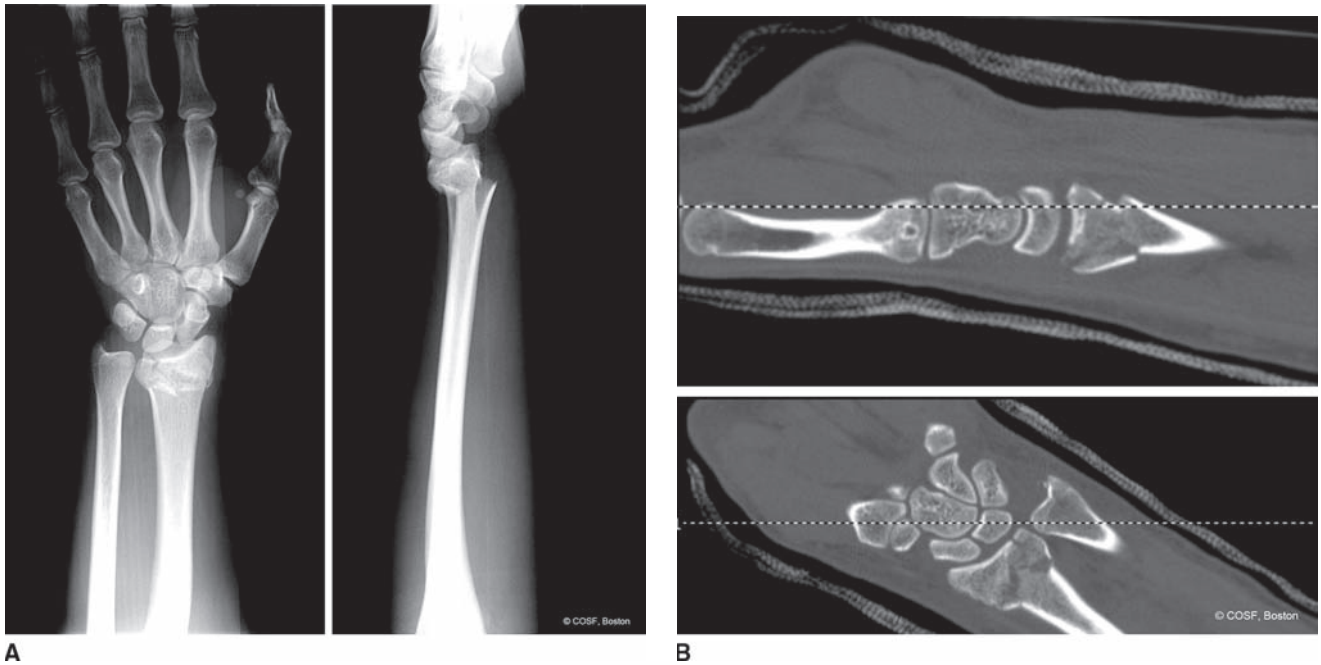


FIGURE 34-11 **A:** Injury films of displaced metaphyseal fracture with intra-articular extension. **B:** CT images of articular alignment.

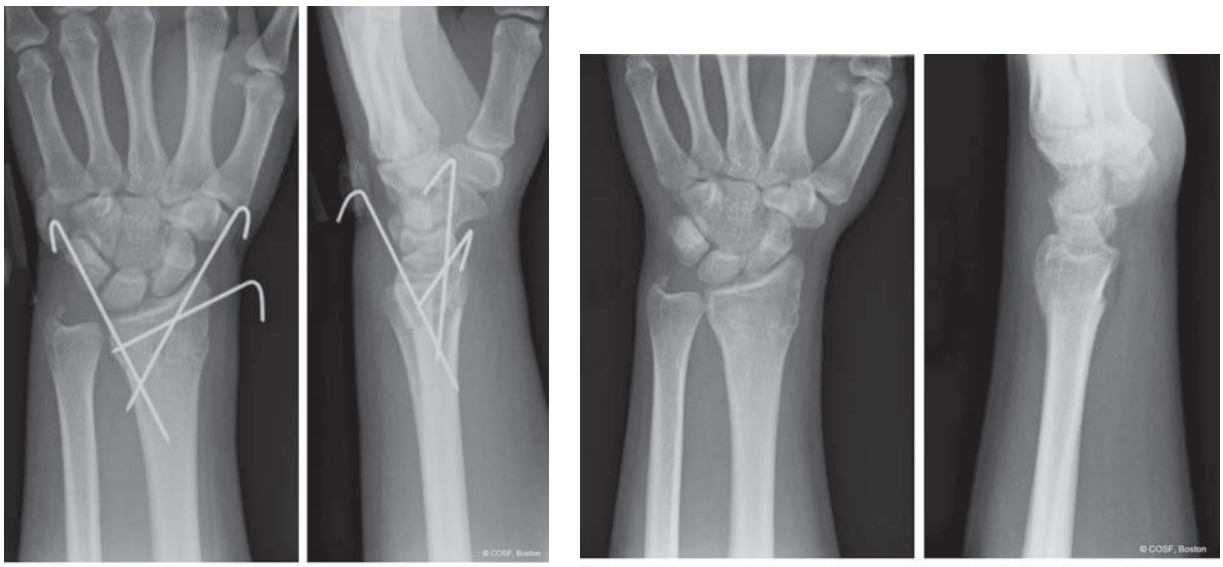


FIGURE 34-11 *(continued)* **C:** CRPP with stabilization of fracture fragments. **D:** Healed fracture with pins out.

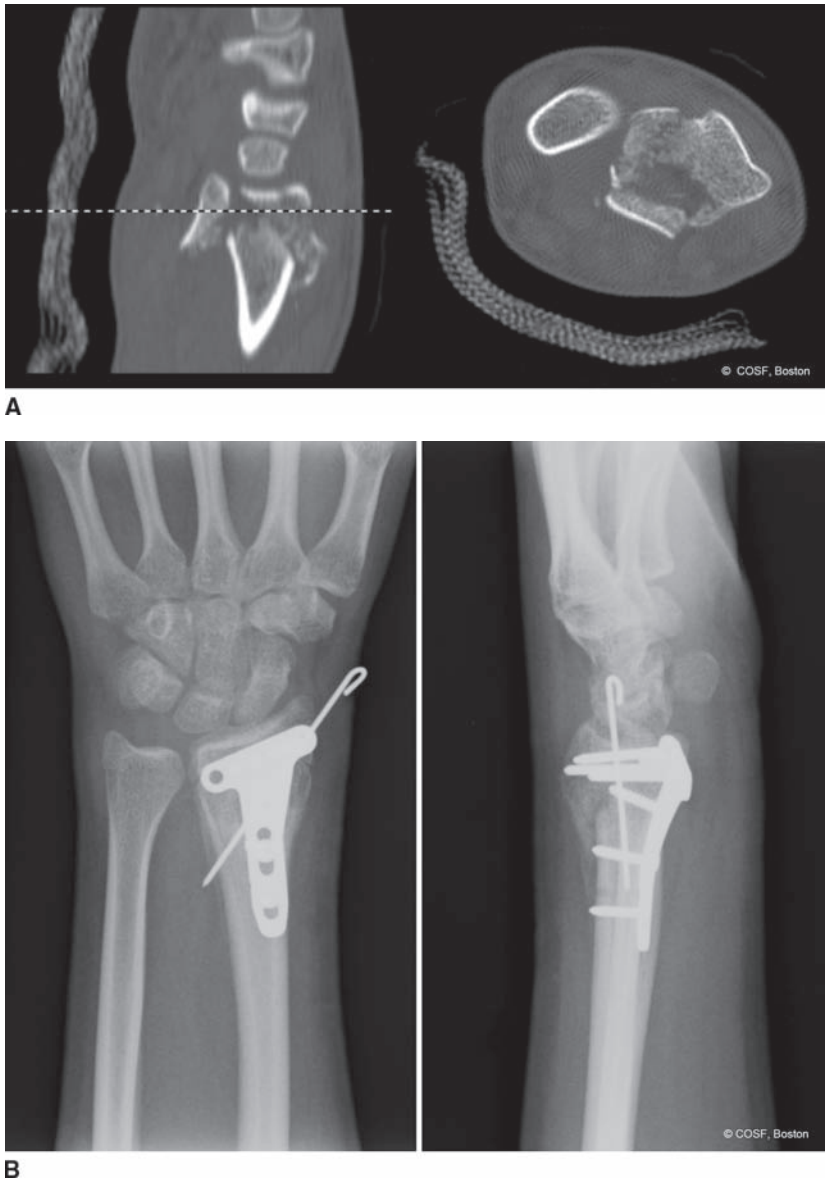
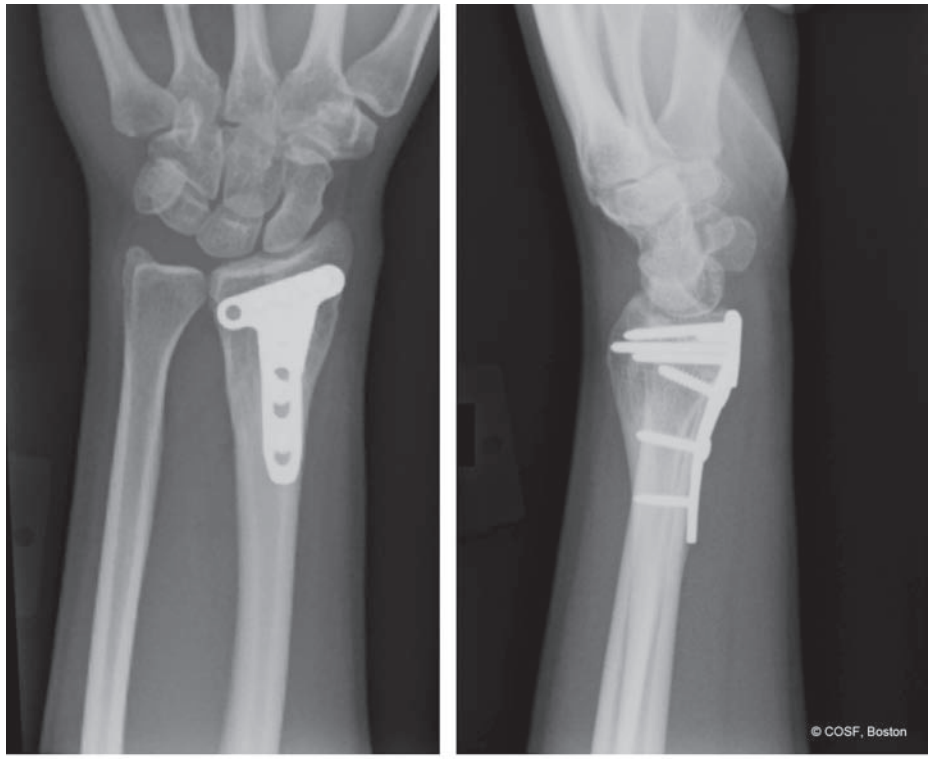


FIGURE 34-12 ORIF of distal radius with T plate and supplemental pin fixation. **A:** Injury CT scan revealing intra-articular displacement. **B:** ORIF with T buttress plate and supplemental styloid pin 1 month postoperative.



C

FIGURE 34-12 *(continued)* **C:** One year after ORIF with anatomic alignment and asymptomatic hardware.

A

FIGURE 34-13 **A:** Displaced distal radius metaphyseal and intra-articular fracture.

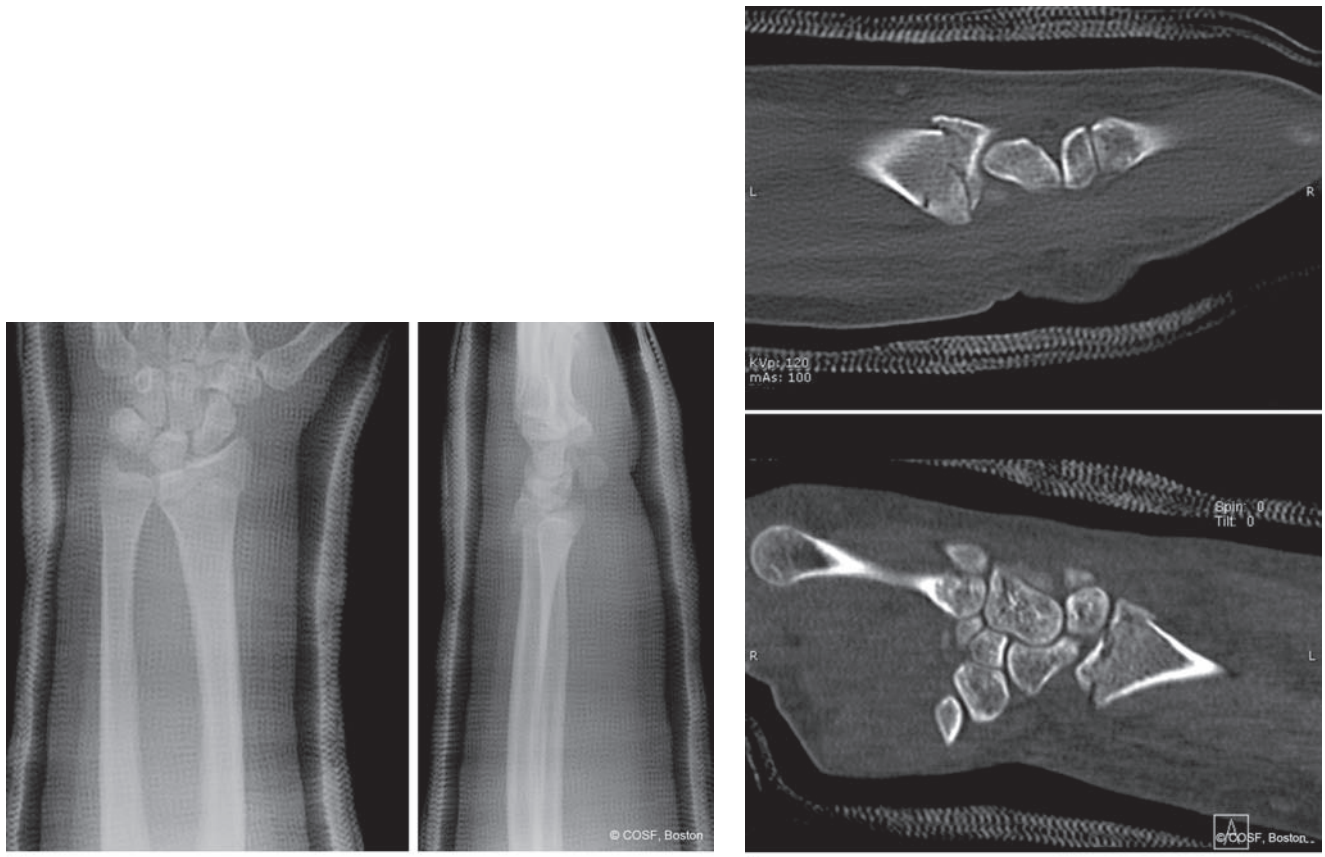
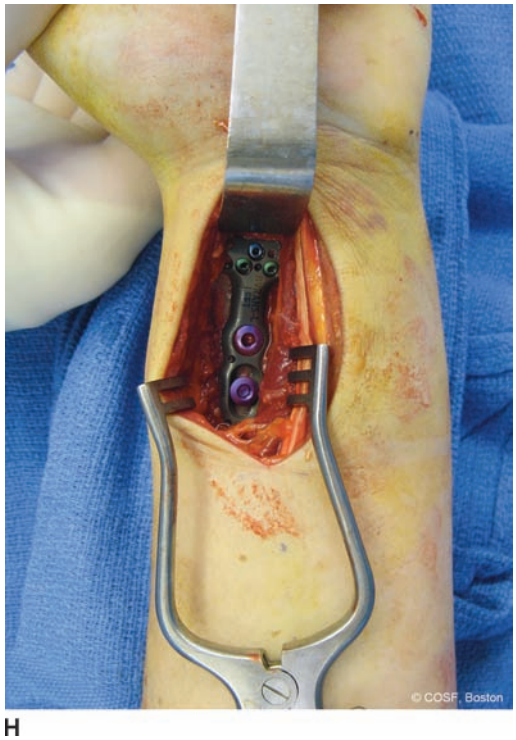


FIGURE 34-13 *(continued)* **B:** Emergency department postreduction radiographs in cast. **C:** Representative postreduction CT scan images revealing joint displacement. **D:** Clinical appearance after decreased swelling over 5 days preoperatively. **E:** Planned plate for fracture fragment specific volar fixation.

F

G



H

I

FIGURE 34-13 *(continued)* **F:** Volar approach via FCR tendon sheath. **G:** Exposed fracture site with reduction. **H:** Plate fixation of fracture anatomically. **I:** Radiographs of ORIF with volar plating system.

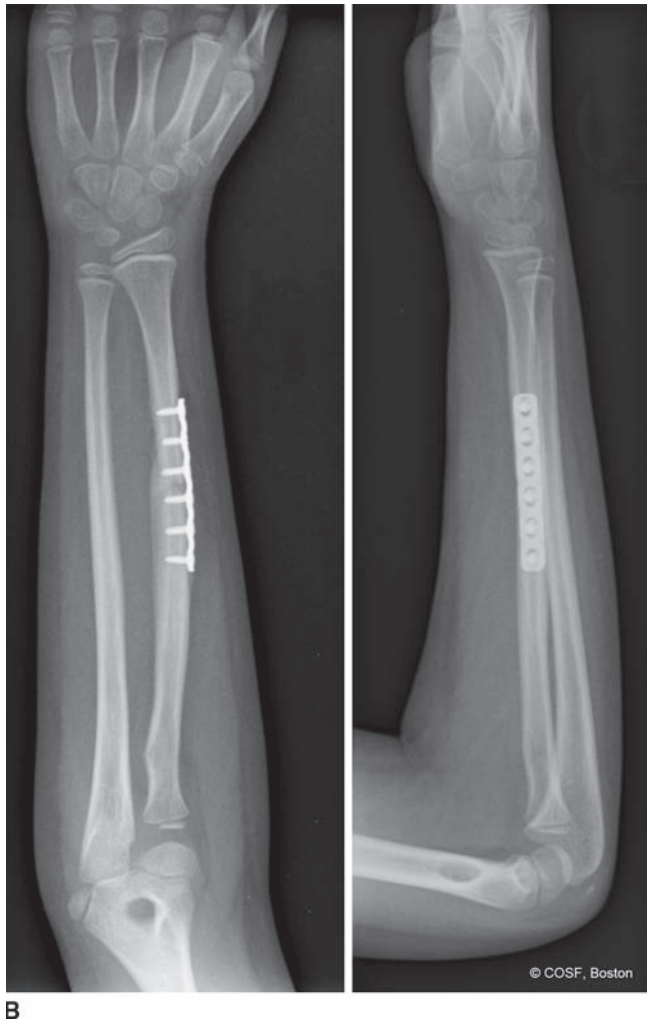
Galeazzi Fracture Dislocations

Galeazzi fracture dislocations are defined as a fracture of the distal radius and DRUJ dislocation. In children, the injury is more commonly a distal ulna physeal injury than a DRUJ ligamentous disruption and is called a Galeazzi equivalent lesion.[59–65] Galeazzi fracture dislocations are rare injuries and are classified by the type (incomplete or complete) and direction of displacement of the radius fracture

(volar or dorsal). Most lesions have dorsal displacement of the radius fracture. Incomplete injuries can be successfully closed reduced. The more common apex volar, dorsally displaced incomplete fracture is a supination deformity as well. Pronation and dorsal-to-volar pressure will reduce the fracture and align the DRUJ. The opposite reduction maneuver is performed for the apex volar, pronation deformity: The forearm is supinated and volar-to-dorsal pressure is applied to reduce the radius fracture, ulnar physeal fracture, or DRUJ. If the DRUJ is unstable with a true Galeazzi, then parallel, transverse, percutaneous pinning of the ulna to the radius is performed to reduce the DRUJ anatomically.

With complete radius fractures, ORIF of the radius is performed (Figure 34-14). The volar approach to the radius through the FCR sheath is utilized. The PQ and origin of the flexor pollicis longus are elevated off the radius subperiosteally. The fracture is debrided of hematoma and callus. The radius fracture is anatomically reduced with bone- and plate-holding clamps. Compression plating is performed. The ulnar physeal fracture or DRUJ is anatomically reduced before plating, and then the stability tested after plating. If stable, then the forearm is held in pronation for apex volar fractures and supination for apex dorsal fractures. If the DRUJ is unstable, two transverse smooth pins are placed from ulna to radius below the physes to maintain anatomic ligament positioning during soft tissue and bony healing (Figure 34-15). The pins are removed in the office at 4 weeks when the cast is changed from long to short arm. A total of 6 weeks of immobilization is performed. In the case of displaced ulnar physeal fractures, a radiograph at 6 months is recommended to identify a growth arrest before deformity occurs.

A



B

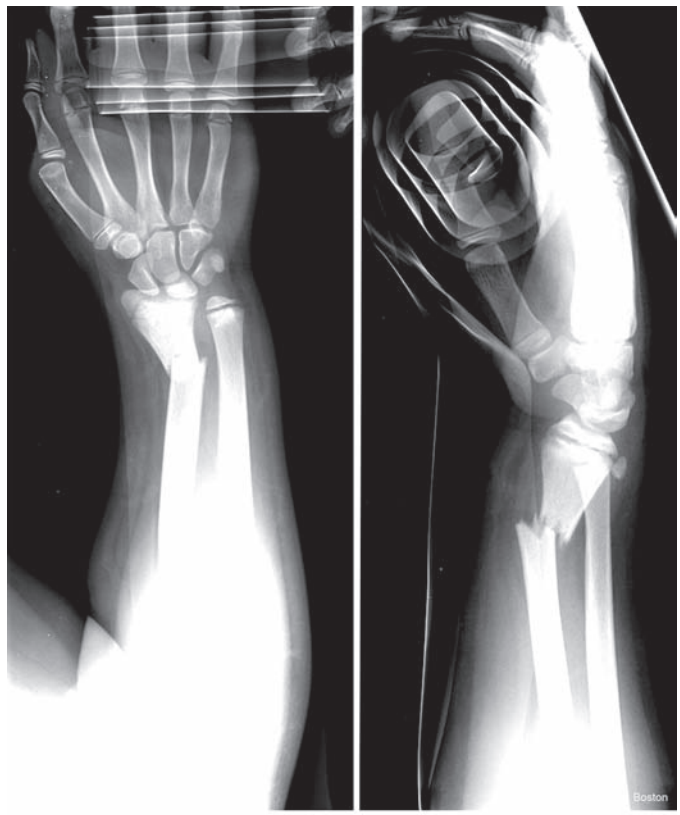
FIGURE 34-14 **A:** Injury film with diaphyseal radius fracture and displaced DRUJ. **B:** ORIF of radius fracture with stable closed reduced DRUJ that healed anatomically. Full, stable range of forearm, wrist, and elbow motion was restored.

ORIF of Acute Displaced Scaphoid Fractures and ORIF of Scaphoid Nonunion with Bone Graft

Winning is overrated. The only time it is really important is in surgery and war.
—Al McGuire

All scaphoid nonunions require open repair. There are some acute and subacute scaphoid fractures that are displaced and require reduction and stabilization. Use of CT scans will distinguish these operative fractures from nonoperative or percutaneous fixation fractures. The sagittal views will reveal a flexed scaphoid ("humpback" deformity) and an extended lunate (DISI) pattern. There may be volar comminution that will require supplemental bone graft, like a nonunion, to restore anatomic carpal alignment. Without operative reduction and fixation, these fractures are at risk for nonunion and eventual arthrosis.[66] All established scaphoid nonunions will require bone graft to restore carpal alignment. In the adolescent population, nonvascularized bone graft (iliac crest) is highly effective, so vascularized grafting is rare in this age group.[67,68] Any persistent nonunion will eventually result in wrist arthrosis (scaphoid nonunion advanced collapse [SNAC] wrist) if restoration of carpal alignment and scaphoid bony healing is not achieved.

Although smooth pins have been successfully used for fixation in both acute fractures and nonunions, the standard now is an intraosseous screw (Acutrak, Acumed, Hillsboro, OR; Herbert, Zimmer, Inc., Warsaw, IN; or Synthes, West Chester, PA). Volar and dorsal surgical approaches have been used successfully. Our preference is a volar approach to directly visualize the fracture



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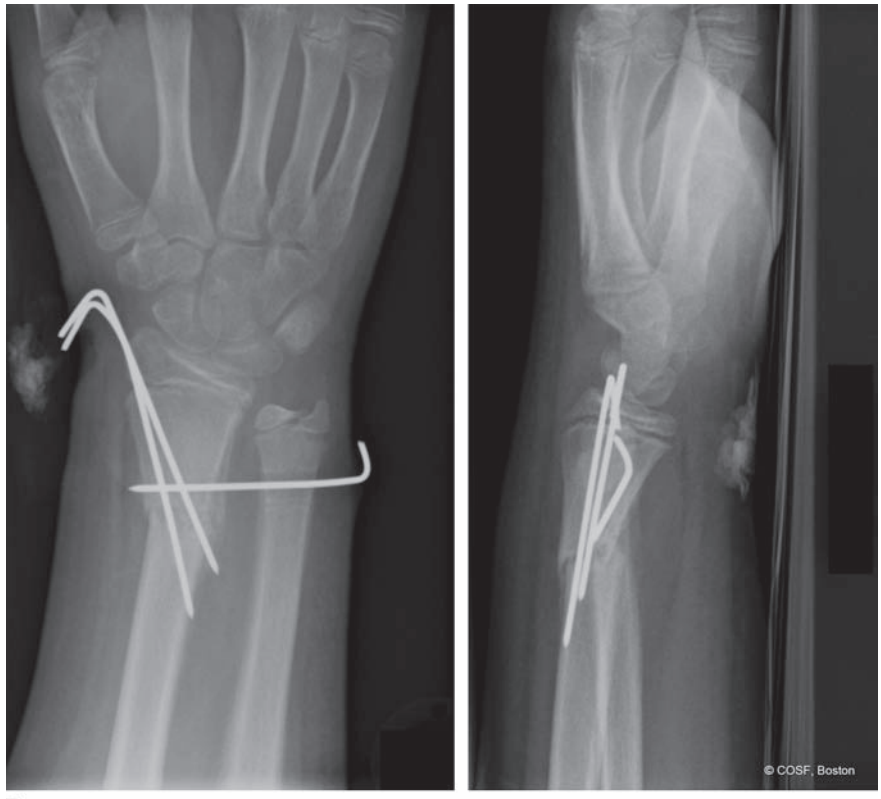


B

FIGURE 34-15 **A:** Multiple trauma motor vehicle accident patient with open ankle fracture, closed chest trauma, and displaced distal radius and ulna physeal (Salter-Harris type III) fractures as noted by injury radiographs. **B:** CRPP of radius performed with cross pin stabilization of DRUJ.

or nonunion site; assess fracture reduction or nonunion defect; and, if necessary, exactly measure the bone defect and size of graft needed to restore anatomic alignment.[69] In cases with DISI deformity, a temporary oblique smooth wire (0.62") is placed from the radial styloid across the lunate into the distal carpal row to colinearly align the lunate fossa, lunate, and capitate. By anatomically positioning the lunate, the volar defect of the scaphoid is precisely measurable.

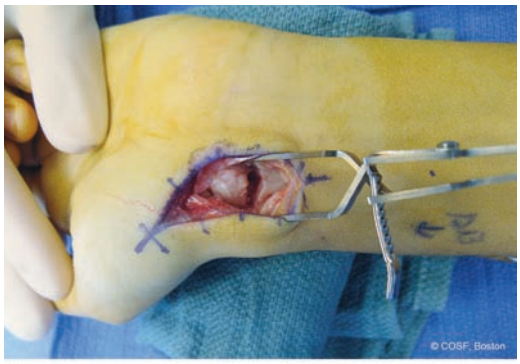
A volar curvilinear approach, centered over the scaphoid tubercle, is used. The distal FCR sheath is incised and the tendon mobilized. Distally the dorsal edge of the thenars is elevated while protecting any radial sensory nerve cutaneous branches that may cross the operative field. The volar branch of the radial artery is isolated and protected. A preoperative Allen test to identify the patient with an incomplete carpal vascular arch is mandatory in case the volar artery branch is ligated or used as a pedicle graft in nonunion surgery.[70] The wrist capsule is incised over the waist of the scaphoid while protecting the FCR tendon. The displaced fracture or nonunion site is identified. Often the radioscaphocapitate ligament can be preserved. If it is incised, it is repaired with wound closure. Capsular elevation off the scaphoid distal pole, scaphotrapezial joint, and radial trapezium is performed. The entry site for the cannulated smooth pin and screw is isolated. At times, proper pin alignment in the "1-1" position (exactly centered on the AP and lateral scaphoid fluoroscopic images) requires rongeur removal of the radial, volar trapezium. Smooth curved retractors (either from the system or Freer elevators) are placed in the radioscaphoid joint to elevate the scaphoid and allow full visualization of the entire scaphoid. Distraction of the thumb ray by an assistant or your nondominant hand is very helpful. Small towel rolls under the wrist allow for more extension and ulnar deviation to better visualize the scaphoid waist and align the proximal and distal poles.

The fracture is anatomically reduced. If there is a volar defect, the appropriate amount of radial or iliac crest autograft, allograft, or bone morphogenetic protein (BMP) is used (Figure 34-16). Our preference is structural autograft, both for healing and prevention of collapse with screw compression. In the cases of nonunion, the proximal and distal poles are debrided of fibrous tissue back to bleeding bone. Measurement of the volar defect is made. A tricortical iliac crest graft is obtained (see Sidebar). The bone graft is meticulously trimmed to be an exact fit with dorsal-to-volar and radial-to-ulnar tilting of the trapezoidal graft. The cortex of the graft is set to align with the proximal and distal pole cortices. Once the acute fracture or nonunion graft is impacted in place, the "1-1" positioned cannulated wire is passed from the distal pole into the proximal scaphoid. Pin measurement is made from the instrumentation system used, but you need to take into account the length loss with screw compression. In most systems, a 2- to 4-mm reduction in screw length from the cannulated pin length measurement is necessary to prevent screw penetration into the joint. Depending on the system, drilling over the wire is performed. The graft needs to be either manually stabilized or held in place with a second smooth wire during drilling and screw placement. The appropriate-length screw is placed over the wire while inspecting intermittent fluoroscopic images. The screw needs to be completely buried in the bone, without proximal extrusion or distal penetration into the joint. Compression across the fracture or nonunion site is necessary while restoring anatomic scaphoid alignment. All of this is confirmed by fluoroscopic images (Figure 34-17). If a translunate wire was placed to restore carpal alignment, that smooth pin is now removed. The lunate should stay in neutral alignment at rest and with wrist motion. The scaphoid should move as a single, stable unit. No crepitus should be heard or felt with full wrist motion. If there is, then the screw is too long and needs to be changed. The graft should be

SIDEBAR

Iliac Crest Bone Graft

Autograft has the advantage of being both osteoconductive and osteoinductive. The major disadvantage of autograft is donor site morbidity, and the minor disadvantage is bone substitute alternatives that may have less risk to the patient, such as allograft and BMPs. (They also could be more expensive.)[118,119] A bicortical or tricortical piece of iliac crest bone graft is used for scaphoid nonunion reconstructive surgery. Through a small anterior incision, the bone graft is harvested. The incision is placed below the belt line (not always easy to tell where the pants will sit in some modern-day teenagers) to avoid scar irritation later. The incision is always at least 2 cm lateral to the anterior superior iliac spine to avoid injury to the lateral femoral cutaneous nerve or iliac wing fracture. Dissection is carried in layers to the periosteum. In the young, the iliac apophysis has to be split and then repaired after bone graft harvest. The nonunion site is measured and a structural piece of graft is obtained that is slightly larger than the desired three-dimensional graft. Additional cancellous bone can be obtained if there is marked cyst formation in the scaphoid that will need to be packed into the proximal and distal pole defects. Gelfoam (Baxter Healthcare Corp., Hayward, CA), followed by bone wax, is applied to the iliac crest donor site. Care is taken to obtain meticulous hemostasis to lessen the risk of hematoma formation and/or deep infection. A tight closure is performed of the apophysis, periosteum, fascia, and subcutaneous and skin layers with absorbable suture. Drains are not used. Local anesthesia is generously injected within the limits of body weight restrictions. Sterile dressings are applied to prevent superficial wound problems.



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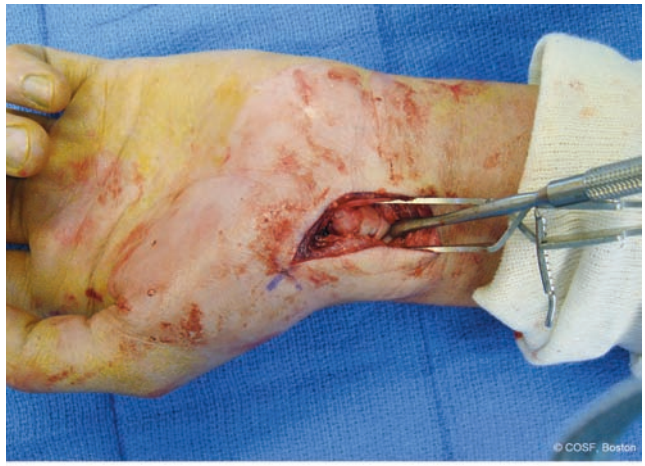

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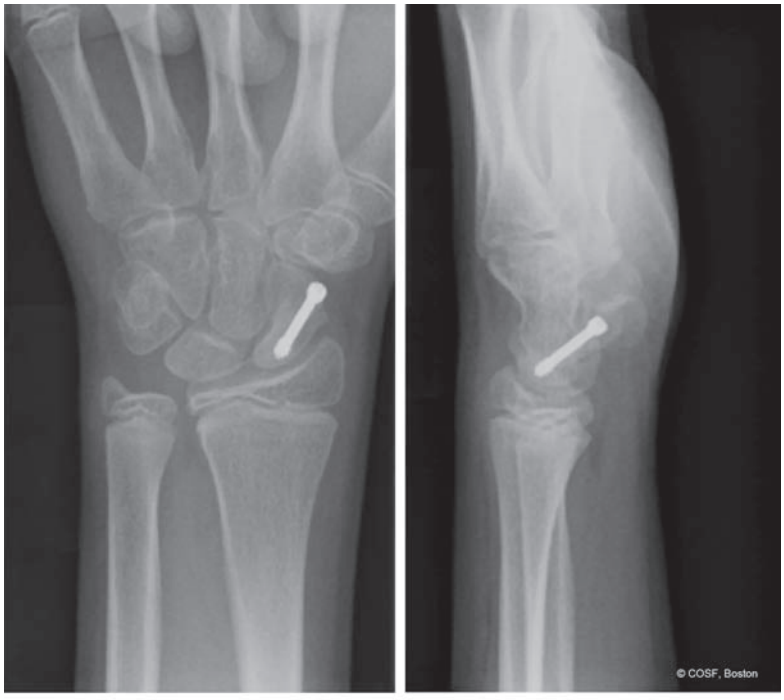


C

FIGURE 34-16 **A:** Scaphoid nonunion is exposed and defect measured. **B:** Iliac crest is inset before screw fixation. **C:** Healed scaphoid nonunion with screw in desired location.

stable and not impinge with full radial deviation or flexion. If it protrudes volarly and impinges, the graft edges need to be gently trimmed with small rongeur without destabilizing the graft or fixation. Capsular closure including any incised volar ligaments is performed with absorbable suture. Layered closure is completed while protecting the radial artery. A bivalved short-arm thumb spica cast is applied.

Ulnar Shortening Osteotomy and Radial Growth Arrest and Ulnocarpal Impaction

Ulnocarpal impaction syndrome occurs with ulnar positive variance and is associated with TFCC tears, lunotriquetral ligament tears, and chondromalacia of the triquetrum and lunate. The patients present with ulnar-sided wrist pain that is exacerbated by forearm supination and ulnocarpal compression with ulnar deviation. In the extreme situations, there is a block to forearm rotation and a dislocated DRUJ.[71] Radiographs will reveal a positive ulnar variance that is either idiopathic (symmetric to the opposite side) or post-traumatic (radial physeal arrest with continued ulnar growth in the skeletally immature patient). The variance can range from mild (1 to 2 mm) to extreme (>10 mm) (Figure 34-18). A preoperative MRI may reveal a TFCC or lunotriquetral ligament tear. Surgery is indicated for leveling the ulna to neutral or 1- to 2-mm

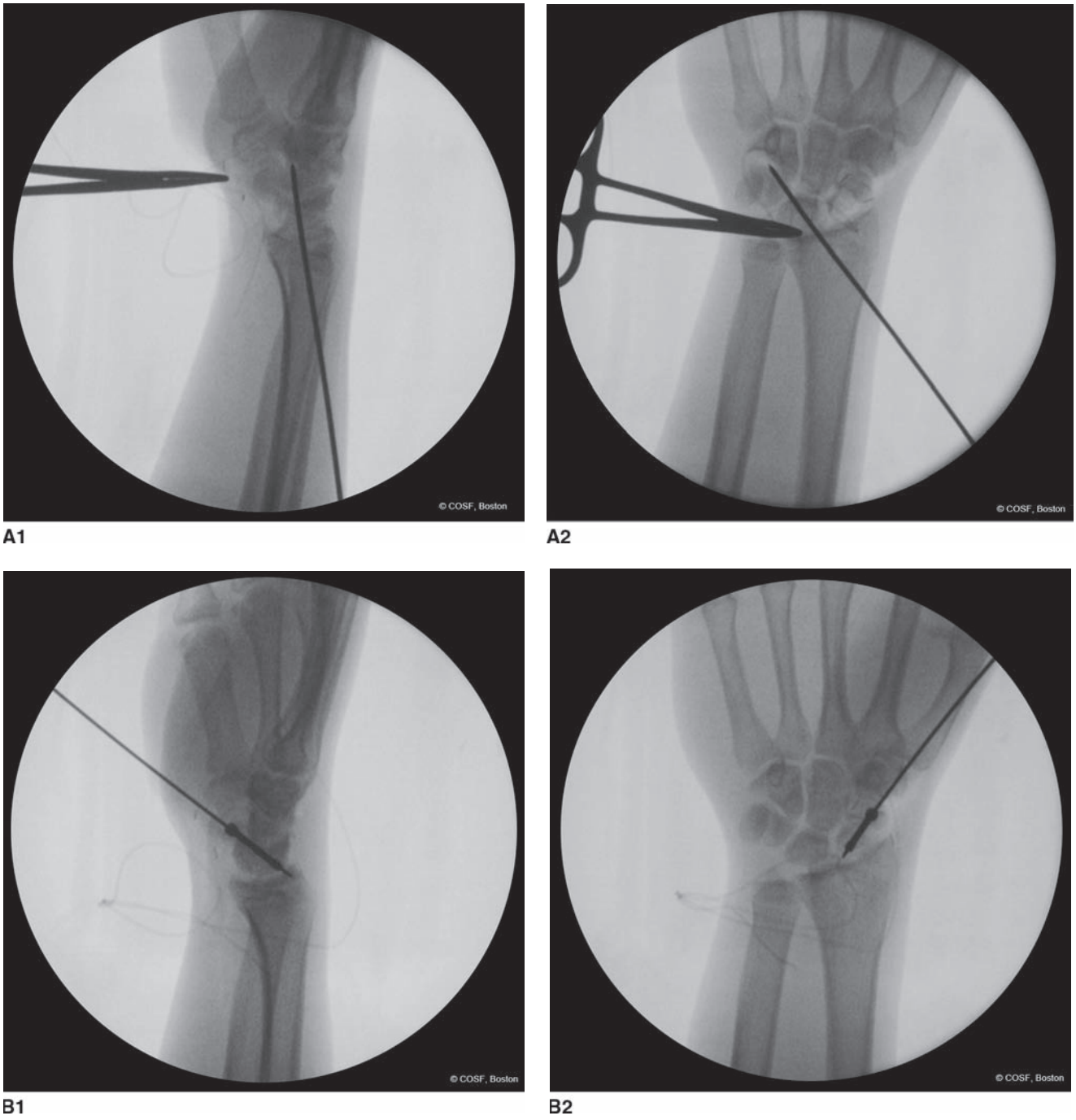


FIGURE 34-17 **A:** Transradial temporary fixation of the lunate anatomically in order to restore carpal alignment with ORIF and bone graft. **B:** Cannulated screw technique noted by fluoroscopic images with anatomic scapholunate articulation.

negative variance to resolve the ulnocarpal impaction. Wrist arthroscopy is performed during the same surgery after the ulnar shortening osteotomy is stabilized to assess the TFCC and perform a debridement or repair as appropriate (see Chapter 42).

Preoperative standardized radiographs of the affected and unaffected sides for ulnar variance (wrist neutral, forearm pronated, elbow flexed 90 degrees, and shoulder abducted 90 degrees) are compared to determine the planned extent of ulnar shortening.[72] Under general and/or regional anesthesia, the arm is prepped and draped on a fluoroscopic arm board with the shoulder abducted. A straight incision and approach to the distal ulna metaphysis and diaphysis is utilized. The extensor carpi ulnaris and flexor carpi ulnaris interval is split to the periosteum. Distally the branches of the ulnar sensory

FIGURE 34-18 **A:** Ulnar positive variance with ulnar impaction syndrome that is symptomatic requires ulnar shortening osteotomy and, at times, (**B**) a radial osteotomy as well. (From Beaty JH, Kasser JR. *Rockwood & Wilkins Fractures in Children.* 7th ed. Philadelphia, PA: Lippincott Williams & Wilkins, 2010.)

nerve are protected from iatrogenic injury if they cross the field. The periosteum is incised, and subperiosteal elevation is performed. With direct visualization and fluoroscopic guidance, a five-or six-hole dynamic compression plate or two double-stacked semitubular plates (Synthes, West Chester, PA) are placed on the dorsal aspect of the ulna. The distal two screw holes are drilled and measured, and an appropriate-length screw is partially placed through both cortices in each of the distal two plate holes. The screws are not yet fully tightened to prevent stripping of the cortical purchase later after completion of the osteotomy. The planned,

ulnar shortening osteotomy site is marked precisely. The shortening osteotomy cuts are oblique, parallel to one another, and exactly measured for desired postoperative ulnar variance. The width of the oscillating saw blade from the two parallel cuts needs to be taken into account in the measurement and to end up with the planned shortening. The ulna bone is marked longitudinally with an osteotome proximal and distal to the osteotomy site to assure no malrotation will occur with the shortening. With free-hand osteotomies, the distal cut is made through one cortex, and a rectangular portion of a sterile plastic ruler or a thin saw blade is placed in that cut. The more proximal, second cut is then made exactly parallel to the plastic or metal indicator of the first cut. The osteotomy is completed, and the bone is removed for later morselized bone graft. For more extreme shortenings (10 to 20 mm), a Z-cut shortening is used to create bone overlap and union of the osteotomy site.[73] The plate(s) is reapplied distally and distal screw fixation completed. The osteotomy is then closed manually while maintaining rotational alignment. A bone- and plate-holding clamp is applied, and the osteotomy and ulnar variance is checked on fluoroscopy. Modifications are made if necessary. Once the desired shortening has been achieved, the proximal screws are placed with compression technique. The oblique osteotomy should close precisely. If necessary, bone graft is applied around the osteotomy site before periosteal reapproximation. Besides individual case measurements and free-hand cuts, there is a commercially available system for parallel osteotomy saw cuts from 2.5 to 18 mm of shortening.[74] (Rayhack Ulnar Shortening System, Wright Medical Group Inc., Arlington, TN; Ulnar Osteotomy Plate, Trimed, Inc., Valencia, CA).

After completion of the ulnar shortening osteotomy, wrist arthroscopy is performed in standard fashion. Osteochondral lesions are debrided to a stable base. Synovitis and osteochondral loose bodies are excised. Palmer type IB or ID TFCC tears are repaired and 1A lesions are debrided (see Chapter 42). All wounds are then closed and a long-arm bivalved cast applied.

◆ Percutaneous Screw Fixation of Acute Scaphoid Fractures

A tough day at the office is even tougher when your office contains spectator seating.
—Nik Posa

The indications for percutaneous screw fixation of an acute scaphoid fracture are relative.[75,76] Displaced fractures need reduction and fixation. This can be achieved either by an ORIF or percutaneous stabilization, potentially with arthroscopic assistance.[77] If there is no volar comminution, then percutaneous fixation is appropriate. Proximal pole fractures are at highest risk for AVN and nonunion. Proximal pole nonunion is a complex problem with higher rates of operative failure and may require vascularized bone graft to achieve bony healing.[78] Therefore, percutaneous screw fixation with compression of a proximal pole scaphoid fracture is indicated in our practice (Figure 34-19). Finally, there is a choice among patients with nondisplaced scaphoid waist fractures: cast versus percutaneous screw treatment.[79] Both have statistically high rates of healing in the adolescent. The percutaneous screw treatment heals faster if performed properly. Parents, patients, and surgeons will have strong opinions about what they want, and in a clinically equipoised situation such as this one, that is permissible.

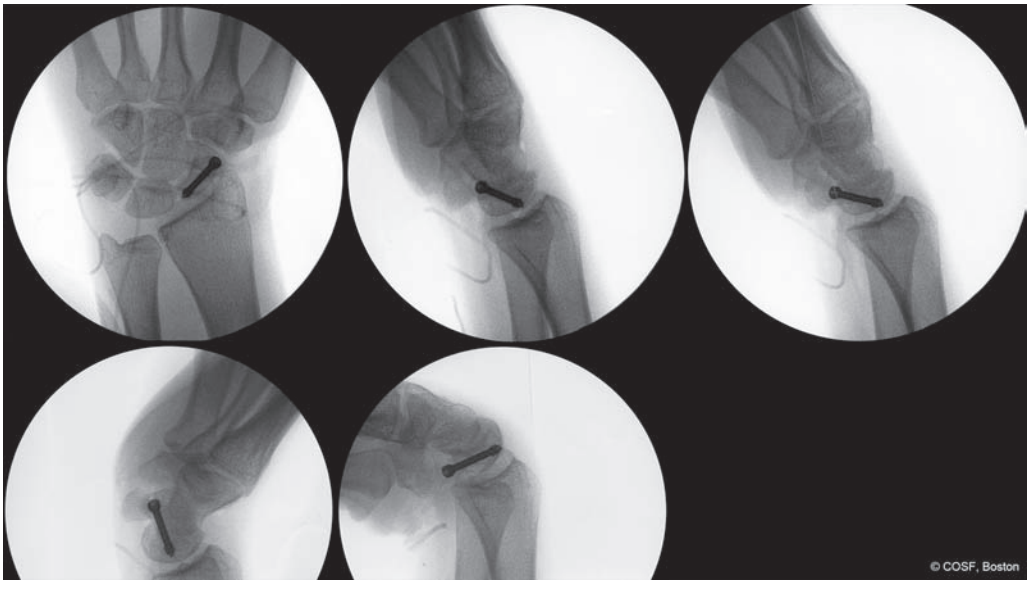


FIGURE 34-19 Volar percutaneous fixation of a scaphoid fracture.

Percutaneous screw fixation of an acute scaphoid is an operation that appears easier than it is. You have to get the guide pin in the "1-1" position centered in the scaphoid on the AP and lateral fluoroscopic images. In essence, that is the entire operation. It is the hard part, and too often surgeons stop before they achieve an anatomically aligned scaphoid with the pin in the center. The risk of a nonunion increases if the screw is placed eccentrically. The resultant loose screw banging around in the wrist leads to bone and joint deterioration that can make the problem worse.

The choices for percutaneous screw fixation are to enter distal volarly or proximal dorsally. If the volar approach is used, the procedure follows the anatomy outlined in the ORIF section but with a mini-incision volarly. If the dorsal approach is used, the patient has to have enough wrist flexion to bring the proximal pole of the scaphoid beyond the dorsal ridge of the radius.[80] Many teenagers are ligamentously lax enough for that to happen. With the proximal pole then just beneath the skin, the entry site in the bone can be reached easily. Fluoroscopy is used to identify the proximal pole, and a small incision is made on the dorsal wrist. The extensor tendons are retracted, usually the extensor pollicis longus, and the capsule is entered. The proximal pole and scapholunate interval can be directly visualized. The pin for the cannulated screw is placed on the proximal pole with soft tissue guide protection. The scaphoid will align with the entire thumb ray, so pin placement is easiest if you follow the thumb. Confirming fluoroscopic radiographs are obtained before drilling and screw placement. At times, this can be a dance because the pin and distal radius can impinge on one another. Some surgeons will pass the pin out of the distal pole of the scaphoid and volar skin before screw placement. Once the "1-1" position is achieved, screw length is measured, and the compression scaphoid screw is placed. Direct and fluoroscopic visualization is performed to be certain that the screw does not penetrate the joint or sit eccentrically in the bone. Full wrist motion should be without crepitus. A short-arm bivalved thumb spica cast is applied. The cast is changed every month until bony healing is achieved. Not all patients are trustworthy for removable splint treatment.

Distal Radial Osteotomy

Unfortunately, not all distal radius and/or ulnar fractures heal anatomically or remodel to an acceptable alignment (Figure 34-20). The distal radioulnar malalignment can restrict forearm rotation; the radiocarpal malalignment can lead to midcarpal instability and ulnocarpal impingement. Malunions with functional restriction of motion and/or pain are candidates for an osteotomy. Usually you fix the bone with the problem (i.e., the radius), but there are times when the radial deformity and forearm skeletal imbalance are addressed with an ulnar shortening osteotomy (see "Ulnar Shortening Osteotomy" section).

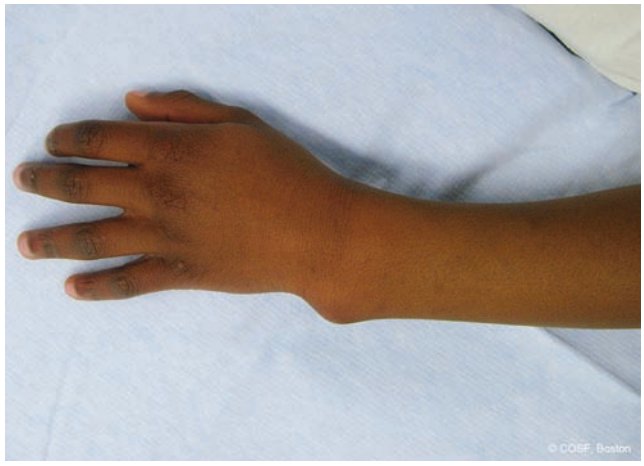


FIGURE 34-20 Preoperative clinical photograph of a malunion of the distal radius.

Most situations can be resolved with a radial osteotomy (Figure 34-21), but some malunion patients require osteotomies of both the radius and ulna to achieve skeletal balance, restore motion, and relieve pain.[81]

Initially malunions were treated with a dorsal opening wedge osteotomy and bone graft[46,82,83] (Figure 34-22A). The volar locked plating systems lessen the risk of hardware irritation and/or extensor tendon disruption (Figure 34-22B). The surgical approach is the same as for ORIF of the radius. The FCR sheath is incised, and the PQ muscle is elevated. Subperiosteal elevation allows for full visualization of the malunion and radius proximally and distally. With full subperiosteal elevation, a dorsal opening wedge osteotomy can often be performed from a volar approach, making a two-incision technique rare. The site of maximum deformity is visualized and confirmed by fluoroscopy. If the deformity is merely extension malangulation, an opening wedge will correct the problem. If there is malrotation and malangulation, then an osteotomy in the plane of maximum deformity will allow for correction of both the malrotation and malangulation. The plate is aligned with the articular surface and fixed distally. This will lead to an anatomic joint and plate alignment with completion of the osteotomy. The osteotomy is performed as previously planned pre- and intraoperatively. The plate is reduced to the bone proximally, which corrects the bone and joint malalignment. The osteotomy and plate reduction is confirmed fluoroscopically, and then the plate is fixed proximally. Excessive bone is trimmed and can be used as bone graft. Other bone graft options are iliac crest or radial autograft, allograft, and commercial bone substitutes and stimulants. Full motion should be possible without impingement. Radial articular alignment on AP and lateral images, ulnar variance on the AP image, and DRUJ alignment on the lateral image are assessed to be certain all preoperative goals have been met. If there is residual deformity or restriction of motion that requires an ulnar osteotomy, that is performed now. In

FIGURE 34-21 **A:** Distal radius malunion with painful, restricted forearm rotation and dorsal wrist pain. **B:** Corrective radial osteotomy alone resolved his motion restriction.

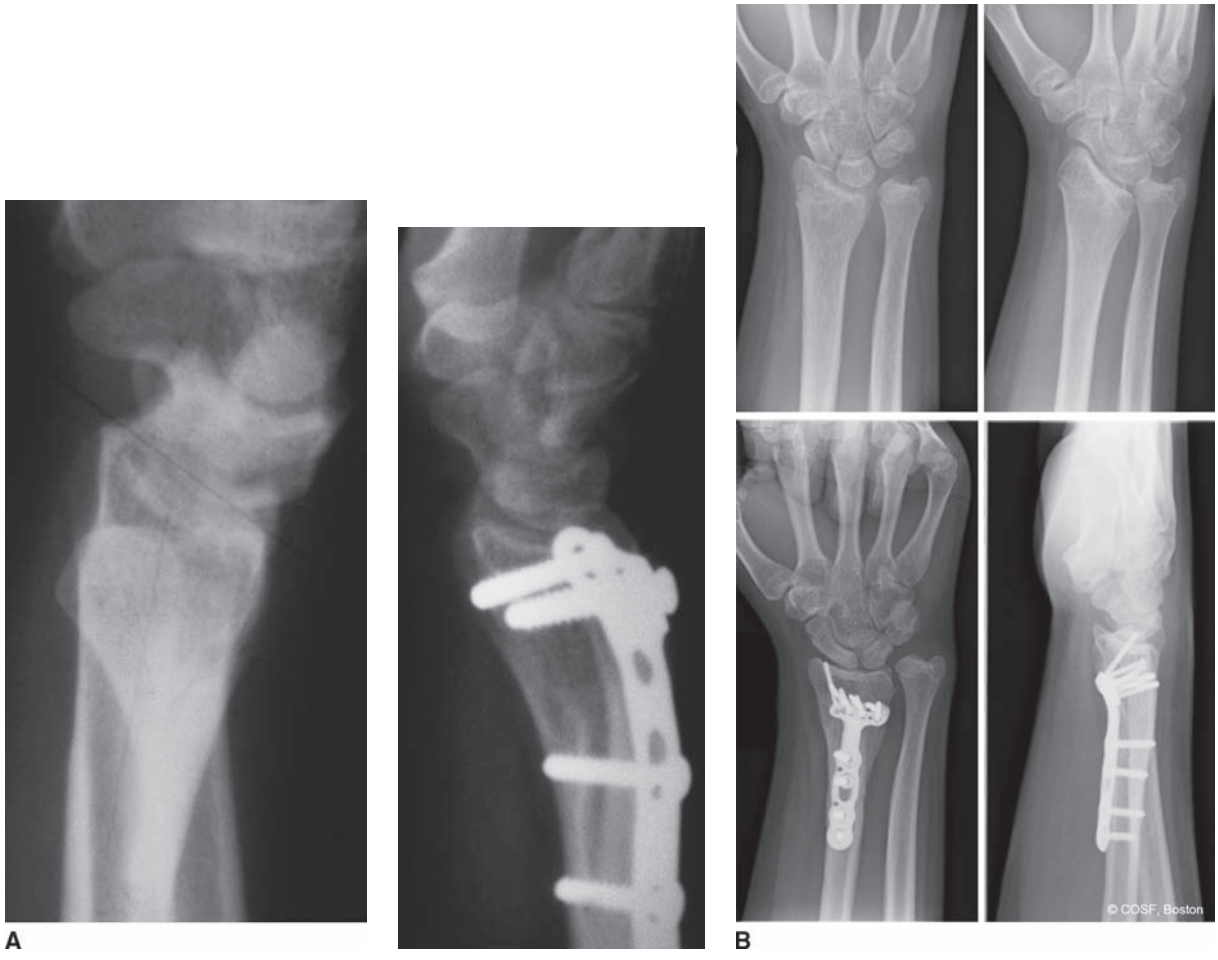


FIGURE 34-22 **A:** Distal radius malunion surgically treated with dorsal plating and bone grafting. Now that surgery is most often performed volarly. **B:** Distal radial malunion treated with volar plating and bone grafting. (**A** from Beaty JH, Kasser JR. *Rockwood & Wilkins Fractures in Children*. 7th ed. Philadelphia, PA: Lippincott Williams & Wilkins, 2010.)

these rare, complex cases (Double Black Diamond level), the ulnar correction is often both rotational and angular. The surgical approach and technique are similar to the ulnar shortening procedure described, but the rotational and angular corrections are more complex than a straight shortening procedure. At the completion of the dual osteotomies, full motion without impingement should be achieved. Due to the extensive nature of the surgery, prophylactic forearm fasciotomies are performed prior to closure to lessen the risk of postoperative compartment syndromes. Postoperative immobilization and initiation of motion are dependent on the extent of surgery, stability of fixation, and psychosocial maturity of the patient.[84]

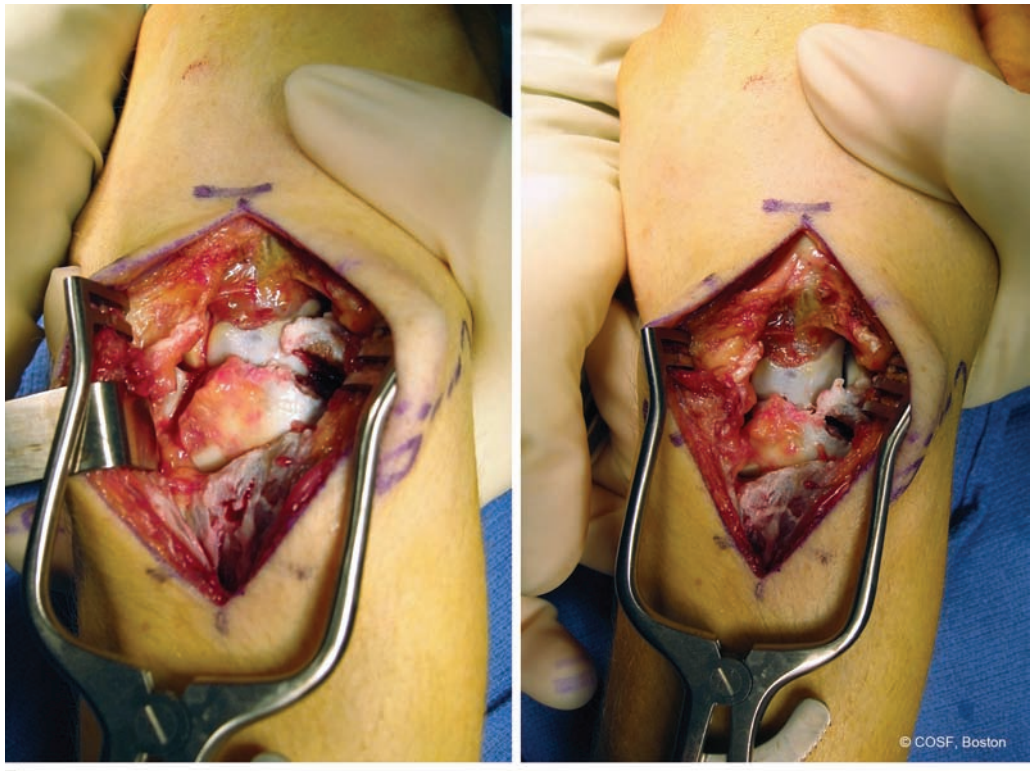
◆◆ ORIF of Perilunate Dislocations

Trans-scaphoid or true perilunate dislocations occur rarely in children and adolescents. Motor vehicle accidents or extreme sports are usually the cause. Many pediatric orthopaedists have never seen the injury after residency, so radiographic interpretation can be confusing due to lack of experience in pediatric facilities (Figure 34-23). Perilunate dislocations are at risk for median neuropathy and acute carpal tunnel syndrome due to direct trauma, tenting of the nerve by the volarly dislocated lunate, and excessive swelling. Acute reduction is desired. A CR approach under conscious sedation can improve the situation in the emergency room. There have been advocates for CRPP of these cases. Most hand surgeons agree that open reduction and operative repair of disrupted ligaments have the best long-term outcome. If feasible, these cases should go to the operating room acutely.[85,86]

An extensile volar approach through the distal forearm carpal canal allows for (1) release of the carpal canal to decompress the median nerve and Z-plasty reconstruction of the transverse carpal ligament to prevent future bowstringing of the nerve and postoperative pillar pain, (2) open reduction of the volarly dislocated lunate, and (3) open repair of the disrupted volar radiocarpal ligaments with nonabsorbable mattress sutures. Some surgeons feel this is unnecessary as CR in the operating room will reduce the lunate, decompress the carpal canal, and align the ligaments so they can heal biologically.

A

FIGURE 34-23 **A:** Preoperative radiographs of trans-scaphoid perilunate dislocation.



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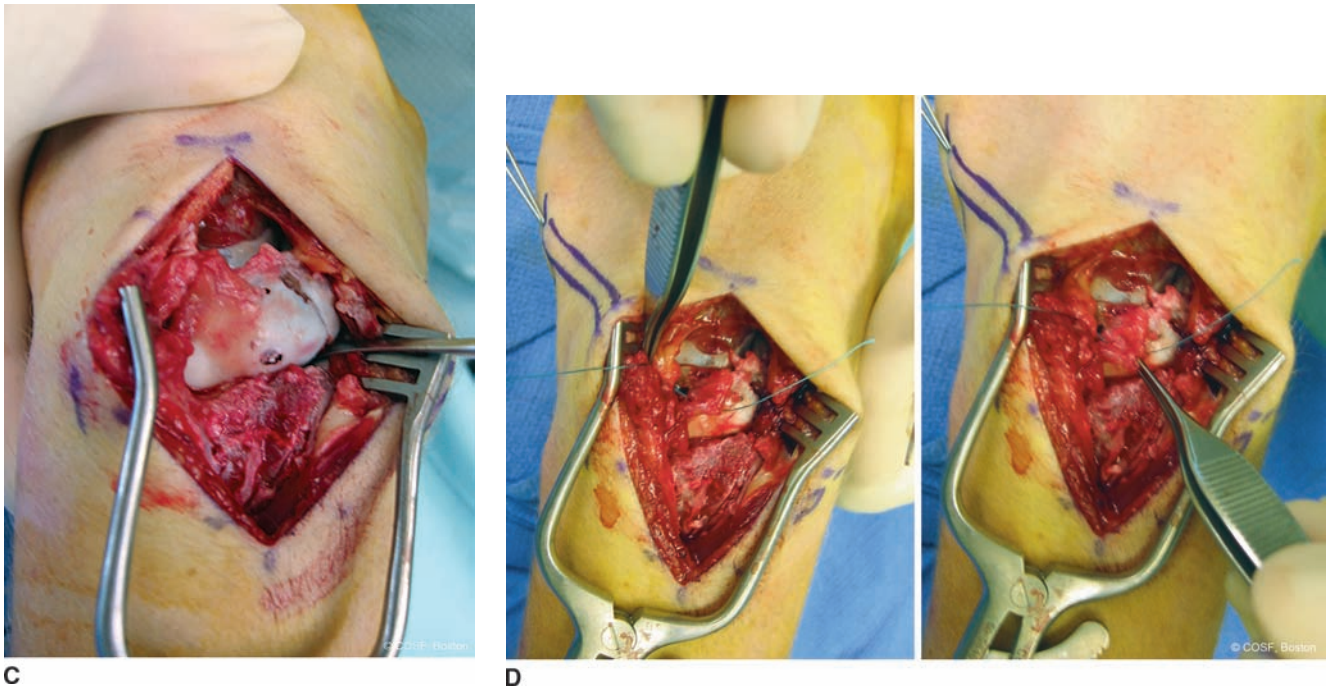


C D

FIGURE 34-23 *(continued)* **B:** Displaced scaphoid fracture noted from extensile dorsal exposure. **C:** Internal fixation of scaphoid with osseous screw after anatomic reduction. The screw was further countersunk. **D:** Repair of lunotriquetral ligament disruption with osseous suture anchors.

An isolated dorsal approach, or as a part of a two-incision technique, allows for (1) anatomic open reduction of the lunate dislocation; (2) open reduction screw fixation of the displaced scaphoid fracture; (3) reduction and pin fixation of all the carpal malalignments in and between the proximal and distal carpal rows and radiocarpal joint; and (4) open repair of the disrupted scapholunate, lunotriquetral, and dorsal/or carpal ligaments with osseous suture anchors.[87,88]

◆◆ Physeal Bar Resection and Fat Graft Interposition for Distal Radius Growth Arrest

About 4% of distal radius physeal fractures develop a growth arrest. Most of these physeal arrests occur near the end of growth and involve more than 50% of the physeal cartilage. Thus, adolescent arrests are rarely candidates for physeal bar resection and fat graft interposition surgery. If they are identified early, an ulnar epiphysiodesis can be performed before ulnar overgrowth occurs. This is performed through a small longitudinal incision over the distal ulna physis. The physeal cartilage is located with a needle by fluoroscopy and direct visualization. Drilling of the physis and curettage is performed. Bone graft is inserted, and the small wound is closed in layers from the periosteum to the skin.[89,90]

If the patients with a physeal arrest present later with ulnar overgrowth and ulnocarpal impaction, an ulnar shortening osteotomy and potential TFCC repair are indicated. If the arrest is localized (<30% of the physis by three-dimensional MRI analysis) and the patient is young, then a physeal bar resection is indicated. These rare cases are often secondary to a missed Salter-Harris type III or Salter-Harris type IV fracture.

A limited,[91] direct approach to the physeal bar through the metaphysis is performed dorsally with fluoroscopic guidance. A power burr is helpful for the tunnel through the metaphysis directly to the osseous bar in the physis. A headlamp is used to distinguish the bar from the normal physeal cartilage and to be certain all of the osseous bar has been resected. The bar is gently resected with small curettes and rongeurs. Bone wax is meticulously packed to prevent bleeding that could promote recurrence of the bar. With the tourniquet down, the area needs to be "bone dry" before placing the interposition spacer. A fat graft, often from the proximal, lateral thigh, is interposed once the resection is complete. Small metallic markers are placed on either side of the physis to measure postoperative growth. Initial wrist arthroscopy may be indicated to debride painful articular flaps from the malunited Salter-Harris type III or IV fracture before the bar is resected. A second-stage ulnar shortening osteotomy may be necessary to achieve skeletal balance and resolve the ulnocarpal impaction pain if there is marked overgrowth. Restoration of radial growth once neutral to slight negative ulnar variance has been achieved will maintain forearm osseous balance through to skeletal maturity (Figure 34-24). The alternative is a complex radial lengthening and forearm rebalancing procedure(s).[92]

POSTOPERATIVE

Postoperative care for each of these procedures depends on the degree of bony stability with casting, pinning, or plating; time to expected healing; and the age and psychosocial maturity of the patient and family. The CR casting and CRPP of radial metaphyseal and physeal fractures are protected in casts until radiographic signs of healing are seen, usually at 4 to 6 weeks. Rigid internal fixation with scaphoid and distal radius fractures leads to an early (2 to 4 weeks) conversion to removable splints for restoration of motion in the right patients. (The ones you can't trust, or admit they can't trust themselves, should be casted until healed.) Nonunion and malunion reconstructive surgery of the radius and scaphoid follows the same rules as acute fractures, but the intercalary bone grafts make us a bit more cautious (4 to 6 weeks before conversion to a removable splint and motion therapy); full bony healing takes longer (up to 3 months).

ANTICIPATED RESULTS

My only feeling about superstition is that it's unlucky to be behind at the end of the game.
—Duffy Daugherty

Anatomically aligned distal radial metaphyseal radius and ulna fractures should heal without long-term complications. Minimally to mildly displaced metaphyseal or physeal fractures with 2 years or more of growth remaining will remodel and not have long-term issues. There can be a problem in more skeletally mature patients when: (1) the pediatric orthopaedic caregiver assumes there is sufficient growth remaining for remodeling and there is not, (2) the patient suffers a loss of reduction and is not evaluated again until malunited, or (3) the patient presents late for initial evaluation after the fracture is malunited.

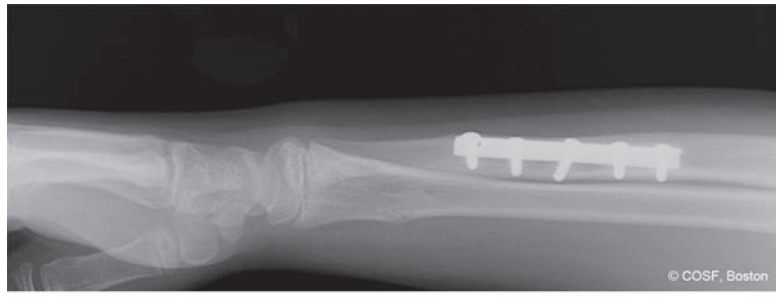
Aligned scaphoid fractures usually (~95%) heal with cast immobilization in children and adolescents.[18,93] Distal pole fractures treated by casting should heal without complications within 6 weeks. Proximal pole fractures are more at risk for AVN and nonunion even when aligned by radiographs and CT scans.[78] For this reason, we recommend percutaneous screw fixation for all proximal pole scaphoid fractures (Figure 34-25). The biggest issue with scaphoid waist fractures is nonunion: (1) in a patient who failed to seek medical attention at the time of injury and presents later with an established nonunion and carpal deformity (very common) or (2) in a patient who did seek acute medical attention that failed to diagnose the fracture clinically or radiographically.[19,94]

COMPLICATIONS

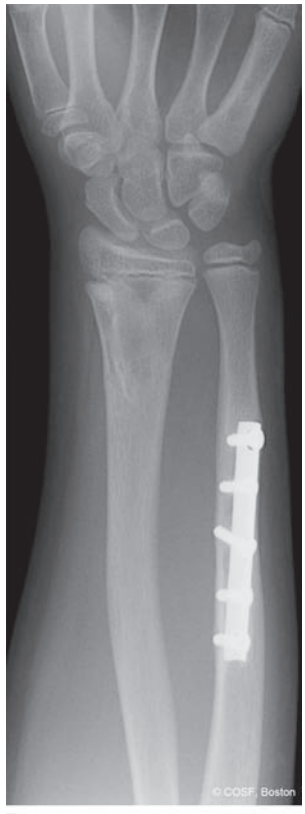
There's more to boxing than hitting. There's not getting hit, for instance.
—George Foreman

Malunion is common in distal radius and/or ulna metaphyseal and physeal fractures.[44,45,49,95] Remodeling is anticipated in the young[96–98] since the angular malunion

A



B2



B1

C

FIGURE 34-24 **A:** MRI scan of an 8-year-old male with central distal radius physeal arrest from an unrecognized Salter-Harris type III fracture of the distal radius treated with cast immobilization. He presented 6 months postinjury with intra-articular and ulnocarpal pain and deformity. **B:** Staged procedures performed. Physeal bar resection with fat interposition performed after initial arthroscopic debridement of articular flap lesion and ulnar shortening osteotomy. Radiograph is 4 years after reconstruction. **C:** Ten years after surgical reconstruction, he is skeletally mature, asymptomatic, and a skilled high school baseball player.

FIGURE 34-25 **A:** Radiographs without evidence of fracture in patient with snuffbox tenderness. **B:** Three weeks later, pain persisted, and MRI scan reveals aligned proximal pole fracture and intact vascularity. **C:** Percutaneous dorsal screw fixation led to healing.

is usually in the plane of motion of the joint (extension); adjacent to the physis; and up to 80% of the forearm growth comes from the distal radial physis. Rotational malunion will be unlikely to remodel.[99,100] Angular malunion >20 degrees will result in loss of forearm rotation at 1:2 ratio degree loss.[101,102] Some malunions do not cause clinical problems, but those that significantly limit forearm rotation (especially supination), cause DRUJ malalignment, midcarpal instability, and/or ulnocarpal compression will require corrective osteotomy if they do not remodel.[46,83,103,104] The sooner the surgery is done, the better the results.

Growth arrest of the distal radius occurs in about 4% of physeal fractures.[105–107] This raises the issue if displaced physeal fractures in the skeletally immature that are reduced

should be screened with a radiograph for physeal arrest 6 to 12 months after treatment. We follow that policy since a simple ulnar epiphysiodesis can alleviate major forearm malalignment if the radial growth arrest is not recognized before ulnar overgrowth becomes problematic at the DRUJ and ulnocarpal joint. Ulnar physeal arrest is more common (up to 60%) with displaced physeal fractures, and all those patients should have screening radiographs 6 to 12 months later.

Post-traumatic radioulnar synostosis rarely occurs.[108] If the synostosis is partial by CT scan analysis, then successful resection and restoration of motion are feasible. If the synostosis is complete, then either: (1) leave it alone if the patient is in a functional position (neutral forearm) and can compensate through the wrist and shoulder or (2) perform a rotational osteotomy for extreme malpositioning (full supination or pronation).

With distal radius and ulnar fractures, NV impairment can occur.[109,110] Nerve injury, laceration, or even entrapment is more common in open fractures. Median nerve injury is common in displaced physeal fractures[54] (for treatment, see Chapter 37).

Serious, deep-spaced infection is a concern with open fractures. All open fractures, regardless of grade, should be treated in the operating room with extension of the open wound, thorough inspection of both ends of the bone and surrounding soft tissues, and meticulous irrigation and debridement. Amputations from gas gangrene and multibacterial infections from inadequate surgical treatment of open fractures have been reported in children.[111] Need we say more?

Scaphoid fracture nonunions do occur, most commonly in the proximal pole, followed by the waist, and are almost reportable in the distal pole.[32–34] Since scaphoid nonunions will eventually lead to degenerative arthritis,[112,113] all nonunions should be treated.[32,34,114] Of note, persistent proximal pole AVN and nonunion may require a vascularized bone graft to achieve union.[78,115]

Hardware problems do occur. These range from superficial pin track infections that respond to pin removal and oral antibiotics; to pin migration that requires local anesthesia, conscious sedation, or general anesthesia depending on the situation; to recurrent bursitis over a plate that necessitates operative removal (most common with ulnar plates and exceedingly rare with volar radius plates). The risk of refracture needs to be addressed with plate removal. Finally, there have been reports of tendon rupture with both volar and dorsal plates for distal radius fractures.[116,117]

Careful attention to operative detail, mobilization and soft tissue protection of the tendons, and judicious removal of the plates and screws is imperative to lessen the risk of tendon rupture.

CASE OUTCOME

The subacute scaphoid fracture was treated with ORIF. Since there was already early cyst formation, a volar flexed scaphoid, and DISI deformity of the carpus, supplemental bone graft was used with an intraosseous screw. The fracture healed by 10 weeks, and the patient regained full motion and strength (Figure 34-26).

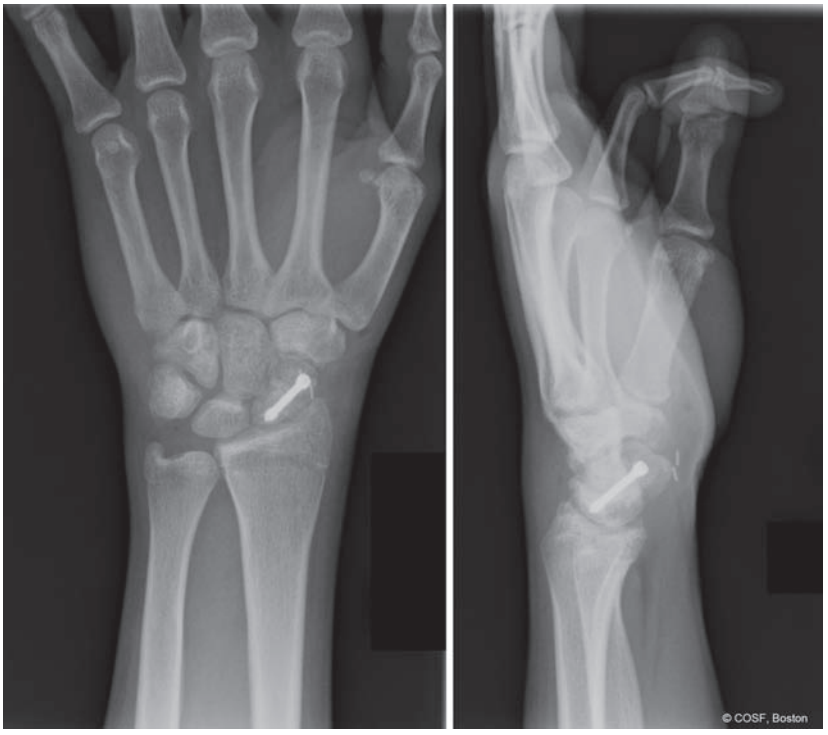


FIGURE 34-26 Healed subacute scaphoid fracture treated with ORIF and bone grafting.

SUMMARY

Distal radius and/or ulna fractures are common injuries. Displaced fractures can be unstable and need very careful radiographic monitoring of the first 3 weeks of cast treatment to identify loss of reduction and prevent malunion. Older patients will have adult-like injuries that require CRPP or ORIF. In subspecialty referral practice, there will be a number of malunion cases that require realignment osteotomies each year.

Scaphoid fractures are more common in adolescents with high-intensity sports participation. Waist fractures can go on to nonunion. Nonunions will require ORIF with bone graft to prevent late degenerative arthritis (SNAC wrist).

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CHAPTER

35

Problematic Hand Fractures

CASE PRESENTATION

A 6-year-old male presents for evaluation of a "stiff and crooked" index finger. The patient reports that 4 weeks prior to presentation, the finger was "jammed" while catching a football. There were no wounds or lacerations, and no obvious dislocation was present. The injury was attributed to a "sprain," and no medical evaluation was sought or treatment provided. Given persistent swelling, stiffness, and deformity, the patient presents for hand and upper extremity consultation. Radiographs are shown in Figure 35-1.

CLINICAL QUESTIONS

- How common are pediatric hand fractures?
- What are the most commonly injured bones? In which digits?
- What are the problematic hand fractures that require surgical care?
- What are the surgical principles and specific techniques used to treat problematic hand fractures?
- What are the anticipated results?
- What are the indications for corrective osteotomies of hand fracture malunions?
- What are the common complications of hand fractures following nonoperative and surgical treatment?

THE FUNDAMENTALS

To climb steep hills requires slow pace at first.
—William Shakespeare

Hand fractures are fundamental problems cared for by every pediatric hand and upper extremity surgeon. Although many guiding principles and surgical techniques are universally applicable, children are not small adults, and a number of distinctions exist. Indeed, the pediatric hand surgeon must have a firm grasp of characteristic injury patterns, issues of skeletal growth and remodeling, more precise physical examination and surgical fixation techniques, and a rationale approach to postoperative immobilization and stiffness.

Etiology and Epidemiology

Hand injuries are common in the pediatric patient population.[1–3] Prior studies regarding the epidemiology of hand fractures in the United States, Canada, and England have demonstrated that the incidence of hand fractures is 2 to 9:1,000 children and adolescents per year. There is a bimodal distribution of injuries; toddlers between 0 and 4 years of age typically sustain distal phalangeal fractures and fingertip injuries as they use their hands to explore the world around them, while adolescents between 10 and 14 years of age (a time of rapid skeletal growth) more commonly have phalangeal and metacarpal fractures sustained from sports activities.[2–4] Overall, the proximal phalanx of the border digits (particularly the small finger) is most commonly fractured.[5] Metacarpal fractures are usually diaphyseal, whereas phalangeal fractures typically involve the proximal metaphysis or physis. Indeed, physeal fractures represent 20% to 30% of all hand fractures in children; Salter-Harris type II patterns predominate.[5–7] Despite the frequency of growth plate involvement, however, post-traumatic growth disturbance rarely occurs in closed fractures.

Clinical Evaluation

Clinical evaluation begins with a careful history, with particular attention to the chronicity of the fracture, mechanism of injury, and presence of any associated wounds or lacerations. Careful history taking is particularly important in the young child, where cooperation with the physical examination and radiographic evaluation may be limited.

Physical examination of the injured hand can be challenging, particularly in the anxious, noncompliant, or nonverbal child. Careful observation, utilization of anatomic principles, such as the tenodesis effect, and gentle maneuvers are mandatory to obtain the information needed for accurate and timely diagnosis. The presence of swelling, ecchymosis, guarded active motion, or soft tissue injury will guide the examiner to the region of pathology. Tenodesis

FIGURE 35-1 Lateral radiograph depicting a displaced phalangeal neck fracture. Note is made of early callus formation, consistent with an incipient malunion.

effect (passive wrist extension produces passive digital flexion and passive wrist flexion results in digital extension) or gentle pressure applied to the more proximal muscle bellies of the forearm (away from the site of injury) will aid in the assessment of both tendon integrity and angular or rotational deformity (Figure 35-2). Assessment of rotational deformity is critical, as rotational malalignment exhibits little remodeling and may result in compromised hand function due to digital overlap or underlap. Malrotation may also be assessed by careful examination of the nail beds of adjacent digits in extension; rotation of >10 degrees out of the plane of adjacent nail plates should alert the examiner to rotational malalignment, though these differences are often subtle and difficult to quantify. In addition, people are usually symmetric and so always compare the rotational alignment of the injured to the uninjured hand. Additional assessment of rotational deformity can be made by evaluation of digital alignment with attempted finger flexion if the child is cooperative. In general, the index through small fingers point to the scaphoid tubercle in flexion, roughly in symmetric alignment to the opposite hand; often patients normally exhibit some degree of digital underlap, small beneath ring fingers. In young anxious or nonverbal patients unable to actively flex their digits during physical examination, the tenodesis effect may be used; gentle passive extension of the wrist should also allow for obligate digital flexion to assess for rotational alignment. Only after all information is derived from observation and indirect examination techniques should direct palpation and/or stress testing be performed.

Appropriate radiographic imaging is imperative in the evaluation of the child's injured hand. In general, dedicated anteroposterior (AP), lateral, and oblique radiographs of the injured digit are preferred over hand radiographs, in which overlying structures, projectional

A

B

FIGURE 35-2 Tenodesis maneuver to assess digital malrotation. **A:** With the wrist flexed, no obvious rotation deformity is seen. **B:** With passive wrist extension and obligate digital flexion, there is clear overlap of the index finger onto the long finger, signifying malrotation.

artifact, and lack of bony magnification or detail may lead to errors in diagnosis. In situations in which expedited or very comprehensive radiographic assessment is needed, the use of fluoroscopy and/or a mini-image intensifier may assist in obtaining appropriate views of the injured digit, comparison views of the contralateral hand, or dynamic assessment of bony and articular stability.

Be aware of the normal sequence of skeletal ossification as well as common radiographic normal variants, which may be mistaken for traumatic injuries.[8,9] The physes of the phalanges are proximal and distal in the metacarpals except the thumb. In general, the proximal phalangeal epiphyses become visible radiographically between 10 and 24 months of age and in females prior to males. The epiphyses of the middle and distal phalanges ossify approximately 6 to 8 months later. Physeal closure proceeds in a distal to proximal direction, typically between the ages of 14 and 16 years. The index through small metacarpal epiphyses ossify at 12 to 27 months of age and fuse between 14 and 16 years of age. The thumb metacarpal epiphysis, however, does not typically ossify until 24 to 36 months of age.

Common radiographic normal variants include the appearance of a pseudoepiphysis of the distal thumb metacarpal and the proximal index metacarpal.[10] The pseudoepiphyses become radiographically apparent at an early age, do not contribute to the longitudinal growth of the metacarpal, and typically fuse to the metacarpal diaphysis by the seventh year of life. Other anatomic variants include the double epiphysis, most commonly appearing in the index and thumb metacarpals. These physeal variants can be misinterpreted as a fracture.

Classification of skeletal injuries remains anatomic and descriptive, with injuries described according to location, displacement, and angulation. In the subset of physeal fractures, the Salter and Harris system continues to be used, owing to its simplicity and its ability to guide fracture management and prognosticate outcomes.

Surgical Indications

While the vast majority of pediatric hand fractures may be successfully treated with nonoperative care, there are several characteristic injuries that require surgical care.[6,11] Indeed, these problematic hand fractures account for the small percentage of hand fractures that are responsible for a large percentage of complications.

In the now classic series published by Hastings and Simmons,[6] 354 pediatric hand fractures were retrospectively analyzed with a minimum 2-year follow-up. In that series, several "high-risk" fractures were identified, including displaced articular fractures, Seymour fractures, phalangeal neck fractures, and open fractures. Risk factors associated with malunion and ultimately poor clinical results included failure to assess clinical deformity, failure to obtain proper AP and true lateral radiographs of the affected digit, failure to obtain adequate postreduction radiographs, and false assumptions regarding skeletal remodeling potential. Rather than provide a comprehensive survey of all pediatric hand injuries, it is these problematic hand fractures that will be the focus of this chapter.

SURGICAL PROCEDURES

Many strokes overthrow the tallest oaks.
—John Lyly

A few overarching principles apply to the surgical care of pediatric hand fractures. First, due to the small size of the skeletal structures and relative abundance of surrounding subcutaneous fat and soft tissue, closed or open surgical fixation requires the use of smaller implants placed with greater precision. Second, given the desire to avoid iatrogenic injury to the adjacent or affected growth plate, "physeal-friendly" fixation is preferred, typically utilizing smaller caliber smooth wires avoiding passage across the physis whenever possible. In addition, while it diminishes the risk of delayed union or nonunion—particularly in closed injuries—the robust biological healing potential in children narrows the window of opportunity to effectuate fracture reduction using closed techniques. Furthermore, as children and adolescents will exhibit varying degrees of compliance with postinjury or postoperative care, more restrictive immobilization is required to maximize maintenance of reduction and long-term outcomes. Fortunately, the use of more restrictive immobilization is not associated with as much long-term stiffness in children as opposed to adults. Finally, as with all hand fractures, every effort should be made to utilize the simplest, least invasive technique possible to achieve the desired result. Never open or plate a pediatric finger fracture unless you have to.

Closed Reduction Percutaneous Pinning of Phalangeal Neck Fractures

Phalangeal neck fractures are characteristic pediatric injuries. Classically due to "door jamb" injuries in which a digit is caught in a closing door and forcefully withdrawn, phalangeal neck fractures are now occurring with greater frequency from sports-related mechanisms. Regardless of the cause, the injury mechanism imparts both extension and rotational forces on the affected digit. Border digits are most commonly affected, and the middle phalanx is injured more frequently than the proximal phalanx. The fracture occurs at the level of the phalangeal neck, and the distal articular segment typically displaces into extension with varying degrees of rotation. Patients will present with swelling, tenderness, ecchymosis, and limited interphalangeal (IP) joint motion, though the latter is often difficult to appreciate in the acutely injured child.

Given that the deformity occurs in the sagittal plane, standard AP views of the affected digit or hand may appear benign.[6] A true lateral radiograph of the injured digit is necessary, and a high index of suspicion for rotational deformity must be maintained. In very young patients in whom the

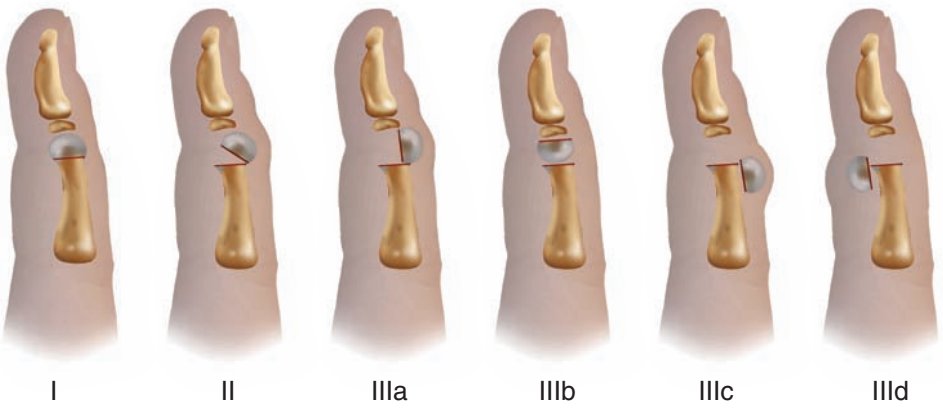


FIGURE 35-3 Schematic diagram of the classification of phalangeal neck fractures.[12]

phalangeal head is predominantly cartilaginous, subtle or seemingly innocuous "bony flecks" should raise suspicion for a displaced "cartilaginous cap" or osteochondral fracture. Displaced phalangeal neck fractures result in both abnormal sagittal plane alignment as well as obliteration of the concave subcondylar fossa; this causes a block to IP joint flexion, as the more distal phalangeal base abuts the bony prominence at the distal end of the proximal fracture fragment.

Al-Qattan classification of extra-articular phalangeal neck fractures is clinically useful, as it portends prognosis and guides treatment[12] (Figure 35-3). Type I fractures are nondisplaced. Type II fractures are partially displaced with some bony/cortical contact. Type III fractures are completely displaced without bony apposition. Cast immobilization is sufficient in cases of nondisplaced injuries, though serial radiographic evaluations should be performed to monitor maintenance of reduction.

As the phalangeal physis is proximal, and phalangeal neck fractures occur distally, remodeling potential is limited. Indeed, while there have been a handful of case reports documenting remodeling of displaced phalangeal neck fractures, it is apparent that skeletal remodeling: (1) is more likely in very young patients, (2) occurs over many years, during which persistent IP joint flexion is limited, (3) may be incomplete, and (4) will not spontaneously correct rotational malalignment.[13–16] Based on this,

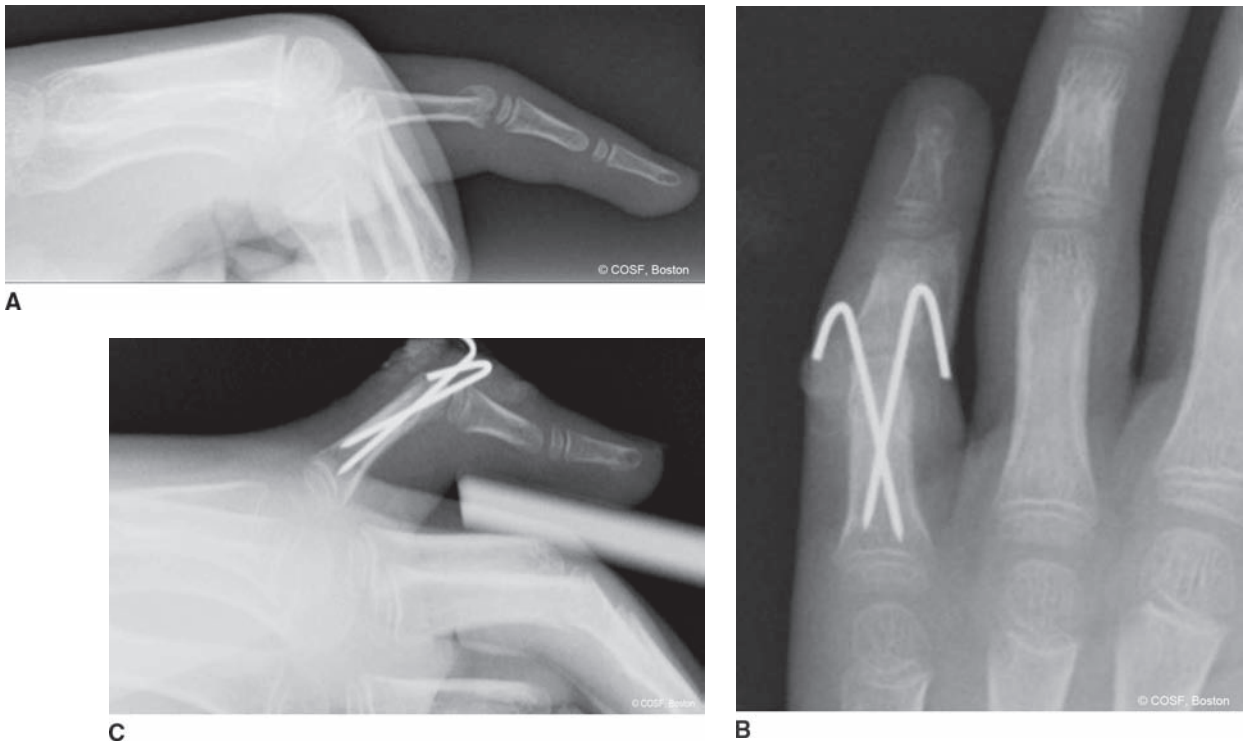


FIGURE 35-4 Closed reduction and percutaneous pinning of an acute displaced phalangeal neck fracture. **A:** Injury lateral radiograph depicts the fracture displacement. **B, C:** Postoperative radiographs demonstrating reduction and cross pin configuration.

observation of displaced phalangeal neck fractures should only be considered if there is no rotational or radioulnar deformity, congruent reduction of the adjacent IP joint, considerable remaining skeletal growth, tolerable loss of IP joint flexion, and willingness on the part of the patient and family to wait months to years for remodeling to occur.[13]

Closed reduction and splinting/cast immobilization alone are insufficient in the treatment of type II and III fractures; therefore, closed reduction and percutaneous pin fixation are recommended for displaced injuries[12] (Figure 35-4). Under general anesthesia and with fluoroscopy available, the angular and rotational alignment of the affected digit is assessed. The normal digital cascade of the contralateral hand should be assessed preoperatively to identify what is normal for each individual patient. Closed reduction is then performed with longitudinal traction, followed by correction of the angular and rotational deformity, and subsequent IP joint flexion. Retrograde crossed percutaneous pins (most commonly 0.035″ in size) are then placed, beginning in the collateral recess and engaging the far cortex of the proximal fragment, with care taken to avoid crossing the pins at the fracture site. The starting point is more distal than is usually suspected, and inexperienced surgeons often entirely miss the distal fragment with initial pin placement. Intraoperative imaging will confirm appropriate bony alignment and implant placement. The pins are bent and cut outside the skin in the usual fashion, followed by application of a sterile petroleum gauze (Xeroform, Covidien, Mansfield, MA) and a hand-based short-arm cast.

In late-presenting fractures with nascent malunions and passive IP joint flexion <90 degrees, percutaneous pin osteoclasis may be performed if the fracture is still radiographically visible and there is still tenderness to palpation at the fracture site[17,18] (Figure 35-5). Under fluoroscopic guidance, a small, smooth K-wire (0.035″ or 0.045″) is percutaneously placed on either side of the extensor apparatus and used to liberate the distal fracture fragment by disrupting the fracture callus. The same smooth pin may then be used to lever the distal fragment into a more anatomic position. After reduction is achieved, the fracture is fixed using one or two retrograde crossed pins. Given the narrow diameter of the intramedullary canal and the

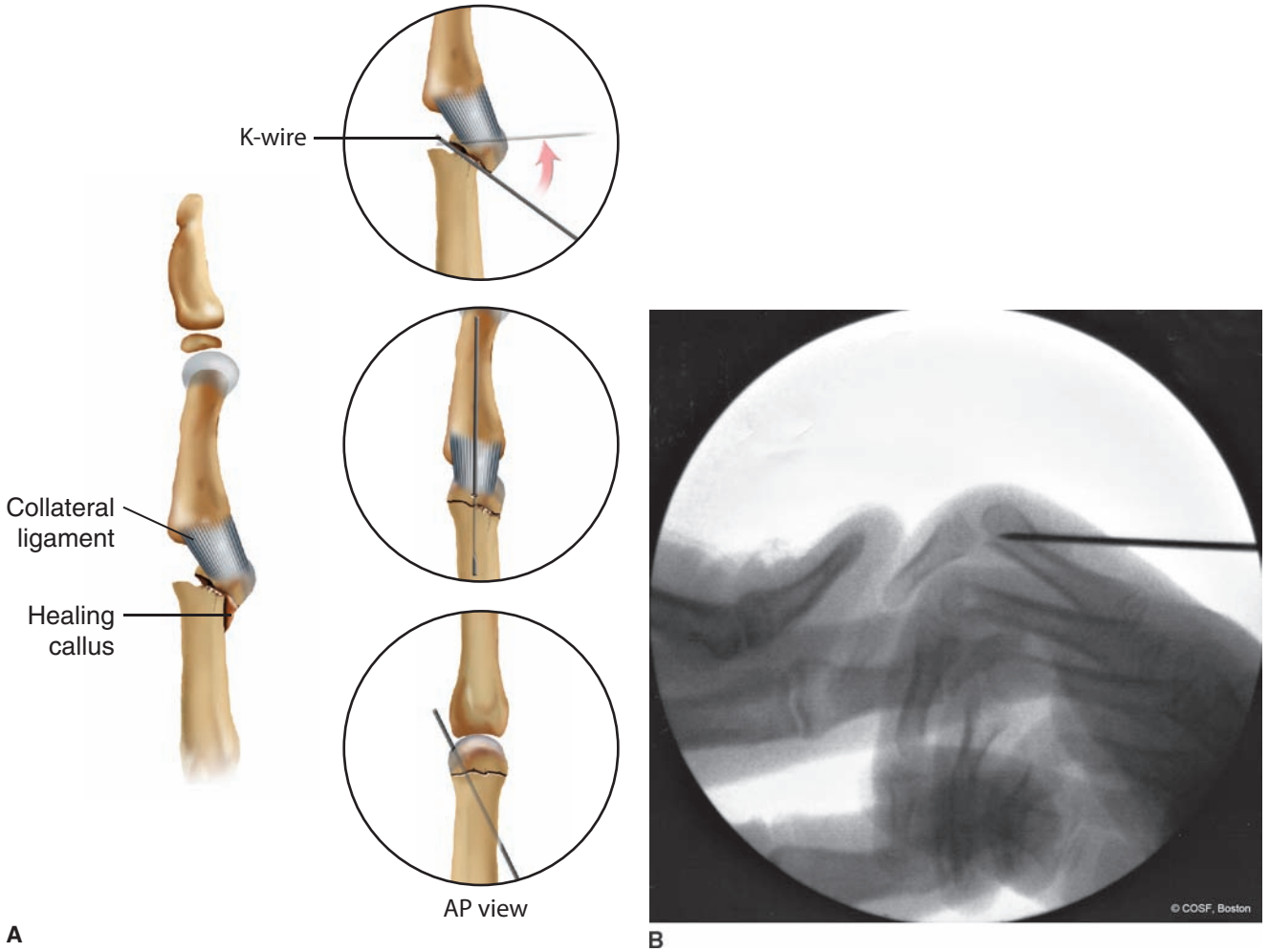


FIGURE 35-5 **A:** Schematic representation of the percutaneous osteoclasis technique for incipient phalangeal neck malunions. **B:** Intraoperative image depicting the use of the percutaneous pin at the malunion site.

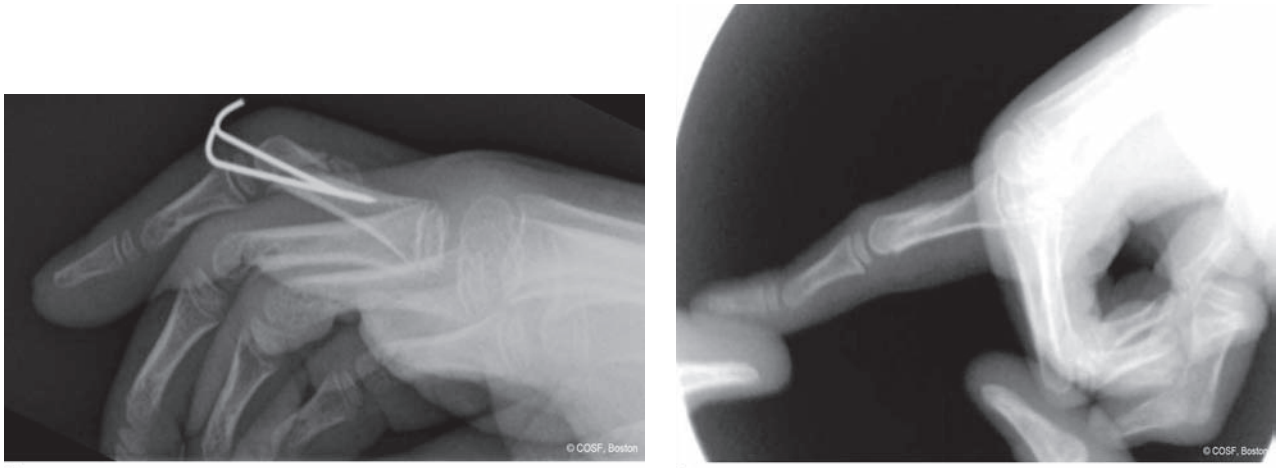


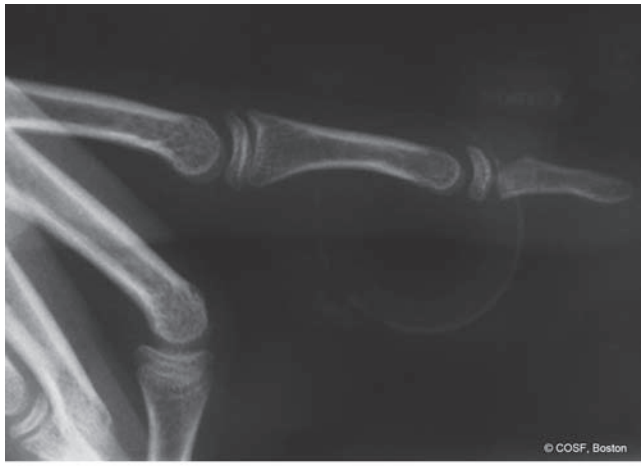
FIGURE 35-5 *(continued)* **C:** Postoperative lateral radiograph after osteoclasis and pinning. **D:** Postoperative radiograph after pin removal.

stability imparted by the fracture callus, often only one pin is placed. Radiographs are taken to confirm alignment and pin placement, and a hand-based short-arm cast is applied.

Repair of Seymour Fracture

"Seymour fractures" refer to displaced distal phalangeal physeal fractures accompanied by an overlying nail bed laceration.[19,20] These are also characteristic childhood injuries, typically resulting from crush mechanisms. Often there is interposed soft tissue (i.e., germinal matrix) within the displaced physeal fracture. This is technically an open fracture, and treatment should consist of nail plate removal, irrigation and debridement of the fracture site, liberation of any interposed soft tissue, open reduction of the physeal fracture, and meticulous nail bed repair. Failure to recognize and appropriately treat Seymour fractures may result in complications of nail plate deformity, physeal arrest, and chronic osteomyelitis[21] (Figure 35-6).

FIGURE 35-6 Complications of missed Seymour fractures. **A:** Nail plate deformity. **B:** Osteomyelitis and soft tissue infection.



C

FIGURE 35-6 *(continued)* **C:** Lateral radiograph depicting radiolucency of the dorsal metaphysic consistent with osteomyelitis.

Repair of a Seymour fracture may be performed in the emergency department setting under local anesthesia or in the operating room (Figure 35-7). Under digital tourniquet and after nail plate avulsion, incisions in the dorsal skin are made from both angles of the dorsal nail fold proximally and slightly obliquely toward the distal interphalangeal (DIP) joint extension crease. Skin flaps are carefully raised to expose the germinal matrix and nail bed laceration, while preserving the terminal tendon attachment to the dorsal epiphysis. With hyperflexion, the physeal fracture is exposed and any interposed soft tissue extracted. The fracture is irrigated, debrided, and anatomically reduced under direct visualization. The nail bed laceration is then repaired using interrupted 6-0 sutures (Chromic, Ethicon, Inc., Somerville, NJ). Often a tight repair requires two outside-in horizontal mattress sutures through the eponychium, grasping the proximal germinal matrix and pulling it under the dorsal hood. The fracture may be stabilized with a retrograde percutaneous longitudinal K-wire, entering the digital tip and crossing the fracture and DIP joint. Alternatively, replacement of the trephinated nail plate beneath the dorsal nail fold after nail bed repair is completed may confer sufficient bony stabilization. The back cuts in the dorsal nail fold are similarly closed with interrupted 5-0 chromic suture. A sterile bandage is applied, followed by a hand-based cast.

Open Reduction and Internal Fixation of Intra-articular Fracture

Intra-articular fractures of the phalangeal head include unicondylar, bicondylar, and comminuted fracture patterns.[22]

A

B

FIGURE 35-7 **A:** Lateral radiograph of a displaced distal phalangeal physeal fracture, consistent with a Seymour fracture. **B:** Clinical photograph demonstrating the rent in the germinal matrix and open physeal fracture, exposed via elevation of the dorsal nail fold.

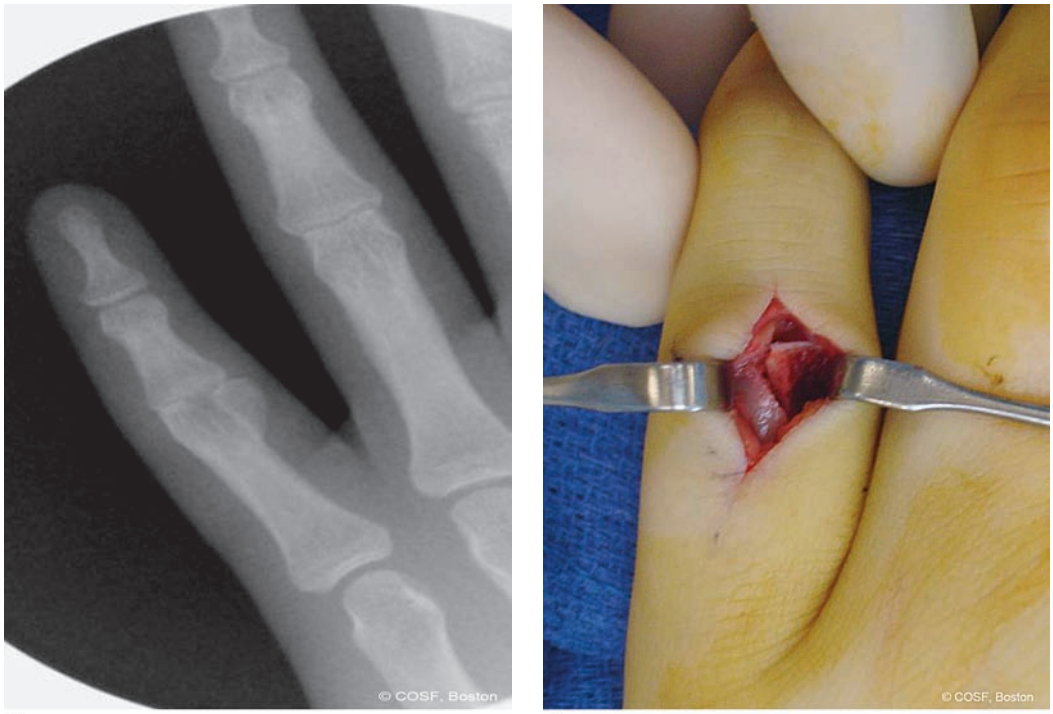
Treatment is based upon articular congruity and angular/rotational deformity. Nondisplaced injuries may be treated with cast immobilization. In these situations, however, weekly radiographic examinations are performed to confirm maintenance of reduction and articular congruity. In fractures with >5 to 10 degrees of angulation or 1 to 2 mm of articular incongruity, surgical intervention is recommended. Closed versus open reduction with smooth K-wires or interfragmentary screw fixation is recommended.

Although open approaches to finger fractures are generally avoided, it is imperative that an anatomic reduction is achieved to promote healing potential, restore joint congruity, and maximize functional results. In cases where closed reduction is not feasible, open reduction is performed, allowing for visualization of the articular surfaces while carefully preserving the collateral ligament and other soft tissue attachments to the condylar fracture fragment(s) in an effort to preserve their vascularity. With careful surgical technique, restoration of motion and preservation of joint stability and articular congruity may be expected. Patients and families should be counseled, however, regarding the potential for long-term stiffness and arthrosis, particularly in severely displaced injuries requiring open treatment.[23]

An open reduction and internal fixation (ORIF) approach using smooth pins (or less commonly screws) is performed via a dorsal curvilinear incision centered over the affected IP joint, with the convexity directed to the side of the fracture (Figure 35-8). Skin flaps are elevated, preserving the dorsal veins and subcutaneous nerves if possible. A longitudinal incision between the extensor tendon and lateral bands is then made, and the overlying extensor apparatus is carefully retracted. The joint capsule is then incised, allowing exposure and access to the fracture line and articular surface. Care is taken to preserve soft tissue attachments (e.g., periosteum, collateral ligament origin) to the displaced fracture fragment(s) in an effort to maintain vascularity and ligamentous stability. Under direct visualization, the fracture is reduced, and articular congruity is confirmed. Fixation may then be performed with interfragmentary screws, smooth K-wires, or combinations thereof. Two screws or pins are necessary to provide rotational stability and prevent loss of reduction.[22] Intraoperative fluoroscopy is used to confirm the quality of reduction and pin/screw placement. Pins are bent and cut outside the skin to allow for subsequent removal. The joint capsule, extensor apparatus, and skin are closed in layers, and the patient is placed in a splint or hand-based short-arm cast.

Open Reduction of Complex Metacarpophalangeal Joint Dislocation

Dislocations of the metacarpophalangeal (MCP) joint are common, typically due to hyperextension forces and most commonly affecting the thumb and index finger. If there is no soft tissue interposition, simple closed reduction maneuvers are successful in attaining a stable and



A B

FIGURE 35-8 ORIF of a small finger, unicondylar phalanx fracture. **A:** Injury AP radiograph, demonstrating fracture displacement. **B:** Intraoperative exposure of the displaced fracture fragment, which has rotated 90 degrees.

C

D

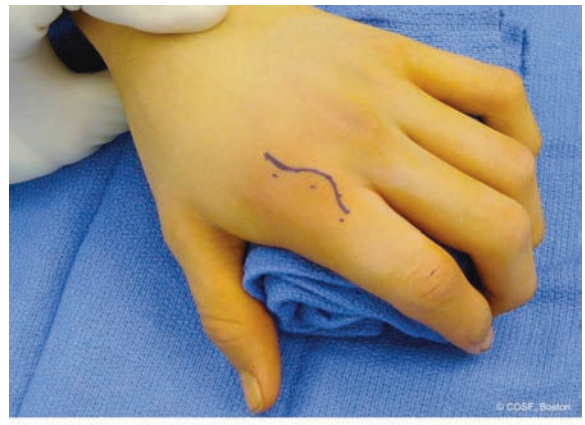
FIGURE 35-8 *(continued)* **C:** Intraoperative appearance after anatomic reduction. **D:** Radiograph following reduction and pin fixation, demonstrating restoration of the articular alignment and joint congruity.

congruent reduction. Straight longitudinal traction should be avoided for fear of converting a "simple" dislocation into a "complex" one. Instead, reduction maneuvers should consist of wrist flexion (to lessen the tension on the digital flexors) and MCP hyperextension, followed by volarly directed pressure on the base of the proximal phalanx as the phalanx is brought out and over the metacarpal head.

Occasionally, patients will present with complex, irreducible MCP dislocations due to either their mechanism of injury or inappropriate initial reduction maneuvers. Clinically, the metacarpal head buttonholes in the interval bounded by the flexor tendons ulnarly, lumbrical radially, transverse metacarpal ligament proximally, and natatory ligament distally.[24] Radiographs will often provide insight into the injury pattern: In simple dislocations, the MCP joint lies in hyperextension, whereas in complex dislocations, there is often bayonet apposition and shortening of the proximal phalanx over the metacarpal head.

In cases of complex MCP dislocations, surgery is required to effectuate a reduction (Figure 35-9) (see Sidebar).

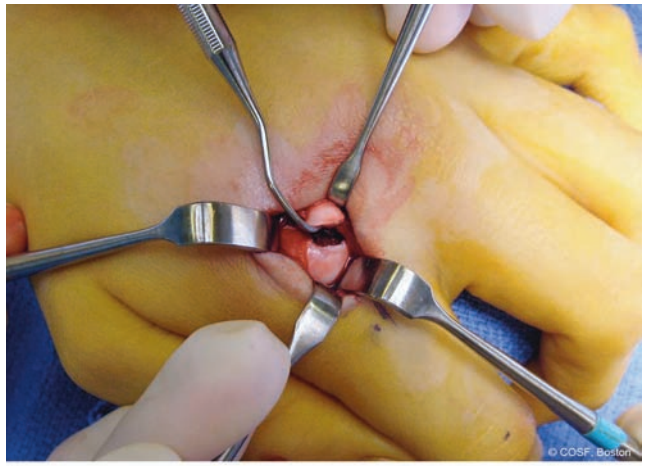
A



B

FIGURE 35-9 Complex MCP dislocation. **A:** Injury radiograph depicting a dorsal dislocation of the index MCP joint. **B:** A dorsal curvilinear incision is created.

C



D

E

F

FIGURE 35-9 *(continued)* **C:** The dislocation is easily visualized and chondral surfaces inspected. **D:** After MCP reduction, note is made of an osteochondral shear fracture of the metacarpal head. **E:** Reduction and fixation are performed with an epiphyseal screw. **F:** Postoperative radiograph demonstrating screw fixation and joint reduction.

Under general anesthesia and tourniquet control, a dorsal curvilinear incision is created, centered on the MCP joint (see Coach's Corner). Skin and subcutaneous flaps are raised, preserving the dorsal venous apparatus and cutaneous nerve branches. The incision is through the ulnar sagittal bands (to avoid risk of subsequent extensor tendon subluxation), and a longitudinal capsulotomy is performed. Fracture hematoma is evacuated, and the MCP joint is visualized.

In complex MCP dislocations, the volar plate is interposed and typically avulsed from the metacarpal head/neck. Using a Freer elevator, forceps, or blunt probe, the volar plate is pushed volarly, over the head of the metacarpal. Reduction of the proximal phalanx is often accompanied by a "click" as the volar plate is returned to its anatomic position. In cases where the volar plate cannot be easily reduced, a longitudinal incision may be performed. Following joint reduction, the articular surfaces of the metacarpal head and base of the proximal phalanx are inspected for cartilaginous or osteochondral fractures. If detected, these may be fixed using countersunk screws or bioabsorbable implants. The dorsal capsule is then

repaired, as is the ulnar sagittal band. Following skin closure and sterile bandage application, the hand is immobilized in a short-arm thumb spica cast. Care is taken during cast application to avoid excessive padding in the first web space, which may result in inadvertent hyperextension of the MCP joint of the thumb.

◆ Malunion Osteotomy

It's hard to beat a person who never gives up.
—Babe Ruth

With appropriate diagnosis and timely treatment, hand fractures may be successfully treated with the expectation of good radiographic and clinical results. There are situations, however, when patients will present late or after inadequate nonoperative care with symptomatic fracture malunions. Excessive malalignment, resulting in digital overlap with attempted fist formation and persistent functional limitations, is a relative indication for osteotomy.[25–37] Surgical reconstruction is a high-risk, high-reward endeavor, however, given the potential complications of persistent deformity, nonunion, stiffness, and pain. Patients and families must be counseled about the attendant risks of osteotomy, and each individual's complaints and functional demands should be considered.

In cases of angular malunion of the proximal and middle phalanx, correction may be performed using closing wedge osteotomy in the index through small fingers. The technique is similar to that used for clinodactyly (see Chapter 6). Closing wedge osteotomy of the digits is preferred as it is simple, does not require the use of bone grafting, and the resulting phalangeal shortening does not impede digital function. Via a midaxial incision over the apex of the frontal plane deformity, skin flaps are raised and the neurovascular bundle is retracted with the volar flap. An incision is made between the lateral band and extensor tendon, and careful subperiosteal elevation is performed. The apex of the angular deformity is identified, and small osteotomes are used to create the closing wedge osteotomy cuts. Preservation of the far (concave side) cortex and periosteum will provide some stability. The wedge is carefully removed and the osteotomy site closed. Smooth K-wire fixation is achieved, typically by placement of a longitudinal retrograde or oblique pin. Fluoroscopy is utilized to assess deformity correction and pin placement. Careful intraoperative evaluation of rotation is performed using the tenodesis maneuver.

In the setting of intra-articular malunion following prior unicondylar fractures, careful assessment of the original fracture line and three-dimensional nature of the deformity is made. If there is joint subluxation or intolerable digital malalignment markedly impeding hand function, corrective osteotomy may be performed using the condylar advancement technique of Teoh et al.[37] (Figure 35-10).

FIGURE 35-10 Schematic diagram of the unicondylar advancement osteotomy.

Rotational malunion also occurs. When functionally limiting but <15 degrees of malrotation, correction may be achieved via metacarpal rotational osteotomy for phalangeal deformity.[38] Advantages of metacarpal rotation include greater healing potential and less risk of postoperative tendon adhesion and stiffness due to the region of dissection and osteotomy. Disadvantages include limits to the amount of correction that may be obtained, owing to the restraining transverse metacarpal ligaments. Refinements of the technique have involved Z- or step-cut osteotomies to "dial in" the amount of derotation achieved.[34] Via a dorsal incision over the metacarpal of the affected digit, extensor tendons are retracted, and subperiosteal dissection of the metacarpal diaphysis is performed. Care is taken not to injure the metacarpal physis, which lies distal in the index through small rays. A transverse osteotomy through the distal metadiaphysis is created, and the distal segment and finger are rotated to a corrected position. In older and larger patients, dorsal plate and screw fixation may be used to stabilize the osteotomy site; in these situations, it is helpful to predrill the planned screw

holes proximal to the planned osteotomy site to facilitate later fixation across the osteotomy site. In the rare young patient undergoing osteotomy, transmetacarpal or oblique K-wire fixation may be sufficient. The periosteum and soft tissues are closed in layers, and a hand-based short-arm cast is applied.

POSTOPERATIVE

Patients are typically cast immobilized for 3 to 4 weeks postoperatively. Provided there is clinical and radiographic evidence of bony healing, percutaneous pins are removed and range-of-motion exercises initiated. Patients are restricted from sports participation until they demonstrate near full motion and strength.

ANTICIPATED RESULTS

Adhering to the principles and techniques outlined above, bony healing and restoration of hand function can be expected in closed fractures without associated soft tissue injuries. In cases of Seymour fractures, fracture debridement and reduction with meticulous nail bed repair will result in good aesthetic and functional outcomes.[19] In a prior study of 25 Seymour fractures in children and adults, 4 of 18 patients developed infection or persistent flexion deformity after closed reduction and splinting alone, whereas all fractures treated with appropriate fracture care and K-wire fixation went on to uncomplicated healing.[19]

In a previously published series of 66 patients with 67 phalangeal neck fractures, 13 fractures were nondisplaced and went on to good-to-excellent results with nonoperative care.[12] Type II fractures accounted for the majority of injuries, and results were highly dependent upon treatment. Patients treated with closed versus open reduction and K-wire fixation went on to successful bony healing with good-to-excellent results. Type II injuries treated with closed reduction without surgical stabilization went on to fair-to-poor results in 66% of cases. Of the 7 type III injuries, failure to perform surgical reduction and K-wire fixation uniformly led to fracture nonunion and poor results.

Results of intra-articular unicondylar fractures of the phalanx vary according to the pattern of injury and treatment. In the classic series of 38 (adult) patients with unicondylar fractures, all went on to bony healing.[22] At mean 3-year follow-up, 5 of 7 nondisplaced fractures treated with immobilization alone and 4 of 10 displaced fractures treated with closed reduction and single K-wire fixation had loss of reduction. The best final IP joint motion was seen in those who underwent multiple K-wire fixation. Furthermore, patients with volar oblique fracture patterns had the worst ultimate joint motion.

Overall, surgical reduction of complex MCP joint dislocations is associated with uniform success with regard to joint reduction and stability. Stiffness is often prolonged, but generally full range of motion occurs over 3 to 6 months of therapy.

COMPLICATIONS

I never thought I didn't have a card to play.
—Jim Lovell

Complications of problematic hand fractures typically arise from delayed diagnosis, suboptimal nonoperative treatment, or excessive soft tissue adhesions following surgical care.

Stiffness is the most common complication of both nonoperative and surgical care of hand fractures. Thankfully, children tend not to develop as much posttraumatic adhesions and scar tissue as adults, and usually occupational therapy for edema control, scar molding, splinting, and range-of-motion exercises will resolve the nearly ubiquitous initial stiffness. Several factors within the surgeon's control may lessen the risk of stiffness. First, excessive duration of immobilization should be avoided. Four weeks of cast immobilization is usually sufficient for most uncomplicated hand fractures, and as clinical healing precedes radiographic union, determination regarding discontinuation of immobilization should not be dependent upon radiographic findings alone. Second, anatomic reduction will afford the best opportunity for return of motion; special attention to those problematic hand fractures requiring surgical care is needed, particularly with intra-articular injuries. Finally, surgical goals should be fulfilled using the least invasive means possible to avoid iatrogenic soft tissue disruption and therefore greater scar formation and tendon adhesions.

Fracture nonunion is rare in children and typically occurs only in combined injuries with associated soft tissue trauma, poor vascularity, or infection. In cases of fracture nonunion, autogenous corticocancellous bone grafting after soft tissue homeostasis has been achieved will usually yield bony union.

Osteonecrosis remains a concern, particularly after open reduction of intra-articular fractures. Every effort should be made to avoid excessive soft tissue stripping and devitalization of fracture fragments, particularly in cases of predominantly cartilaginous unicondylar injuries. When established, treatment is predicated on clinical symptoms rather than radiographic findings. The need for secondary salvage procedures is rare.

Finally, arthrosis may occur in children. Usually, this is seen in patients with neglected or complicated intra-articular fractures, with long-standing osteonecrosis, or following infection or complex combined injuries of the hand.

CASE OUTCOME

The diagnosis of a phalangeal neck fracture was made, and, given the chronicity from injury and evidence of periosteal bone formation, an incipient malunion was present. As there was tenderness at the fracture site, radiographically apparent fracture line, and limited IP joint motion, the patient underwent percutaneous pin osteoclasis and fixation (Figure 35-5). Clinical and radiographic healing was noted at 4 weeks, when the pin was removed, and range-of-motion exercises began. By 4 months postoperatively, the patient demonstrated full digital flexion without pain or functional limitations.

SUMMARY

While most hand fractures in children may be successfully managed with nonoperative means, pediatric hand and upper extremity surgeons must be aware of characteristic problematic fractures requiring surgical care. Careful assessment of alignment and rotation, thorough evaluation of appropriate radiographs, restoration of articular congruity and joint stability, and appropriate fixation and postoperative immobilization will help to maximize both bony healing and hand function.

SIDEBAR

Joint Injection/Insufflation to Reduce a Complex MCP Dislocation

In cases of a complex MCP dislocation, there is a less invasive procedure that may achieve joint reduction without the need for an open arthrotomy. Injection or insufflation of the joint may serve to push the interposed volar plate out of the articular space and allow for a closed reduction.[39] While not universally successful, this procedure may be attempted prior to surgical open reduction to avoid the morbidity and risks of anesthesia and arthrotomy.

Under sterile conditions with the patient awake or sedated, an 18- or 20-gauge needle is placed into the MCP joint, typically via a dorsal approach in the obvious "dimple" of the skin. A mixture of 1% lidocaine and 0.25% bupivacaine without epinephrine is injected intra-articularly; approximately 5 to 10 mL of local anesthetic should be quickly and forcibly instilled, with the hope of displacing the volar plate back into a reduced position. Fluoroscopic imaging or plain radiographs are used to assess the adequacy of the reduction. If acceptable, the thumb or digit may be immobilized in a splint or cast. If no reduction is achieved, open reduction may be performed as described above.

COACH'S CORNER

Dorsal versus Volar Approach to the Complex MCP Dislocation

Surgery for the complex MCP dislocation may involve either a dorsal or volar approach, each with its own set of advantages and disadvantages. The dorsal approach is straightforward and avoids risk of iatrogenic injury to the displaced neurovascular bundles.[40–43] The dorsal approach also allows excellent visualization of the articular surfaces of the proximal phalanx and metacarpal head. This will facilitate reduction and fixation of any associated osteochondral fractures. Conversely, the volar approach has been advocated by many, as it allows direct access to all the anatomic structures that ensnare and envelope the metacarpal head.[24,44–46] The volar plate, transverse metacarpal ligaments, and flexor and lumbrical tendons are easily accessible through a volar incision but are not visualized from the dorsal side. The main drawback of the volar approach is the proximity of the digital artery and nerve, which are tented by the displaced metacarpal head and lie immediately beneath the skin, at risk for iatrogenic injury during incision and dissection. Both approaches are useful, and both should be in the armamentarium of the pediatric hand and upper extremity surgeon.

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CHAPTER

36

Amputations

CASE PRESENTATION

A 2-year-old child presents for emergent evaluation regarding a finger amputation. He was playing at home 3 hours earlier when his finger was caught in the wheel of an exercise bicycle. There was a traumatic avulsion of the digit but no other injuries. Patient and family were subsequently transported via ambulance to the emergency department for care, accompanied by the amputated part.

CLINICAL QUESTIONS

- What are the indications for replantation and revascularization of digits in children?
- What is the preferred method of caring for the amputated digit during transport to a medical facility?
- What are the important aspects of the history and physical examination of the patient with an amputation?
- How soon after injury should replantation and/or revascularization be performed given concerns regarding tissue necrosis?
- What are the surgical principles and techniques of replantation and revascularization?
- What postoperative measures are taken to maximize viability following replantation and/or revascularization?
- What are the anticipated results following replantation?

THE FUNDAMENTALS

Perhaps no surgical procedure better demonstrates the power of reconstructive surgery and requires greater surgical skill than digital replantation. Replantation of amputated parts, by the use of microsurgical techniques, has been performed in children and adolescents for decades; indeed, the first replantation was performed in a 12-year-old boy who sustained a transhumeral-level amputation in a train accident in 1962.[1] Reports of successful digital replantation soon followed.[2] Following the great advances in microsurgical techniques in the 1970s, similar procedures have been performed throughout the upper extremity in patients of all ages. As technology has advanced and experience grown, so too has our ability to perform tissue replantation in the pediatric hand and upper limb. The fundamental principles and techniques of revascularization and replantation should be familiar to the pediatric hand and upper extremity surgeon.

Clinical Evaluation

The lowest ebb is the turn of the tide.
—Henry Wadsworth Longfellow

While the initial clinical evaluation is often rushed and conducted under stressful circumstances, a few salient points should be covered in every situation. In addition to history regarding hand dominance, functional demands, and pertinent medical conditions and comorbidities, an understanding of the mechanism of injury is critical. Clean, sharp, guillotine-like amputations have a much more favorable prognosis than contaminated, crush and/or avulsion injuries, and as much information as possible should be gleaned regarding the injury mechanism.[3]

Physical examination should characterize the level of tissue loss, degree of wound contamination, and associated soft tissue injury (Figure 36-1). The "red-line sign," for example, refers to the hematoma formation along the digital neurovascular sheath and is seen in cases of crush and avulsion injuries, connoting a more extensive zone of vascular injury and poorer prognosis (Figure 36-2). Similarly, the "ribbon sign" may be seen on the amputated part, signifying extensive injury and the need for more complex reconstructive techniques.[4] Further examination of the limb proximal to the zone of amputation should be performed to assess for upstream or segmental proximal injuries. If there is excessive arterial bleeding from the wound, simple compressive bandages should be applied. Vascular clamps and electrocautery should not be used in the emergency department, for fear of imparting greater vascular injury. A tetanus booster and prophylactic antibiotics are administered at the time of initial evaluation.

FIGURE 36-1 Clinical photograph of sharp amputations of the index and long fingers. The level of amputation is through the proximal phalanx, and the wound is relatively clean. Given the quality of the amputated parts, these digits would be deemed good candidates for replantation.

Radiographs should be obtained of the affected hand and upper limb, in addition to all available amputated part(s). Assessment of the skeletal injuries will allow for proper preoperative planning and provide further information regarding the zone and energy of injury.

The proper care of the amputated part during transport and prior to replantation is well established. The amputated digit should be wrapped in moist, saline-soaked gauze and placed in a plastic bag. The entire bag is then placed in a container on an ice bath and transported with the patient.[5–7] Every effort should be made to save all identifiable parts, as "spare parts" may be used orthotopically during surgical reconstruction. In general, for digital amputations, up to 12 hours of warm ischemia and 24 hours of cold ischemia can be accepted prior to replantation.[7] For more proximal amputation—in which there is more muscle tissue—6 hours of warm and 12 hours of cold ischemia are considered acceptable for successful replantation.

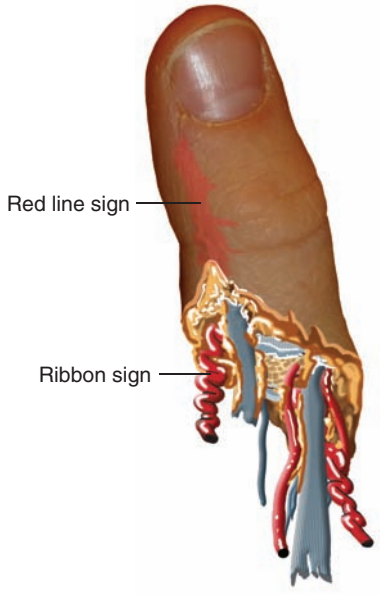

FIGURE 36-2 Schematic diagram of the amputated digit, exhibiting the ribbon and red-line signs suggestive of avulsion mechanisms.

Surgical Indications

General indications for replantation in adults include thumb amputations, multiple-digit amputations, amputations through the wrist or proximal, as well as single-digit amputations distal to the flexor digitorum superficialis (FDS) insertion.[8] However, replantation of any amputated part is almost always attempted in a child.

Contraindications to replantation include severely crushed, mangled, or contaminated parts, particularly with segmental injury; amputations in patients with significant medical comorbidities or inability to comply with postoperative restrictions and rehabilitation; and amputations with excessive warm ischemia time.

While these indications are generally well accepted, it is imperative that a frank discussion be had with the patient and/or family regarding the surgical options, treatment priorities, and expected outcomes. Successful replantation, defined as tissue viability, does not always equate with full functional restoration. Furthermore, each patient and family is accompanied by their own set of personal and cultural biases; reconciling the hopes and desires of the family with the realistic expectations of surgical treatment is an important ongoing process that begins at the time of presentation.[9]

SURGICAL PROCEDURES

Great things are done when men and mountains meet.
—William Blake

The treatment principles for the management of digital or upper limb amputations are intuitive. Generally speaking, attention to the amputated part should not detract from care of the overall patient, particularly in multitrauma or more involved injuries. Life comes before limb, and every effort is made to avoid infection, particularly in the severely traumatized extremity. Replantation procedures should not burn bridges to future reconstructive efforts, and heroic, complex operations should not be performed for patients or families unwilling or unable to participate in the postoperative recovery.

Surgically, replantation proceeds through a sequence of established steps: (1) identification of vessels and nerves, which may be tagged with marking sutures for later repair;

(2) thorough irrigation and debridement; (3) skeletal fixation with judicious bony shortening; (4) extensor tendon repair; (5) flexor tendon repair; (6) arterial anastomosis with or without interpositional vein grafting; (7) nerve repair; (8) venous anastomosis with or without interpositional grafting; and (9) loose skin closure. While there are variations in technique, and each patient presents different challenges, the fundamental steps are the same.

◆ Replant of Sharp Amputation with Direct Repair

Sharp traumatic amputation represents one of the most favorable situations for digital replantation.[10–14] Surgery begins even prior to the patient entering the operating room. Whenever possible, the amputated part is transported to the operating theater while the patient is being evaluated in the emergency department. The part is first cleaned with chlorhexidine, betadine, and/or sterile saline solution, and all foreign material is debrided. Under loupe and microscopic visualization, midaxial incisions are created radially and ulnarly (Figure 36-3). Skin flaps are carefully raised. Volarly, each digital artery and nerve is atraumatically identified and circumferentially dissected using microsurgical instruments. Vessel clamps or fine sutures (our preference is to use a blue 6-0 polypropylene suture [Prolene, Ethicon, Inc., Somerville, NJ]) may be used to tag the very ends of the vessels and nerves for later identification. The distal flexor tendon may similarly be identified and a core suture placed for subsequent tenorrhaphy. Dorsal dissection is more delicate, particularly, as the veins of the avascular segment are collapsed and prone to further injury. The dorsal skin flap is raised, and the plane of dissection is performed between the subdermal and deep fatty layers, where the dorsal veins are identified. These may be similarly clipped or tagged for later use.

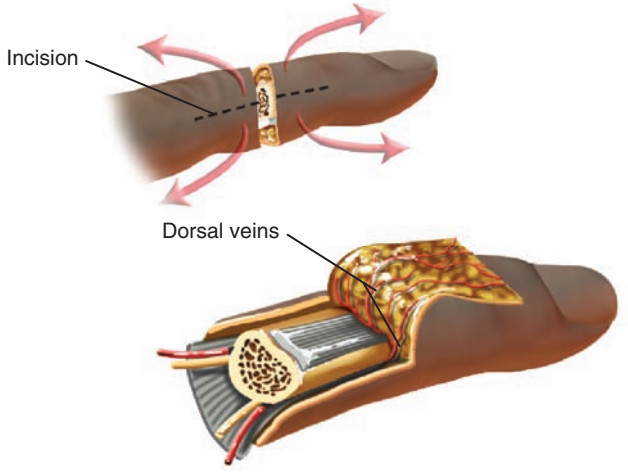

FIGURE 36-3 Midaxial incisions utilized for preparation and exposure of the vessels, nerves, tendons, and bone during replantation.

The extensor tendon stump is also identified, and sutures may be placed. Direction is then turned to the bone. With the use of a microsagittal saw or sharp bone cutter, judicious shortening of a few millimeters is performed, with care taken not to crush the phalanx or injure the adjacent soft tissues.[15,16] Smooth K-wires are then placed in a retrograde fashion (longitudinally or obliquely) in preparation for subsequent fixation to the hand. While plates and screws or interosseous wiring may also be used and have mechanical strength advantages, we find that K-wires are simple, faster, efficacious, and do not add bulk or tension to the surrounding soft tissues.[16–22] Once the soft tissue preparation, bony shortening, and skeletal fixation have been performed, the amputated part is placed in moist gauze on sterile ice to maintain cold ischemia until ready for replantation.

The patient is simultaneously brought to the operating room and anesthetized. Adequate intravenous access is obtained, a urinary catheter placed, and the ipsilateral upper extremity prepped and draped into the surgical field. In cases of proximal replantation or extensive zones of injury, the ipsilateral lower limb is also prepped and draped into the field in the event that vein graft from the leg needs to be harvested.

The amputation site is similarly exposed using midaxial incisions. The digital arteries, nerves, veins, and flexor and extensor tendons are identified and mobilized. Core sutures may again be placed in the flexor tendon to facilitate repair later and prevent recurrent retraction into the more proximal tendon sheath or palm. Thorough irrigation and debridement is performed, removing all nonviable tissue and foreign material. Skeletal shortening of the proximal bone may be performed in a fashion that will appropriately engage the amputated part; in general, transverse shortening is the easiest and most reliably performed.

Bony fixation is then performed, reapproximating the amputated part to the prepared recipient site. The previously placed K-wires are passed into the more proximal bone, and longitudinal alignment and rotational position secured (Figure 36-4). Flexor and extensor tenorrhaphies are then performed in the standard fashion[23] (see Chapter 38).

Attention is then turned to reestablishing arterial inflow. Under microscopic visualization, the proximal arterial stump is evaluated. It is common to see a clot occluding the lumen and varying degrees of adventitial and intimal damage at the site of amputation (Figure 36-5). It is critical for the artery to be trimmed back to a normal, healthy vessel. When this is performed, there will be a brisk, pulsatile flow, which should spurt bright red blood across the surgical field. Once the proximal arterial flow is established, the lumen of the artery is dilated using a microvascular dilator. A smooth vascular clamp mounted on a microsurgical sliding stage is then placed, leaving adequate distal stump exposed for anastomosis. The corresponding distal arterial stump on the amputated part is similarly trimmed back to normal-appearing tissue.

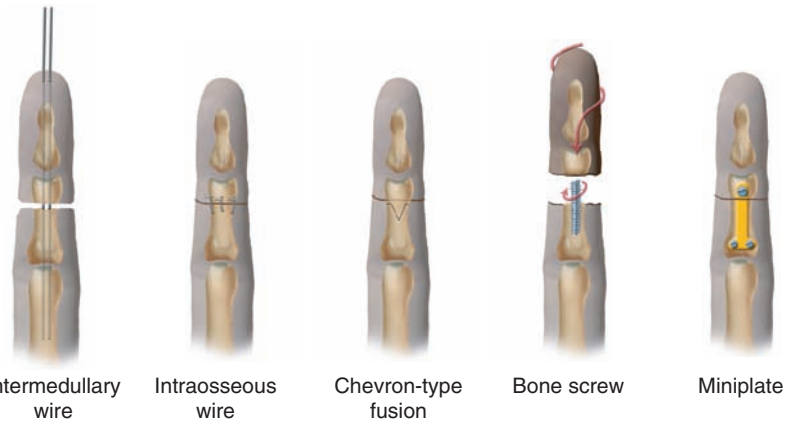

FIGURE 36-4 Diagrams depicting different techniques of skeletal stabilization.

Heparinized saline is infiltrated through the amputated artery, and the vessel wall dilated. The second smooth vascular clamp mounted on the stage is then used to stabilize the distal artery. With confirmation that there is no undue tension and the vessels may be easily reapproximated, microvascular anastomosis is performed, usually with 10-0 simple interrupted nylon sutures. The back wall is reapproximated first, after which the vessel is rotated 180 degrees and the front wall completed (Figure 36-6). Upon completion of the arterial anastomosis, the vessel clamps are released, and confirmation of arterial inflow is made. Additional sutures may be placed if needed. The arterial anastomosis is then covered with the adjacent subcutaneous skin and fat flap. The distal fingertip is observed for restoration of turgor and color.

A number of maneuvers may be used to optimize vascular patency and flow. First, just prior to vascular anastomosis, our preference is to initiate a continuous infusion of dextran 40 at 5 to 10 ml/kg/day. While others have used intravenous heparin, we have found that volume expansion using dextran provides sufficient anticoagulation effect without the risks of fluid overload and cardiac failure seen in adults. Secondly, the ambient room temperature is raised as high as the patient and surgical team can tolerate. Maintenance of appropriate body core temperature is important to avoid peripheral vasoconstriction. Furthermore, topical administration of 10% lidocaine or papaverine (1:20 concentration) to the vessels will also promote vasodilation. Finally, arterial flow needs time to be reestablished. The surgeon and surgical team should be patient before rushing to revise or explore an arterial anastomosis. We wait at least 10 minutes before uncovering the arterial repair. In general, reconstituting a single digital artery is sufficient and is what we perform. If in doubt about the quality of the inflow, repair both arteries.

After inflow is reestablished and while the volar aspect of the hand is exposed, neurorrhaphy is performed of each digital nerve in the standard fashion.[24] Epineurial 9-0 nylon sutures are typically sufficient.

The hand is then flipped and the dorsal aspect exposed. Attention is turned to venous anastomosis. The advantage of anastomosing the veins last is that arterial inflow will serve to backfill the veins on the amputated part, making their identification and manipulation easier. The disadvantage of a "vein last" approach is that the surgical field is often bloody at this stage, providing challenges in visualization. Steps that can be taken to improve visualization include frequent atraumatic blotting or suction, frequent irrigation with heparinized saline or papaverine solution,

FIGURE 36-5 Schematic diagram depicting signs of vascular damage requiring additional trimming prior to vascular anastomosis.

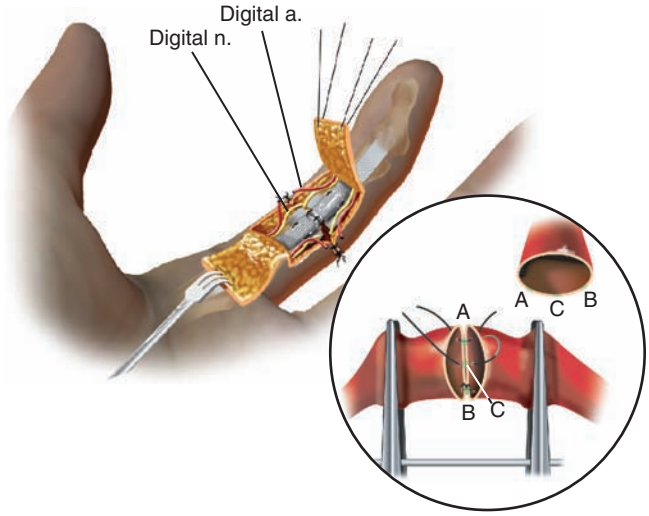

FIGURE 36-6 Technique of microvascular repair.

or temporary use of a pneumatic tourniquet placed in the upper brachium. Venous anastomosis is performed under microscopic visualization, again using 9-0 or 10-0 simple interrupted nylon sutures. Reconstitution of two veins is preferred.[25,26]

At the conclusion of the case, skin flaps are reapproximated and closed loosely with interrupted 4-0 or 5-0 sutures (Chromic, Ethicon, Inc., Somerville, NJ). Care is taken not to make the skin closure too tight for fear of constricting the vascular anastomoses; better to leave the wound a little too open than cause interruption of inflow or outflow. This is yet another advantage of the midaxial approach.

Postoperatively, loose bulky dressing is applied, followed by volar splint or cast immobilization. Care is taken to be certain that there is no external constriction.

◆◆ Replant of Crush or Avulsion Amputation with Grafts

Crush and/or avulsion injuries impart a greater zone of injury. While the principles and surgical steps are the same as in clean, guillotine amputations, often there is wider, more extensive injury to the digital arteries and veins. Even with bony shortening, primary end-to-end anastomoses of healthy vessels may not be possible. In these situations, early recognition and prompt conversion to interpositional vein grafting will be both time saving and more effective in achieving the surgical goals.[27,28]

There are a plethora of suitable donor veins for grafting. In digital injuries where the proximal upper limb is not traumatized, the volar wrist and distal forearm veins are abundant, easily accessible, and the appropriate caliber for interpositional grafting. It is helpful to mark these veins out with a marking pen even prior to beginning a replantation procedure. Via a longitudinal skin incision of the distal forearm, these veins may be identified and harvested. Vascular clips are placed an appropriate distance apart, and the vein is taken. Heparinized saline or papaverine solution is injected into the vein to flush out potentially thrombogenic blood and dilate the vessel wall. A tagging suture or additional vascular clip can be applied to mark the polarity of the vein. (Our preference is to reverse the vein graft in the event that the graft includes any valves that may impede subsequent blood flow.) The vein is then placed into a solution of papaverine until needed.

The microvascular anastomosis from native vessel-to-vein graft is performed using standard techniques (Figure 36-7). Often, these repairs are easier, due to the length and therefore lack of tension of the interpositional graft. Indeed, in multiple digit or thumb avulsions, vein grafts may be plugged end to side into the palmar arch or deep dorsal branch of the radial artery, respectively, if needed.

FIGURE 36-7 Intraoperative photograph following replantation of a right ring avulsion injury; due to the extensive zone of injury, an interpositional vein graft (*arrow*) was needed to restore arterial inflow.

◆◆ Multiple-Digit Replant

If everything seems under control, you're not going fast enough.
—Mario Andretti

Multiple digital replantations add additional complexity to both surgical decision making and technical completion. Two strategies are generally employed. For experienced surgeons, the "one-structure-at-a-time" approach may be used (Figure 36-8). In this technique, all digits are fixed, then all flexor tendons sequentially repaired, then all extensor tenorrhaphies performed, followed by all arterial anastomoses, and so on down the line. While quicker than completing digital replantations one at a time, the potential disadvantage to this surgical strategy is that time and effort may be wasted on severely damaged parts that may not survive or may impart greater functional hindrance if they do. An alternative strategy is to replant digits serially in the order of functional importance. In this tack, if all digits are equally injured and amputated at the same level, the long finger is replanted first, followed by the index, ring, and small fingers. The advantage of this technique is that efforts are concentrated on the digits that will provide the greatest functional benefits. The disadvantage is that the overall surgical time is likely to be longer; the risk of continued warm or cold necrosis increases, and the surgical procedure is more taxing on the single surgeon. These operations often require multiple skilled surgeons to keep the pace and skill level at the highest possible level.

◆◆ Ray Resection

Ray resection is a useful surgical tool in cases of acute, unreplantable digital amputations or for reconstruction of failed replants. This is particularly true when a central digit (long or ring finger) is affected, as the gap caused by the digital loss is both aesthetically displeasing and functionally limiting.

FIGURE 36-8 Intraoperative photograph during a four-finger replantation procedure, using the "one-structure-at-a-time" approach. The digits have been prepared and pinned to the hand. All tendons and neurovascular structures have been identified and tagged with sutures.

Patients with post-traumatic central digital deficiency will often complain of the inability to cup the hand (e.g., dropping objects between fingers) or catching/jamming the exposed border digits when passing the hand through a sleeve or into a pocket. When the gap is more noticeable and problematic than the digital loss, ray resection can provide surprising functional and aesthetic improvements. The potential functional gains, however, must be weighed against the narrowing of the palm in addition to the measurable loss of grip strength.[22,29] In general, ray resections may be performed with or without bony transposition of the adjacent border metacarpal to a more central position in the hand. In the acute setting, we prefer ray resection without metacarpal transposition; we find this technique more reliable, technically easier, and equally satisfactory in terms of aesthetics and functional gains. For technical details of the surgery, see Chapters 8 and 50.

POSTOPERATIVE

Following replantation or revascularization surgery, we utilize a number of postoperative precautions in an effort to optimize vascular patency. First, all patients are placed in a private warm room, with the ambient temperature kept at or above 80 degrees Fahrenheit. Second, dietary restrictions are imparted, and all vasoconstrictive foods and beverages (e.g., chocolate, caffeine, nicotine) are avoided. Furthermore, pharmacologic anticoagulation is instituted. The intravenous dextran infusion begun in the operating room is continued for 5 days postoperatively at a rate of 10 mL/kg/day. Oral aspirin (325 mg) is given daily for 3 weeks postoperatively. In addition, every effort is made to keep the patient adequately hydrated, first by intravenous fluids and subsequently with sufficient oral intake. Finally, every effort is made to provide adequate analgesia. The use of postoperative regional blocks or indwelling catheters is routine.

Careful serial monitoring is performed. Hourly assessment of color, turgor, and warmth is made. Capillary refill, in our experience, is not as reliable an indicator of sufficient vascular inflow and outflow. Transcutaneous oxygen saturation monitors and temperature probes may also be helpful but are technically difficult to apply to the traumatized digital tip.[30,31] Finally, serial hematocrit checks are performed to ascertain adequate oxygen-carrying capacity.

Occasionally, venous congestion will be seen in the postoperative period, particularly in crush and/or avulsion injuries (Figure 36-9). A number of maneuvers may assist in temporarily alleviating venous congestion until neovascularization occurs. Be certain there is no external compression from the dressing and/or splint. Dried blood can become very constricting if the dressing is too tight. Simple elevation can be helpful. Furthermore, the nail plate can be removed, nail bed abraded, and heparin-soaked pledgets applied with regular frequency to allow bleeding and outflow. Finally, medical-grade leeches can be applied to the affected part.[32,33] After stabbing the digital tip with a 18-gauge needle to induce bleeding, leeches are applied. As they draw blood from the digit, venous congestion is relieved. More importantly, the leeches secrete hirudin, a local anticoagulant, which assists in venous outflow and may prevent further microvascular clotting. It is important to remember that leeches carry *Aeromonas hydrophila*, which may cause secondary infections in marginal tissue.[34,35] Appropriate antibiotic prophylaxis with third-generation cephalosporins or trimethoprim-sulfamethoxazole is recommended.

FIGURE 36-9 Postoperative photograph depicting venous congestion of the ring finger following replantation. This resolved after elevation, removal of constricting bandages, and observation.

The viability of the replanted part is most vulnerable in the first 24 to 48 hours postoperatively. Indeed, arterial insufficiency is historically the most common cause of replantation failure.[3,36] In rare situations, if an initially viable digit becomes acutely white and ischemic, prompt return to the operating room for exploration and potential anastomotic revision is needed. Replant failure is unusual if vascularity and viability are maintained beyond the first 48 to 72 hours.

ANTICIPATED RESULTS

When success is defined by tissue viability, replantation is successful in up to 80% of traumatic amputations in children and adults. In one of the largest published series of upper limb replantations and revascularizations in children, Saies et al.[37] reported on 73 replantations and 89 revascularizations in 120 children up to the age of 16 years. Survival was seen in 88% of revascularized and 63% of replanted parts. While there was no obvious association between viability and preoperative ischemia time, level of injury, or type of vascular anastomoses performed, there were clear differences in success depending upon the mechanism of injury and patient age. Of the clean sharp amputations, 72% were successfully replanted, compared to 53% of crush and/or avulsion injuries. Interestingly, younger patients had higher success rates than older patients.

Although viability and tissue salvage may be achieved, functional results are more sobering. Protective sensation is restored in most patients, and approximately 50% of normal total active motion (TAM) and strength is achieved on average.[26,38–43] Better TAM is seen in replantations performed distal to the FDS insertion.[44] The need for secondary reconstructive procedures (e.g., scar release, tenolysis, etc.) is common.

COMPLICATIONS

The man who complains about the way the ball bounces is likely the one who dropped it.
—Lou Holtz

A host of complications may be encountered in the management of traumatic amputations of the hand and upper limb. The most devastating is tissue loss after attempted but unsuccessful replantation or revascularization. Although statistically the success rates of replantation are high, patients who sustain crush and/or avulsion injuries are at highest risk for failed reconstruction and the need for revision amputation.

In addition to tissue loss, functional results may still be suboptimal, even in cases of "successful" replantation. Delayed union or nonunion at the osteosynthesis site may be seen. Furthermore, incomplete sensory return, tendon adhesions, scar contractures, and digital deformity may occur. Finally, temperature sensitivity and cold intolerance are commonly seen after digital replantation or revascularization.[45–48] Patients and families should be counseled in advance regarding the potential need for revision or reconstructive secondary procedures to improve hand function.

CASE OUTCOME

The diagnosis of crush and/or avulsion amputation was made, and the patient was taken emergently to the operating room for successful replantation. One artery and two veins were reconstituted, and viability was restored. Clinically, the digits remained vascularized and well aligned. While digital stiffness was noted, this was not deemed functionally limiting, and therefore no secondary procedures were performed.

SUMMARY

Preservation of tissue and restoration of function are the main treatment goals following severe traumatic hand injuries. Replantation and/or revascularization are generally attempted in all cases of traumatic amputations in children. With conducive injury patterns, prompt treatment, and meticulous technique, viability rates following replantation are very high, though functional return may be incomplete.

COACH'S CORNER

Pederson has previously contended that successful microsurgery requires three things: (1) adequate magnification, (2) appropriate instruments and suture material, and (3) sufficient microsurgical training.[49] We agree with these fundamental tenets and offer a few comments.

While loupe magnification is sufficient for most pediatric hand and upper extremity surgery, we still believe that microscopic visualization is best for traumatic replantation and revascularization surgery. In the ideal circumstances, microscopic work should be performed with the surgeon comfortably seated, feet flat on the floor, knees, hip, and elbows flexed 90 degrees, and hands supported by towels or other supports.

Microsurgical instruments are also critical for replantation and revascularization work. At bare minimum, there should be a No. 3 or 5 jeweller forceps, a curved needle holder, a microscissors, a vessel dilator, vascular clamps of various sizes, and a plastic, colored background material. Irrigation may be provided via small diameter catheters (e.g., 30-gauge ophthalmologic or tuberculin catheters). Our preference is to have 10% lidocaine as well as heparinized saline and papavarine available to us throughout the course of the case.

Suture material is dependent upon a number of patient factors, most notably the size of the neurovascular structures involved. Typically, a 9-0 or 10-0 nylon suture on a 100-μm curved, sharp needle will suffice.

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CHAPTER

37

Traumatic Peripheral Nerve Injuries

CASE PRESENTATION

A 10-year-old female has had no intrinsic ulnar nerve motor function or sensibility in the small and ulnar half of the ring finger since a diaphyseal both-bone forearm was treated with closed reduction 10 months ago. The fractures have healed (Figure 37-1), but there appears to be a slight lucency in the ulnar fracture site on an oblique view. She lacks small finger adduction (Wartenberg sign), extends the thumb metacarpophalangeal (MCP) joint (Jeanne sign), flexes the thumb interphalangeal (IP) joint with key pinch (Froment sign), and has clawing of the ring and small fingers (Duchenne sign). There is flattening of the palm of the hand (Masse sign). She complains of lack of fine motor coordination and grip-and-pinch strength.

CLINICAL QUESTIONS

- Which nerves are most commonly injured with which fractures or dislocations?
- What are the chances of spontaneous recovery of a major (axillary, median, ulnar, or radial) peripheral nerve injury associated with an upper limb fracture and/or dislocation?
- How long should an impaired nerve in a child be observed expecting recovery?
- What are the indications for exploration of a nonfunctioning nerve after blunt trauma?
- When should open lacerations be explored for vital soft tissue injuries?
- What are the surgical options for reconstruction of a chronic nerve palsy?
- What are the indications for nerve decompression, neuroma resection and grafting, or nerve transfers for a peripheral nerve palsy?
- What are the indications for tendon transfers for median, ulnar, and radial nerve palsies?
- Which tendon transfers give the best results?

THE FUNDAMENTALS

Etiology and Epidemiology

Every nerve and blood vessel can be injured by localized blunt or sharp trauma. Nerve injuries can be partial or complete and transient or permanent. Seddon classified, and Sunderland modified, nerve injuries by the extent of anatomic injury and implied recovery. Seddon defined injuries as neurapraxia, axonotmesis, and neurotmesis.[1] Sunderland defined five degrees of injury based on nerve fascicular layers with first-, third-, and fifth-degree injuries closely approximating Seddon neurapraxia, axonotmesis, and neurotmesis categories, respectively.[2] First- and second-degree (neurapraxia) injuries will recover completely, as the endoneurium is intact. Third- and fourth-degree injuries (axonotmesis) will probably have incomplete recovery, as the perineurium is variably intact, and the endoneurial sheath heals with some degree of scar (neuroma in continuity). Fifth-degree (axonotmesis) injuries do not heal because the nerve is no longer in continuity. The trick is figuring out which injury the patient has as early as possible. In children, the odds are that their blunt trauma nerve injuries will be neurapraxia or minor axonotmesis (Sunderland first- and second-degree)[2] injuries and recover fully. The key is figuring out the entrapped, compressed, kinked, or lacerated nerve (about 2% of all nerve injuries associated with non-hand, nonamputation, pediatric upper limb fractures or dislocations) before irreversible nerve and muscle impairment occur. Of note, open fractures are higher risk for nerve entrapment or laceration. Deep glass lacerations are unusual if they do not cut vital soft tissues. A high index of suspicion and precise, thorough exams are imperative to recognize the nerve injuries that will not resolve on their own.

Clinical Evaluation

A complete neurovascular exam is mandatory in the acute setting for every patient presenting with musculoskeletal trauma. The same is true for postreduction and postoperative evaluation of every patient under your care. All patients with an acute nerve injury require important care discussions and decisions regarding further testing, observation, or surgery.

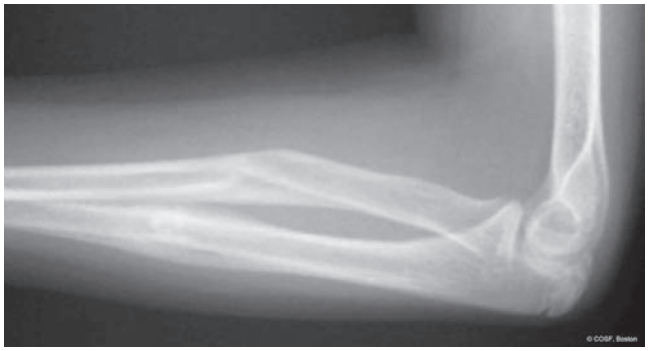


FIGURE 37-1 Healed diaphyseal forearm fracture in patient with complete ulnar nerve palsy at 7 months postinjury.

It is imperative that all pediatric upper limb and hand surgeons know human nerve anatomy and innervation patterns. Neurovascular injuries with musculoskeletal trauma are geographic. If you precisely know the anatomy, you will be able to isolate, protect, mobilize, decompress, and/or reconstruct each nerve in the upper limb. You obviously have to know specifically how to test for each nerve on physical exam for accurate pre- and postoperative assessment.

The *radial nerve* innervates the triceps; wrist extensors (extensor carpi radialis longus [ECRL] and extensor carpi radialis brevis [ECRB]); digital extensors (extensor digitorum communis [EDC], extensor indicis proprius [EIP], and extensor digiti quinti [EDQ]); thumb (extensor pollicis longus [EPL]); and long thumb abductor (abductor pollicis longus [APL]). Sensibility is in the dorsal first web space. The radial nerve departs from the posterior cord of the brachial plexus and enters the upper arm between the medial and long heads of the triceps while innervating both muscles. The radial nerve, after innervating the lateral head of the triceps, enters the intermuscular septum of the humerus, goes around the spiral groove, and exits anteriorly between the brachioradialis (BR) and brachialis. The main nerve innervates the BR and ECRL in the distal humerus before branching into the posterior interosseous nerve (PIN) and superficial radial sensory nerve. The radial sensory nerve courses down the forearm beneath the BR and then emerges above the wrist between the ECRL and BR. The PIN passes around the radial head and neck and enters the supinator. The PIN's branches are to the ECRB, extensor carpi ulnaris, EDC, EDQ, EIP, EPL, extensor pollicis brevis (EPB), and APL. Thumb retropulsion and IP joint extension, MCP joint extension, and wrist extension are the pertinent physical exam tests for radial nerve motor function in the wrist and hand.

The *ulnar nerve* arises from the medial cord of the brachial plexus and passes from the axillae down the posteromedial aspect of the arm. The nerve courses through the arcade of Struthers in the intermuscular septum of the diaphyseal humerus, passes behind the medial epicondyle of the elbow, and courses through the flexor carpi ulnaris (FCU). The ulnar nerve innervates the FCU and the flexor digitorum profundus (FDP) to the ring and small fingers (FDP IV/FDP V). The ulnar nerve is joined with the ulnar artery in the midportion of the forearm, and they course together through Guyon canal at the wrist to enter the palm. The ulnar nerve branches into the hypothenar motor, ulnar fourth and fifth digit sensory, and deep intrinsic motor branches just beyond the pisiform. Reliable ulnar nerve motor testing is by examining the FDP V (extrinsic) and first dorsal interosseous (intrinsic) muscles.

The *median nerve* is formed from medial and lateral cord contributions of the brachial plexus. The median nerve courses down the anteromedial upper arm adjacent to the brachial artery. The nerve passes beneath the lacertus fibrosus and then between the two heads of the pronator teres (PT). The anterior interosseous nerve (AIN) motor branch exits posteriorly and eventually innervates the flexor pollicis longus (FPL), FDP to the index finger, and pronator quadratus (PQ). After giving off the PT and AIN, the median nerve courses under the flexor digitorum superficialis (FDS) arch, between the FDP and FDS muscles and tendons in the forearm, and then at the wrist, enters the carpal canal. The palmar cutaneous nerve branch arises from the median nerve, courses on the radial side of the palmaris longus (PL) in the distal forearm and innervates the radial palmar skin. In the carpal canal, the nerve supplies the thenar motor branch for opposition and then exits to provide sensibility to the thumb, index, long, and radial half of the ring finger. Reliable motor testing for the median nerve is performed by examining thumb FPL-IP joint flexion (extrinsic) and opposition (intrinsic).

Surgical Indications

Displaced fractures and dislocations with a neurovascular injury require prompt reduction of the bony displacement. Nerve injuries that do not show signs of recovery by 3 to 6 months postinjury require exploration, decompression, and reconstruction as appropriate. Median and ulnar neuromas in continuity that do not provide functional muscle activity and good sensibility within the first 6 months postinjury require resection and nerve grafting. Chronic radial neuropathies require nerve (first 6 months) or tendon transfers to improve grip and key pinch function. Opposition and FPL/FDP II transfers are appropriate for chronic median neuropathy. Intrinsic transfers and rebalancing are appropriate for chronic ulnar nerve deficiencies.

SURGICAL PROCEDURES

Observation of Nerve Injuries after Closed Reduction of Fractures and Dislocations

In order not to miss an iatrogenic nerve entrapment, laceration, or impairment caused by a closed reduction or

pin placement after closed reduction, a complete, precise exam of each nerve prior to reduction and pinning is mandatory. Fortunately, most nerve injuries associated with closed fracture dislocations of the upper limb are not entrapments or lacerations and will resolve over a short time with observation. The usual mechanisms of injury to the nerve are direct trauma (contusion) from the displaced bone at the time of the acute trauma and ongoing traction ischemia while the nerve is tented, kinked, and/or compressed by the unreduced bone. Quickly reducing the fracture and/or dislocation to an anatomic alignment lessens the dysvascular effect on nerve function. Nerve injuries are localized to the traumatic anatomic region and correspond to the direction and degree of bony displacement. In the upper limb, these include, among others:[3,4] (see each specific chapter for more detail) (1) axillary nerve with shoulder dislocations;[5,6] (2) brachial plexus and axillary nerve with proximal humeral fractures;[7,8] (3) radial nerve with humeral shaft fractures;[9–11] (4) median, ulnar, and radial nerves and combinations thereof with supracondylar humerus fractures;[12–16] (5) median and ulnar nerves with elbow dislocations;[17–20] (6) radial PIN with anterior Monteggia fracture dislocations;[21–25] (7) median and ulnar nerves with diaphyseal forearm fractures;[26–28] and (8) median nerve with distal radial physeal fractures.[29,30] All of these specific nerve injuries tend to recover as the bone(s) and soft tissues heal.

The nerve recovery can be in days for minor neurapraxia injuries and weeks for more significant neurapraxia or axonotmesis injuries. Signs of a recovering nerve will be (1) an advancing Tinel sign along the anatomic path of the nerve after a brief (up to 30 days) hiatus, (2) initial hypesthesia followed by dysesthesia and then recovering sensibility in the anatomic nerve distribution, and (3) progressive proximal to distal anatomic motor recovery. The nerve recovery pattern, as outlined, needs to begin by 3 to at the latest 6 months after injury. If the nerve does not at least start significant recovery during that time, nerve exploration is warranted. On average, 95% to 98% of the nerve injuries in the upper limb associated with blunt trauma will recover fully with bone and joint treatment and close observation of neural recovery.

Open Reduction and Nerve Decompression

Ability may get you to the top, but it takes character to keep you there.
—John Wooden

If a nerve is out preoperatively, and an open reduction of the fracture and/or dislocation is indicated, nerve exploration and decompression is a safe and effective way to resolve entrapped nerves, repair lacerated nerves, and be certain an impaired nerve is not further injured by operative treatment of the displaced bone (see Figures 27-2 and 27-19). Open fractures have a higher incidence of lacerated or incarcerated nerves than closed fractures. The majority of entrapped acute peripheral neuropathies with skeletal trauma only need an acute decompression to fully recover. Since most nerve injuries are geographic to the bone and joint injury, extending the incision to decompress, mobilize, and protect the injured nerve(s) with operative fixation is appropriate. A tension-free nerve will recover quicker and be less likely to be further injured by retraction during operative reduction and stabilization. Also, be certain at the end of the case that the nerve(s) is not kinked, compressed, and/or entrapped in the bone or joint or by a pin or plate. Of note, it is our practice to visualize, decompress, mobilize, and protect all nerves in the anatomic region of operative fixation. We also fret about and protect nerves on the contralateral side of the bone we are fixing so as to avoid compression, traction, or penetration injury from a retractor, pin, and/or screw.

Management of Acute Hemorrhage

Penetrating trauma, most commonly glass or knife lacerations, can injure both blood vessels and nerves. Open fractures can do the same from the inside out. Complete lacerations of arteries will usually bleed dramatically for a short time and then tamponade with pressure and vasospasm. Side-hole arterial and venous lacerations, and major arterial and venous lacerations above the hand, can continue to bleed, sometimes to the extent of life-threatening hemorrhage. The marked hemorrhage lacerations that do not respond to pressure are operative emergencies. A brief tourniquet to control the bleeding may be required between the emergency room and the operative suite, similar to in-field military transport tourniquet indications. Rapid sequence general anesthesia may be necessary. Pressure is maintained over the laceration until sterile conditions and tourniquet control are established. The open wound is extended proximally and distally. Unessential bleeding vessels are ligated with sutures and/or vascular clips. Essential arteries or veins are repaired with appropriate magnification and suture size. Contaminated wounds are extensively debrided. Open fractures are thoroughly cleansed and treated with external fixation, closed or open reduction depending on the situation. Associated nerve and tendon injuries are repaired primarily or in a delayed fashion as is best for outcome.

Microscopic Nerve Repairs (See Sidebar)

Glass and knife lacerations are the most common causes of traumatic nerve injuries in children and adolescents. Many of these penetrating injuries are associated with vascular and/or muscle-tendon unit lacerations. Thin shards of glass are very sharp and can penetrate deeply through a minor skin laceration. So too can long, thin knife blades.

SIDEBAR

Surgical Magnification and Microsurgical Instruments

All hand surgeons must have a pair of loupes. Surgical magnification loupes are manufactured by several companies and are of varying magnification size (2.5×, 3.5×, and 4.5× are the most common choices), depth of field (normal or expanded), optical working distance (usually 15 to 20" for hand surgery), cost, and eye frame or head support options. The lower magnification loupes (2.5×) are less stressful to the surgeon's neck over the course of a long case or career. The higher magnification loupes, especially with expanded field, allow for more precise surgical care. For many pediatric hand surgery cases, higher magnification expanded field view is preferred. Some nerve and vascular surgery cases, especially bigger nerves and vessels located in difficult places to position a microscope, can be done safely with 4.5× expanded field magnification.

However, most microsurgery cases should truly be performed with the aid of the microscope. Two-headed microscopes are important to actively involve a skilled assist in these complex cases. A three-headed microscope can help educate an additional microsurgical trainee. A fiber optic video connection to an operating room monitor keeps the entire team (surgical scrub, circulator, anesthesia, and trainees) engaged. Learning all the ins and outs of the microscope in your operating room is important for your surgical success. Not all of these cases occur in the light of day when all the knowledgeable help is around to set up and fix any equipment problems.

The saying, "A carpenter is only as good as his tools," does apply to some degree to microsurgery. Precise handling of tissue is imperative to successful outcome. Well-maintained microscopic smooth-tipped forceps; straight, curved, and serrated scissors; straight and curved needle holders; atraumatic clamps, all of various sizes and without burrs or other defects, are critical to microsurgery techniques. A ready supply of 8-0, 9-0, 10-0, and even 11-0 nylon microsutures is necessary for pediatric microsurgery. The usual needle curve is in 75- to 100-μm range. Remember, hand surgery–preferred needles will be different in needle tip (blunt, sharp, tapered, cutting) and curvature than other subspecialty microscopic needles. Beware that you may be handed an ophthalmological 9-0 needle that could sabotage your repair techniques. Without being difficult, you have to be exacting regarding the equipment you need to do this type of surgery.

The relatively benign appearance of the skin laceration will fool the emergency caregiver into believing there are no deep lacerations. Without extension of the minor skin laceration, the deeper lacerated structures will not be visible. (Remember, cut tendons, nerves, and blood vessels move away from the laceration site with changes in digital and wrist position.) A tendon- and nerve-specific clinical exam is necessary for each anatomic structure in the region of the laceration in order to make an accurate diagnosis and provide timely treatment. The children and teenagers just will not tell you, "Hey Doc, my nerve and tendon have been cut." And as with many bad things in these young children's lives, their parents may not find out until much later.

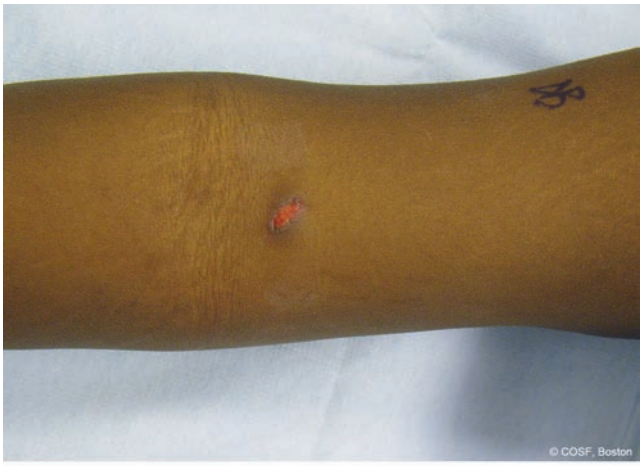
◆ Digital Nerve and Peripheral Sensory Nerve Lacerations

Sharp digital nerve lacerations that are diagnosed and treated within 3 weeks of injury have an outstanding chance of full sensibility recovery in the pediatric and adolescent age group. Lacerations diagnosed later can even go on to full recovery (Figure 37-2), but some may require a segmental nerve graft to have a tension-free repair. Since these patients do so well in terms of sensibility recovery, and since neuromas can be painful and functionally limiting, we repair or reconstruct all digital nerve lacerations regardless of when they present to us. This is especially true of the ulnar side of the thumb; radial side of the index finger; and ulnar side of the small finger, as these are important areas for functional sensibility.

With an acute, isolated laceration of a digital nerve, the skin is closed in the emergency room setting, and elective microsurgery is scheduled for day surgery sometime later that week. The same is true for a digital nerve laceration associated with a tendon laceration. The advantage of waiting is to have all of the skilled-hand team in a calm, nonurgent operative environment. Obviously acute digital nerve lacerations associated with an avascular or amputated finger are surgical emergencies (see Chapter 36).

With late-presenting nerve lacerations, the diagnosis is explained, and the options of late surgical reconstruction (potentially with nerve grafting) versus natural history are described in detail. The potential benefit of neuroma excision to those who have a painful neuroma and sensibility improvement or even recovery in all others is compared to the risks of anesthesia, surgical infection, and failure of the operation to improve their situation. Most, if not all, opt for surgery when described this way, and that makes sense to us. It is what we would do for our own children.

Under general and/or regional anesthesia, the sutures, if present, are removed and sterile prepping and draping



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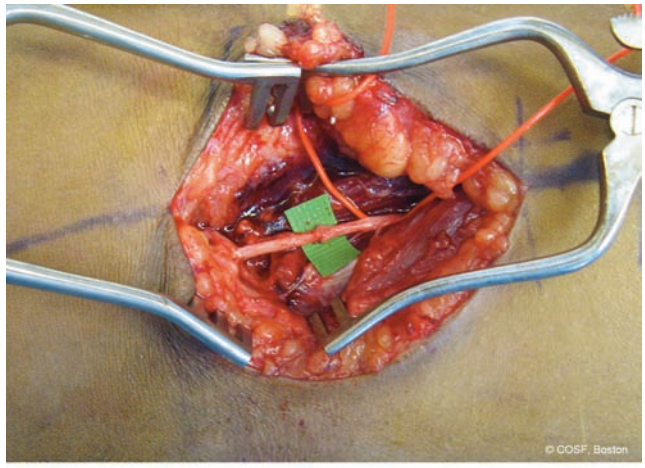


B

FIGURE 37-2 **A1:** Late-presenting laceration of the upper arm with symptomatic numbness and dysesthesia on clinical exam noted by shaded area (**A2**). **B:** Microscopic repair of lateral antebrachial cutaneous nerve.

performed. With tourniquet control and loupe magnification, the traumatic incision is extended in a midaxial or Bruner zigzag incision depending on the situation. The flexor tendons and both digital neurovascular bundles are isolated proximal to the traumatic skin laceration. Confirmation of the integrity of both the superficialis and profundus flexor tendons is performed by visualization of isolated tendon excursion. The neurovascular bundles are followed from the normal proximal nerve distally to the skin laceration. The cut nerve and artery are isolated. The longer it has been since the acute laceration, the harder it is to identify and mobilize the proximal and distal nerve segments. Pacinian corpuscles often lead the way. The cut ends of the nerve can be stuck and require microscopic dissection. Once freed, the nerve ends are further mobilized proximally and distally to allow for a tension-free repair. The microscope is used to trim the nerve ends if necessary for a clean end-to-end repair. If a neuroma is present in a chronic laceration, then it is resected back to healthy fascicles on either side. If the resultant nerve gap prevents a tension-free repair, a PIN graft from the dorsum of the wrist is obtained (Figure 37-3) (see "Nerve Grafting below"). Microscopic repair is performed with segmental epineural suture. Usually 9-0 suture is used, with two to four sutures required for acceptable coaptation of the nerve. Skin closure with 5-0 suture (Chromic, Ethicon, Inc., Somerville, NJ) is performed. Cast protection of the repair is for 2 weeks followed by mobilization and scar management. Nerve recovery is anticipated and monitored over the next 3 to 6 months.

◆ Repair of Major Peripheral Nerve Lacerations

Traumatic lacerations to the musculocutaneous, median, ulnar, radial, radial sensory, dorsal ulnar sensory, and palmar cutaneous nerves do occur with penetrating trauma. Most of these injuries are in association with lacerations to tendons, muscles, blood vessels, and even other nerves. As opposed to digital nerve lacerations, isolated repair of the major peripheral nerves is unusual; most repairs are performed in conjunction with tendon and other soft tissue reconstructions (Figure 37-4) (see Chapter 38). In

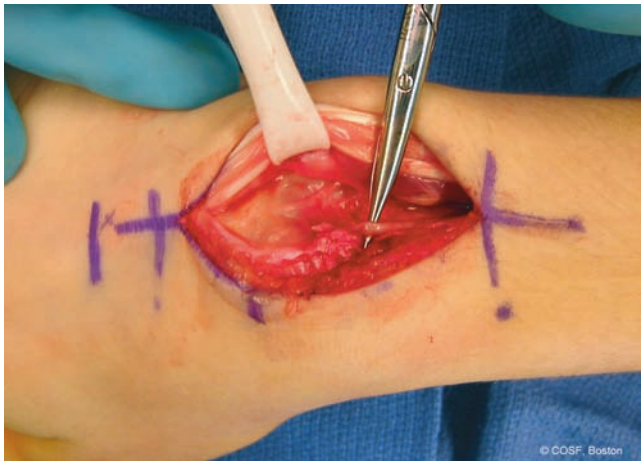
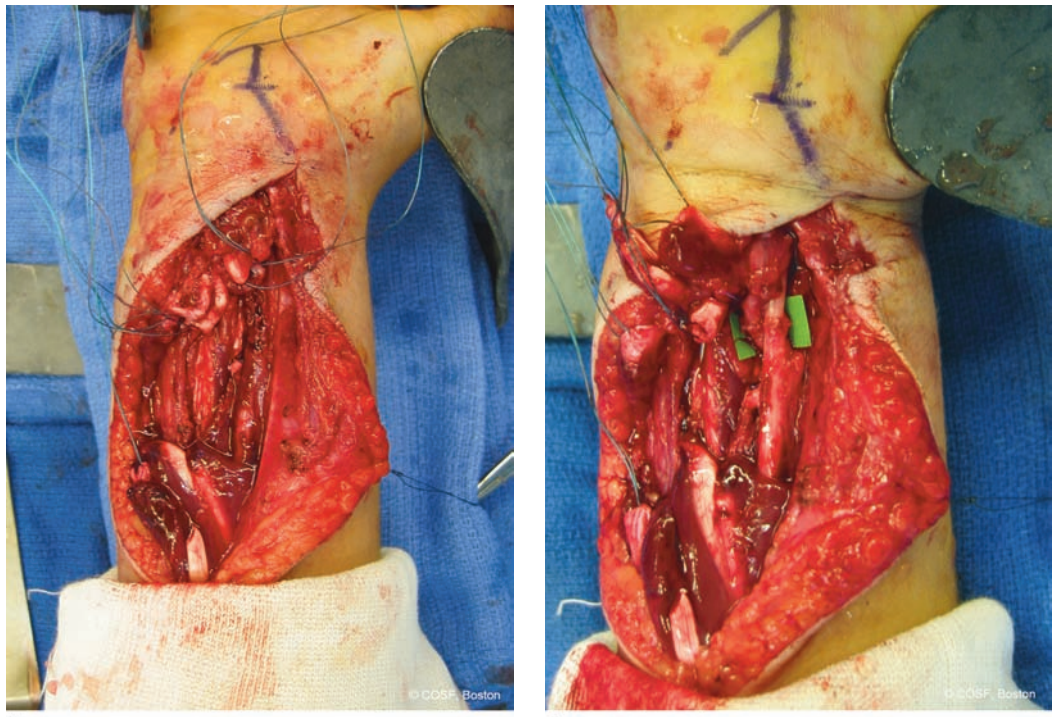


FIGURE 37-3 PIN terminal branch as it inserts into the wrist. The nerve can be found deep in the fourth dorsal extensor compartment beneath the EIP and is used for digital nerve grafts.

addition, median, ulnar, and radial nerve entrapments in dislocated joints or fracture sites have occurred. These nerve entrapments need nerve decompression acutely but potential neuroma resection and end-to-end repair or nerve grafting later.

Almost immediately after nerve transection, stretch, or crush, there is a biologic response to nerve axonal injury with an influx of calcium ions that activate calcium-sensitive protein kinases (calpain). Various kinases (mitogen-activated kinases, JNK, ERK) regulate transcription factors (STAT3) and promote synthesis of growth and neurotrophic factors that initiate axonal regeneration and sprouting within hours of injury. Similarly, the biologic response on the distal axon starts immediately and leads to wallerian degeneration by macrophages over the first two weeks following an injury. Schwann cells upregulate numerous neurotrophic growth factors that are important in axon and myelin regeneration. If the axon fails in its self-regeneration efforts, then the distal endoneurial tube shrinks, making future normal nerve and muscle fiber regeneration less likely. Prolonged denervation should be avoided if possible.

Nerve repair acutely, if the wound is clean, or within a few weeks, if the wound is initially contaminated or the referral for definitive surgical care is delayed, maximizes outcome. Direct end-to-end microscopic repair is still preferred. Proximal and distal healthy fascicles need to be aligned without tension in a well-vascularized bed of surrounding soft tissues. Mobilization of the lacerated nerve is performed with proximal and distal dissection. Longitudinally running vessels and the size and orientation of fascicles are noted to anatomically align the nerve. Proper alignment of the nerve assures motor-to-motor and sensory-to-sensory nerve fascicle healing. The cut nerve



A **B**

FIGURE 37-4 **A:** Intraoperative exposure of a complex volar forearm laceration, involving multiple flexor tendons (with grasping sutures placed) and the median nerve. **B:** Intraoperative appearance after microscopic repair of the median nerve, seen above the green background material.

ends are trimmed back until there are normal sprouting fascicles under the microscope. Hemostasis is obtained with bipolar cautery. The options for end-to-end microscopic suture repair techniques are epineural, group fascicular, and individual fascicle. Most pediatric and adolescent repairs are epineural, and less commonly group fascicular, with tension-free 8-0 or 9-0 microscopic nylon sutures placed 180 degrees apart to anatomically align the nerve. Fibrin glue is often utilized to lessen suture scar reaction in the nerve, which could negatively influence outcome.

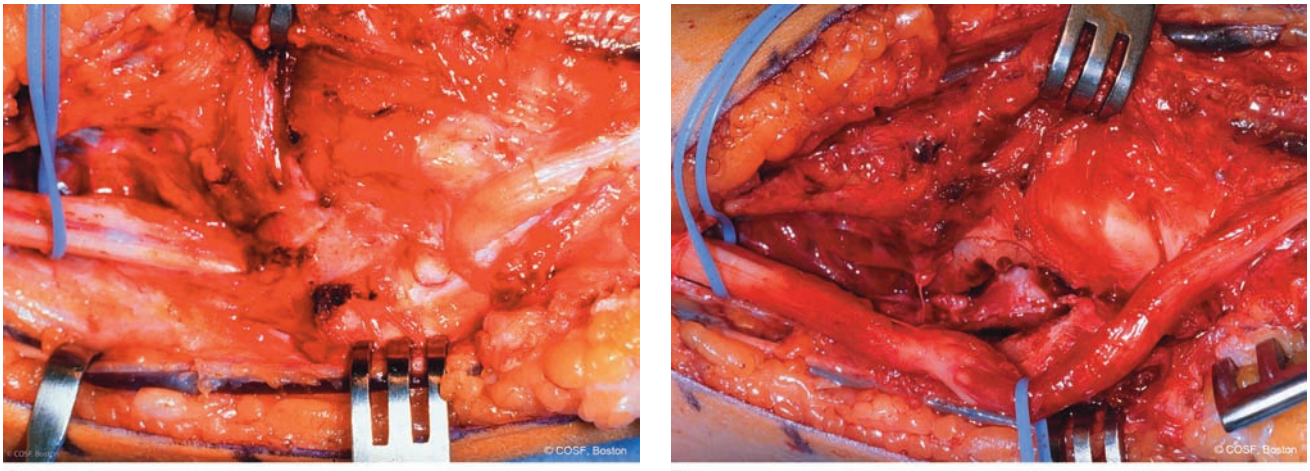
Motor- and sensory-specific neurotropism has led to some enthusiasm for biologic (venous) or synthetic (polyglycolic acid) conduit tubes with planned 1-cm gaps between cut nerve ends. Most of this work is experimental in animals, with clinical conduits acting as auto- or allograft nerve graft substitutes.

◆ Nerve Grafting of Traumatic Peripheral Nerve Lacerations

In the field of sports you are more or less accepted for what you do rather than what you are.
—Althea Gibson

Nerve reconstruction of long-segment peripheral nerve loss (extensive contamination, crush, stretch, neuromas in continuity) requires either nerve grafting, nerve transfers, or tendon transfers. In the subacute setting for most children, grafting of median and ulnar nerve lesions is most often performed due to the high success rate for both motor and sensory recovery. In older adolescents with chronic radial nerve palsies, motor-to-motor nerve transfers (partial median to posterior interosseous radial in the proximal forearm) or tendon transfers are preferred since there is no palmar sensibility loss, and the results of nerve and tendon transfers are very functional.

Nerves that are entrapped in a fracture site or joint need to be extracted, decompressed, and microscopically inspected (Figure 37-5). Decompression and microneurolysis rarely result in a healthy nerve if it was truly entrapped in the bone or joint for a long time. Neuroma resection and grafting are usually necessary for neural recovery (Figure 37-6). With nerve grafting, the nerve ends have to be longitudinally aligned for best results of motor and sensory recovery. Marking the neuroma-in-continuity before resection is beneficial for proper orientation. Untwisting traumatic lacerations so the nerve ends lie free in a healthy vascular bed is helpful in aligning traumatic lacerations with segmental loss. Similar to acute traumatic repairs, the proximal and distal nerve ends are trimmed back under the microscope until there are normal-appearing fascicles. Some surgical teams do histologic staining for acetylcholinesterase and/or histochemistry screening for carbonic anhydrase to enhance outcome. We utilize histologic staining only in complex neuromas in continuity where it is difficult to determine healthy fascicles under the microscope. The turnaround time for each staining is at least 1 hour, and the neuropathologist needs to be consulted in advance. The nerve grafting has to be tension free. Measurement of the gap is precise, and then 10% to 20% additional length of graft is obtained. Sural nerve grafting is most often utilized. Cable grafts of the appropriate length are glued together on the back table and then inset together in the nerve gap (Figure 37-7). The cable nerve grafts are aligned with two 180-degree-apart epineural sutures and then coapted with more Fibrin glue. Range of motion of adjacent joints is tested to be certain that there is tension-free excursion. A healthy but noncompressive vascular bed is closed over the

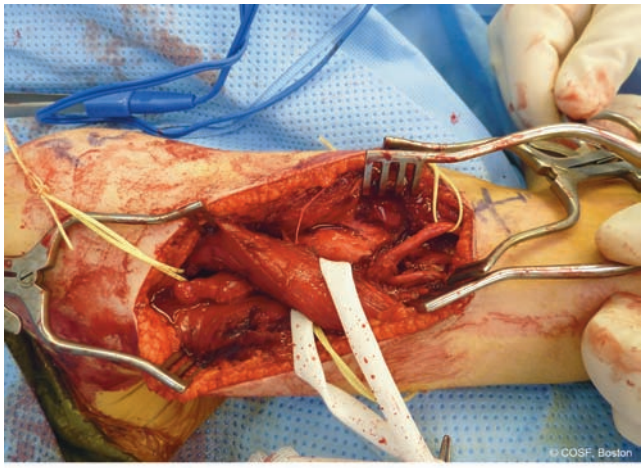


A B

FIGURE 37-5 **A:** Clinical case of complete median nerve palsy and pain with motion after closed reduction of elbow dislocation and associated medial epicondylar fracture. The entrapped median nerve is noted here with operative exposure. **B:** After careful extraction from the fracture site, the nerve has evidence of nonconducting neuroma. The nerve was reconstructed with neuroma excision and nerve grafting.

A

A2



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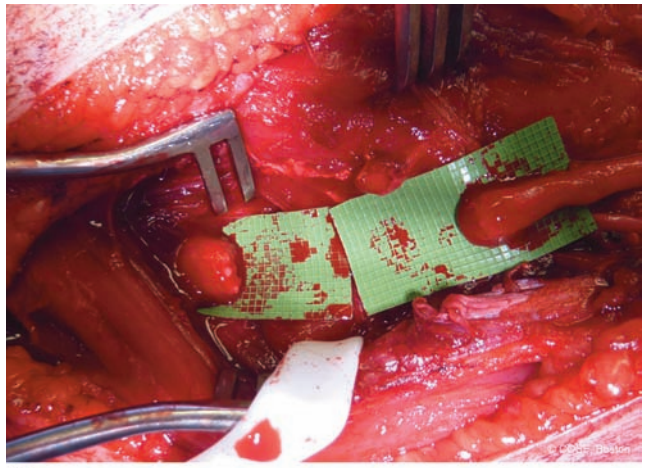
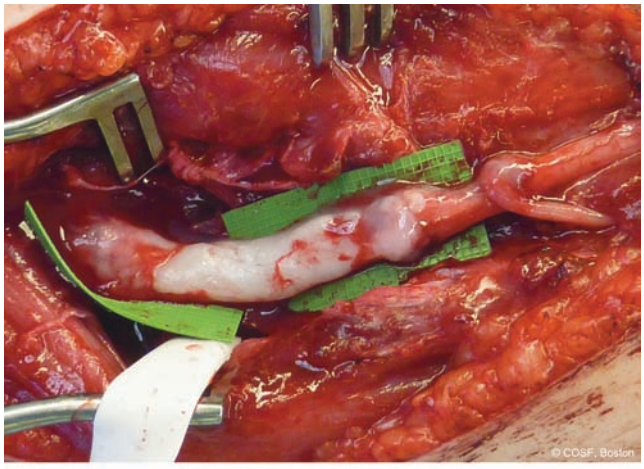


C1



C2

FIGURE 37-6 **A:** Radiographs of a diaphyseal humerus fracture with complete radial nerve palsy. Apparently, the nerve was functional before closed reduction and then lost motor and sensory functions with closed reduction and splinting. **B:** At operative exploration, the nerve is noted to be entrapped in fracture site. **C:** The neuroma was resected and the nerve grafted and fibrin glue utilized as opposed to late tendon transfers or partial utilized median to radial nerve transfer.

A1

A2

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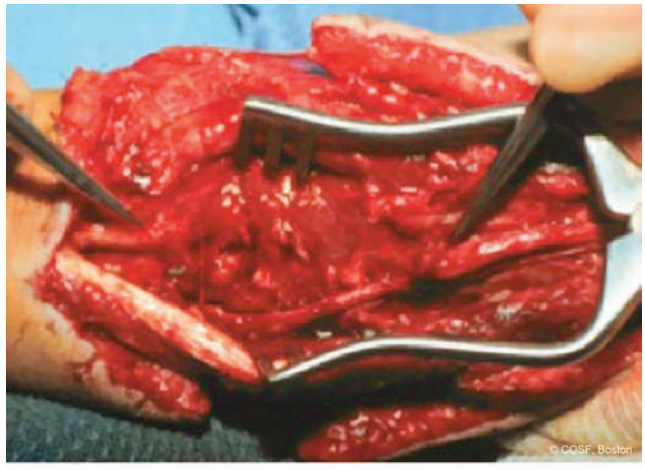
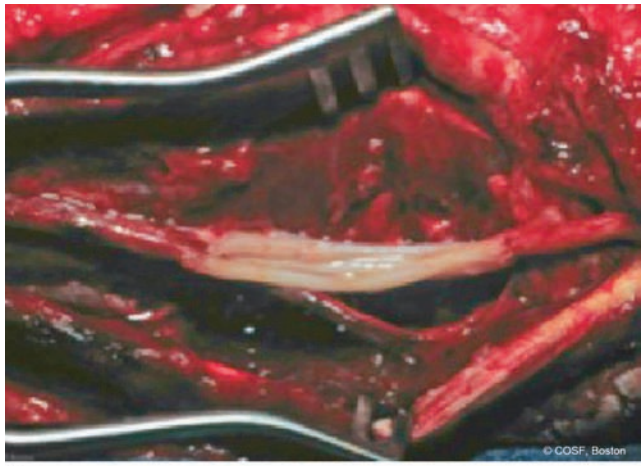


B

FIGURE 37-7 **A:** Radiographs of markedly displaced open distal radius and ulnar fractures. **B:** Ulnar nerve laceration noted after serial debridements of contaminated wound.



C

FIGURE 37-7 *(continued)* **C:** Sural nerve grafting of ulnar nerve defect.

nerve reconstruction. Protective immobilization is utilized for 2 to 4 weeks depending on the patient, associated injuries, and nerve repair status.

◆ Nerve Transfers

Partial Median to Posterior Interosseous

A chronic PIN palsy can be treated with nerve transfer(s) or tendon transfer. Partial median nerve transfers to the PIN and nerves to the wrist extensors have had success in restoring wrist, finger, and thumb extension.[31–33] The benefit is short-segment, tension-free motor-to-motor nerve repair(s).

Under general and/or regional anesthesia without neuromuscular blockade, a proximal forearm extensile incision is utilized for isolation of both the median and radial nerves. The median nerve is identified in the anteromedial distal humerus adjacent to the brachial artery. The lacertus fibrosus is incised, and the median nerve is decompressed between the two heads of the PT through the FDS arch. The brachial artery and basilic vein are protected, but transverse veins and arterial branches are ligated. With microscopic visualization and electrical stimulation assistance, the fascicles to the PT, FDS, PL, FDP, and thenar intrinsics are identified. The most distal FDS fascicles are mobilized away from the remaining motor and sensory fibers and isolated with an elastic loop.

The radial nerve is isolated between the BR and brachialis muscles in the distal humerus. In sequence, the separate branches to the wrist extensors, PIN, and radial sensory nerve are identified. The PIN may need to be decompressed through the two heads of the supinator. The PIN is transected and mobilized medially. The partial median nerve FDS fascicle(s) is transected distally and mobilized to the cut PIN for a tension-free repair. Repair is often with Fibrin glue alone or tracking 9-0 epineural suture(s) and glue. A nerve graft is rarely needed and is avoided if at all possible. The soft tissues are closed in layers, and the nerve transfer is protected for 2 to 3 weeks.

◆ Tendon Transfers for Chronic Neuropathy

Placing first is not the same as winning.
—Roger Ebert

Tendon transfers for chronic neuropathy and specific motor loss have been used for decades by hand surgeons. Fortunately, most humans are born with many muscles that perform the same function, and a brain that can adapt when surgeons use some of those redundant muscles for new functions with tendon transfers. The requirements for tendon transfers include (1) expendable donor muscles; (2) matching muscle amplitude, power, excursion, and synergy between donors and recipients; (3) stable, mobile joints; (4) one tendon–one function; and (4) unscarred soft tissues in a straight line tendon transfer pathway. For each major peripheral nerve injury that fails to recover, tendon transfers are usually a viable option for improving function. As we know from our congenital experience, children can function with deficiencies ("The brain is smarter than the hand"). However, children will function better with successful tendon transfers. A great reference for tendon transfers is Dr. Richard Smith's *Tendon Transfers of the Hand and Forearm,*[34] in which he recognizes his fellowship teachers Mr. Guy Pulvertaft and Dr. Joseph Boyes, and which was completed by his orthopaedic hand surgery student, Dr. Waldo Floyd III after Dr. Smith's untimely death.

◆ Tendon Transfers for Median Nerve Palsy

High Median Nerve Palsy

Loss of extrinsic and intrinsic median nerve motor function in a high median nerve palsy means loss of intrinsic opposition (see "Low Median Nerve Palsy") and extrinsic FPL, FDP II/III, PT, and PQ function. Restoration of FPL and FDP II/III function is achieved with BR transfer to FPL and side-to-side ulnar-innervated FDP IV/V to median nerve–innervated FDP II/III.

Under tourniquet control, a distal radial wrist incision is used to isolate the FPL, BR, and FDP to all the digits. The radial artery and median, radial sensory, and palmar cutaneous nerves are protected. The BR is elevated off the distal radius. There is a very firm attachment to the radius periosteum, which may include physeal attachment. The BR needs to be elevated into the midforearm to achieve maximal excursion (which will be limited). The FPL is then isolated; it lies deep, arising from the radius proximal to the PQ and crossing the PQ into the carpal canal. The FPL's distinctive IP flexion of the thumb makes isolation of the tendon easy. The FDP to the index is isolated from the ulnar innervated FDP tendons. The FDP III and IV are cross-sutured to the FDP II, and the BR is woven through the FPL. The proper tensioning of the tendon transfers is tested sequentially with stay sutures by wrist tenodesis for digital cascade and thumb to index finger pinch. When it is set right, the wound is closed in layers and a bivalved short- or long-arm thumb spica cast is applied for 4 to 6 weeks depending on the age of the patient. Protective splint and skilled therapy are used for an additional 6 weeks as strength and motion are regained.

Low Median Nerve Palsy

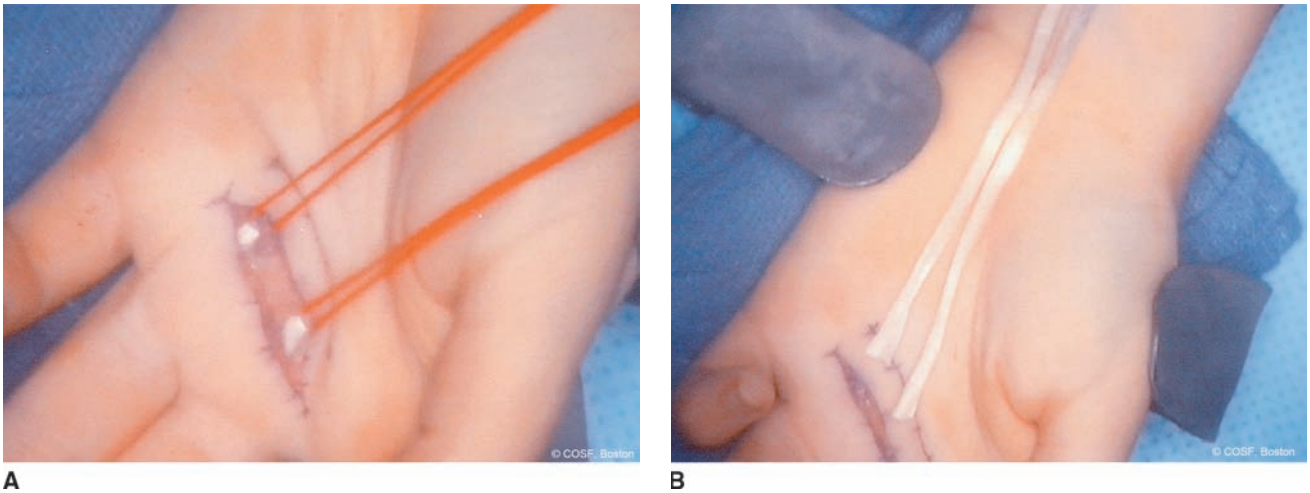
Post-traumatic low median nerve palsy is not uncommon and results in the loss of abductor pollicis brevis and opponens pollicis usually with preservation of the ulnarly innervated flexor pollicis brevis. The opponensplasty experience of reconstruction of congenital hypoplastic thumbs applies here. Ring finger FDS IV is the most common opposition transfer (see Figure 11-5) with abductor digiti quinti (Huber transfer) (see Figure 11-6), EIP, EDQ, and PL used in high median nerve palsies and some low median nerve and combined median and ulnar nerve palsies.

◆ Transfers for Radial Nerve Palsy

Depending on the level of peripheral radial nerve injury, there will be functional loss of wrist extension, finger MCP joint extension and thumb retropulsion, and IP joint extension or just extrinsic finger and thumb extension. Therefore tendon transfers for extrinsic radial neuropathy to the EDC and EPL alone or in combination with a tendon transfer to the ECRB are dependent on the preoperative deficit. Restoration of active wrist extension markedly improves hand function (by tenodesis effect) and power (three- to five-time increase in grip strength). There is no question that a transfer to provide wrist extension is a huge benefit to the affected child.

The musculotendinous units available in an isolated radial nerve palsy include all the median and ulnar innervated extrinsic muscles. There are options for each functional loss. Function of the EDC can be restored by an FCU, flexor carpi radialis (FCR), or FDS IV and/or long ring FDS III tendon transfer (Figure 37-8). Function of the EPL is restored by a PL, BR, or split FCR tendon transfer. Function of the ECRB is restored by a PT. Most of the time, APL function is not restored if there is sufficient thenar intrinsic strength. The PT to ECRB is the most reliable transfer for most surgeons. You either are a fan of FCU transfer or are concerned about loss of FCU power for wrist flexion function and use FDS III/IV or FCR for EDC function. Function of the EPL is restored by a PL transfer to a rerouted EPL. If there is no PL donor (~20% of the population), then most surgeons use an FDS IV to EPL and EIP, though a split FCR to EPL and EDC does work. Our preferred combination is usually PT to ECRB; PL to rerouted EPL; and FCR to EDC.

Under tourniquet control, the initial skin incision is made over the diaphyseal radius to allow for identification of the PT and ECRB. The PT is isolated while protecting the radial sensory nerve and radial artery. The PT

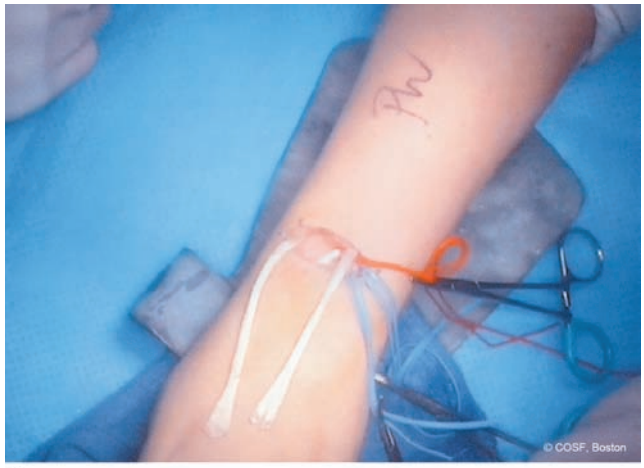


A B

FIGURE 37-8 FDS to EDC transfer. **A:** Clinical photograph depicting identification of the FDS tendons to the long and ring fingers via a transverse volar incision. **B:** The FDS tendons are harvested and withdrawn through a more proximal volar forearm incision.

C

D



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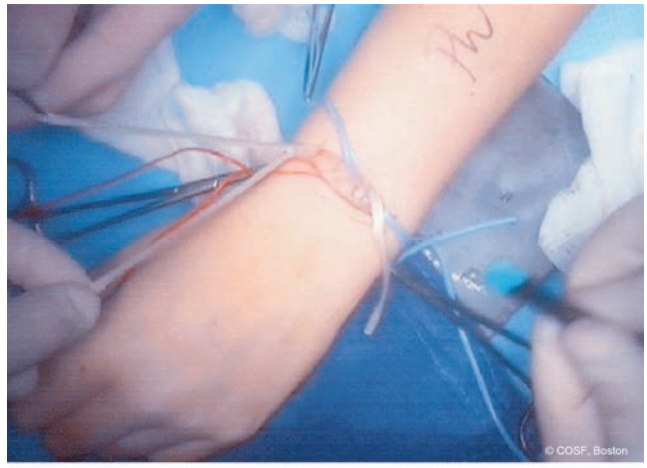


F

G

FIGURE 37-8 *(continued)* **C:** Identification of the dorsal EDC tendons at the level of the wrist. **D:** Blunt dissection will allow for creation of a tunnel for tendon passage. **E:** The FDS tendons are brought through to the dorsal side of the limb. **F:** The FDS tendons are secured to the EDC. **G:** Final appearance after completion of the tendon transfer.

is elevated off the radius with a long strip of periosteum. Maximal excursion while protecting the neurovascular integrity of the PT is achieved with proximal dissection and mobility. The ECRB is identified by its second compartment central wrist extension pull on the third metacarpal base. The ECRB tendon is transected for a weave technique insertion of the PT through the ECRB tendon. The distal ECRB is sutured to the ECRL. A volar transverse incision is made at the wrist over the PL and FCR. Each is transected at the wrist while protecting the median nerve, palmar cutaneous nerve, and radial artery. The FCR and PT tendons are mobilized and passed from volar to dorsal subcutaneously. The EDC and EDQ are isolated in the fourth compartment; the EPL in the third compartment. The EPL is taken out of the third compartment, transected proximally, and mobilized radially. In sequence, the PT to ECRB, FCR to EDC and EDQ, and PT to EPL are repaired with weave technique. The PT to ECRB transfer is set in 30 to 60 degrees of wrist extension, which allows for a resting 20- to 30-degree extension position and passive flexion to 30 degrees. The FCR is sutured to the EDC and EDQ with a progressive cascade of more MCP extension on the radial side (20-degree MCP flexion index finger) to less on the ulnar side (30-degree MCP flexion small finger). The PL to EPL is sutured with the thumb MCP in slight (20 degrees) flexion with the wrist extended (20 to 30 degrees).[34] Sequential closure of all wounds is performed while protecting the transfers. The hand and wrist are immobilized in a long-arm bivalved cast for 4 to 6 weeks with the wrist extended 30 to 40 degrees, the finger and thumb MCP joints flexed 20 to 30 degrees, and protection carried out to the fingertips in slight IP joint flexion and thumb in slight retropulsion. Following cast removal, the hand and wrist are protected in an intermittent splint as active motion and strength are regained over the next 3 months of skilled therapy.

◆ Tendon Transfers for Ulnar Nerve Palsy

Isolated loss of ulnar nerve intrinsic function is fortunately rare but quite devastating when it does occur. There is loss of intrinsic power, fine motor coordination, and dynamic balance to the hand and fingers. Power pinch is lost with absence of adductor pollicis and first dorsal interosseous strength. Transfer of the ECRB with a tendon graft (or FDS IV transfer) to the adductor pollicis restores power pinch. Extrinsic digital flexor and extensor overpull results in MCP joint extension and IP joint flexion. In low ulnar nerve palsy, the ring and small fingers claw, while in high ulnar palsy, clawing does not occur. Clawing can be dealt with by tenodesis (FDS), volar capsulorrhaphy, or dynamic transfers (split FDS).

The ECRB adductionplasty for power pinch is performed under tourniquet control. Through a distal transverse incision, the ECRB insertion into the third metacarpal is identified dorsally and then transected. The more proximal ECRB is isolated either through one incision proximal to the extensor retinaculum or with another incision distal to the extensor retinaculum. The ECRB tendon is pulled proximal to the retinaculum. An incision is made on the ulnar MCP region of the thumb to isolate the adductor insertion into the thumb. A large curved clamp is then used to make a passage from the most distal dorsal incision through the second and third metacarpal interspace over to the thumb adductor insertion. The digital neurovascular bundles, palmar vascular arch, and deep ulnar motor nerve are protected with this passage by staying dorsal to the adductor. A PL free tendon graft is obtained through small transverse incisions. The tendon graft is then sewn into the adductor insertion and thumb periosteum. With the curved hemostat, the PL tendon graft is brought from volar to dorsal through the second-third metacarpal interspace and then into the dorsal incision proximal to the extensor retinaculum. The PL graft is woven through the ECRB tendon with the wrist in neutral and the thumb adducted to just in front of the index finger. Stay sutures are placed while wrist tenodesis confirms that with wrist extension the thumb palmar abducts; and with wrist flexion the thumb comes to the palm. Sequential closure is performed after final securing sutures (Ethibond, Ethicon, Inc., Somerville, NJ) are placed. The wrist is immobilized in 30 degrees of extension and the thumb in mild abduction for 4 to 6 weeks. Skilled therapy and intermittent splinting are required for an additional 6 weeks until motion and strength are attained.

POSTOPERATIVE

Nerve reconstructions only require 2 to 3 weeks of protective immobilization in a bivalved cast or splint. Tendon transfers require 4 to 6 weeks of protection depending on the age of the patient and whether a free tendon graft is needed. However, the occupational therapy splinting and rehabilitation are quite extensive, lasting up to 6 months.

ANTICIPATED RESULTS

If you don't have time to do it right, when will you have time to do it over?
—John Wooden

Taking care of young people has its biologic advantages. This is very evident with nerve injuries. Spontaneous full recovery is expected with nearly all observed nerve injuries associated with blunt trauma and acute nerve lacerations that are repaired.

Even late reconstructions by decompression, neuroma resection and nerve grafting; and nerve transfers do well. Tendon transfers with healthy, expendable donor muscles provide marked improvement in function.

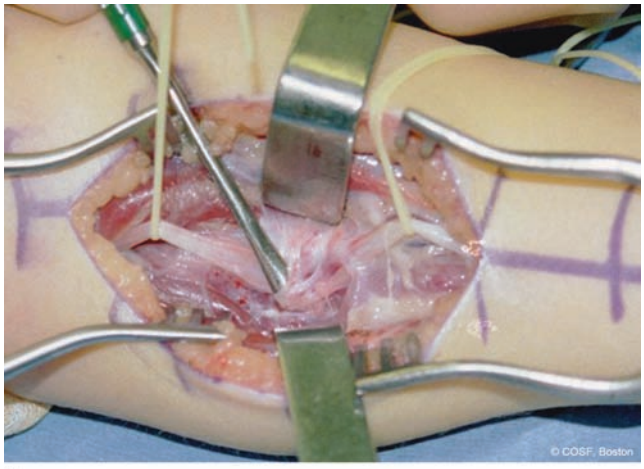
COMPLICATIONS

Failure to recognize an entrapped or lacerated nerve is a risk for suboptimal long-term outcome. Delaying beyond 6 months for exploration, decompression, and reconstruction of a nonconducting nerve can lead to a failed or an incomplete recovery. Technical errors of mishandling of tissues, suture placement, repairs under tension, choosing the wrong nerve fascicle for transfer, among others, can lead to failure or unexpected additional problems with strength and sensibility.

Using donor muscles of insufficient strength and poor excursion in patients with limited range of motion or soft tissue flexibility all can contribute to a suboptimal outcome with tendon transfers.

CASE OUTCOME

The ulnar nerve was explored and discovered to be entrapped in the fracture site (Figure 37-9). The nerve was extracted but did not conduct with stimulation and had healed with a fibrotic neuroma. The neuroma in continuity was excised back to healthy fascicles on both the proximal and distal cut nerve ends. Since the nerve had been stretched by its bony entrapment and forearm motion, there was no need for nerve grafting. The nerve could be repaired end to end without tension. The child went on to full return of intrinsic hand function and two-point discrimination sensibility over the next year.



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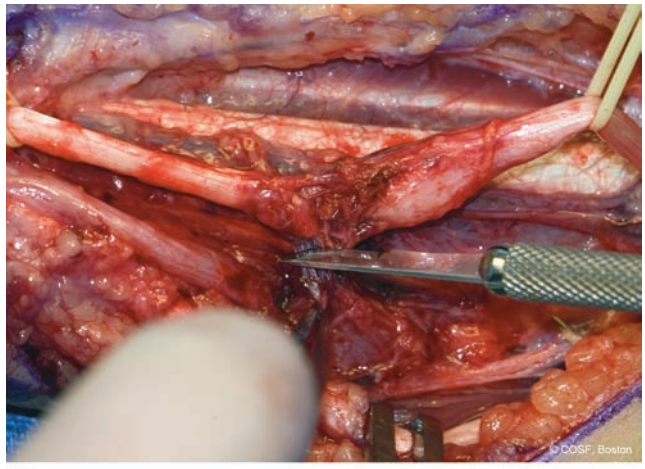

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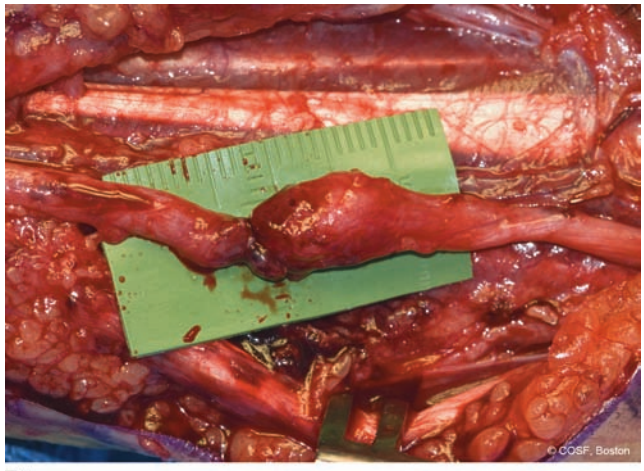
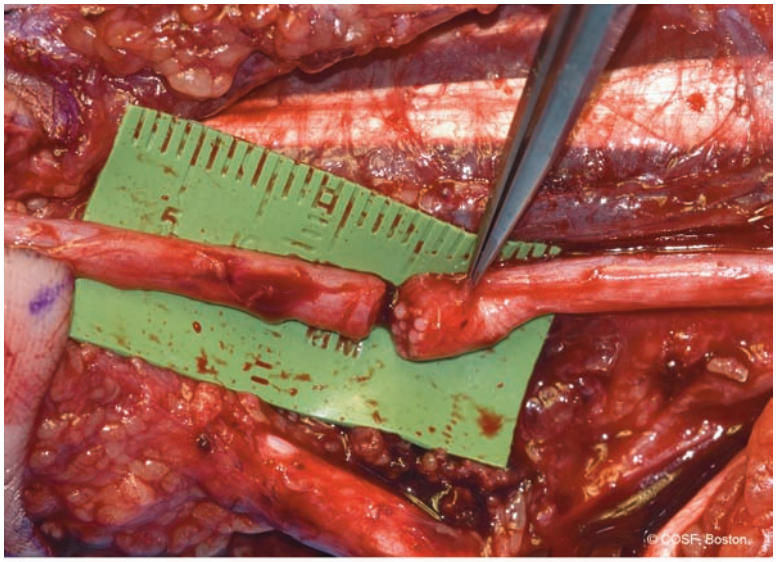


B2

FIGURE 37-9 **A:** With operative exposure, the ulnar nerve (proximal and distal nerve noted by elastic loops) was noted to be entrapped in the fracture. **B:** After decompression, the nonconducting neuroma is evident.



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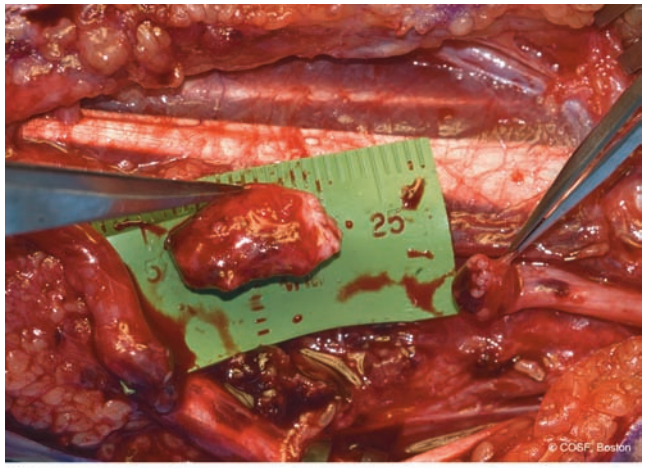

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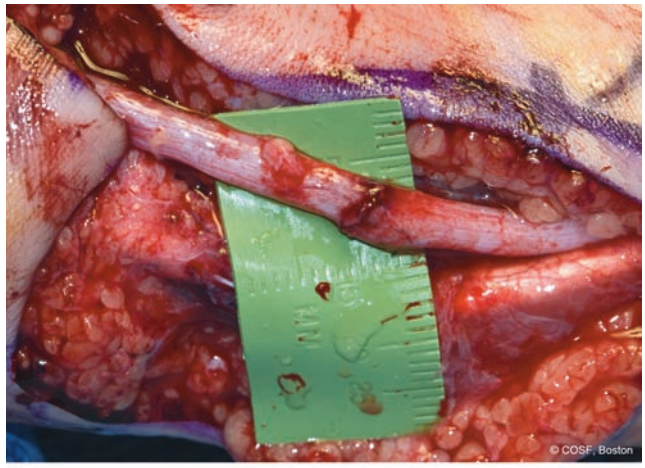

C3

FIGURE 37-9 *(continued)* **C:** Reconstruction was performed with neuroma resection and direct end-to-end microscopic repair without tension. No grafting was necessary.

SUMMARY

Acute and chronic nerve injuries can be among the most challenging and gratifying of cases for pediatric hand and upper limb surgical care. Although most nerve injuries do well with observation, not all do. Expect the unexpected, and be aggressive surgically in the rare injuries that are not recovering as expected.

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CHAPTER

38

Traumatic Tendon Injuries

CASE PRESENTATION

A 14-year-old right hand–dominant male presents for evaluation of a "jammed finger." While playing football 4 weeks ago, he reported "jamming" his ring finger while making a tackle. There was mild pain and swelling but no laceration, deformity, or obvious dislocation. Attributing it to a sprain, he did not initially seek medical attention. He now presents for evaluation due to persistent discomfort and swelling.

CLINICAL QUESTIONS

- What are the mechanisms of flexor tendon injuries in children?
- What are the physical examination and radiographic imaging techniques used to diagnose flexor tendon injuries in children?
- What are the zones of flexor and extensor tendon lacerations in the hand?
- What are the surgical indications and principles for tendon lacerations?
- What are the indications for tenolysis?
- What are the indications and techniques for reconstruction of chronic flexor tendon lacerations?
- How are flexor tendon injuries cared for postoperatively?
- What are the complications of flexor tendon surgery?

THE FUNDAMENTALS

Tendon injuries are common in children. Beware of glass lacerations, as the small external wound is not indicative of more extensive deep damage to nerves, tendons, and/or blood vessels. While the vast majority of injuries are due to deep lacerations or penetrations, closed tendon ruptures also occur. In general, tendon laceration or rupture is a surgical condition, but the technique of repair or reconstruction depends upon a host of clinical factors. Acuity or chronicity of injury, level of injury, associated bony or soft tissue lesions, and individual patient characteristics (maturity, hand dominance, functional demands, and ability to comply with postoperative rehabilitation) all play important roles in evaluation and treatment.

Etiology and Epidemiology

While the fundamental anatomy and basic science of tendon injury and healing are beyond the scope of this chapter, a few anatomic points are worth a review. First, most index through small fingers are flexed by the flexor digitorum profundus (FDP) and the flexor digitorum superficialis (FDS). These tendons have a very distinct anatomic relationship with one another as they pass through the fibro-osseous tendon canal (Figure 38-1). It is important to remember that a substantial proportion of humans do not have an FDS to the small finger. Second, the flexor tendons pass through a fibro-osseous tendon sheath, consisting of annular and cruciate pulleys (Figure 38-2). The tendon sheath and pulley system provide increased mechanical efficiency for joint motion but create challenges in terms of tendon exposure and reconstruction. Furthermore, vascular supply to the flexors is provided by the vincular system; during laceration or rupture, if these vascular connections are disrupted, the tendon may retract, the sheath fill with blood, and attritional changes could occur in the traumatized tendon stumps.

The extensor apparatus is more complex and elegant in its anatomic design (Figure 38-3). Again, the reader is referred to other sources for details regarding anatomy and basic science.[1,2] The basic anatomic principles hold true for children and adults.

In general, tendon injuries are classified according to timing of presentation (acute or chronic), morphology (complete or partial), and anatomic location. Flexor tendon injuries are divided into zones, each with its own set of particular anatomic and surgical implications (Figure 38-4A; Table 38.1). Similarly, extensor tendon lacerations are divided into zones on the dorsal aspect of the hand (Figure 38-4B; Table 38.2).

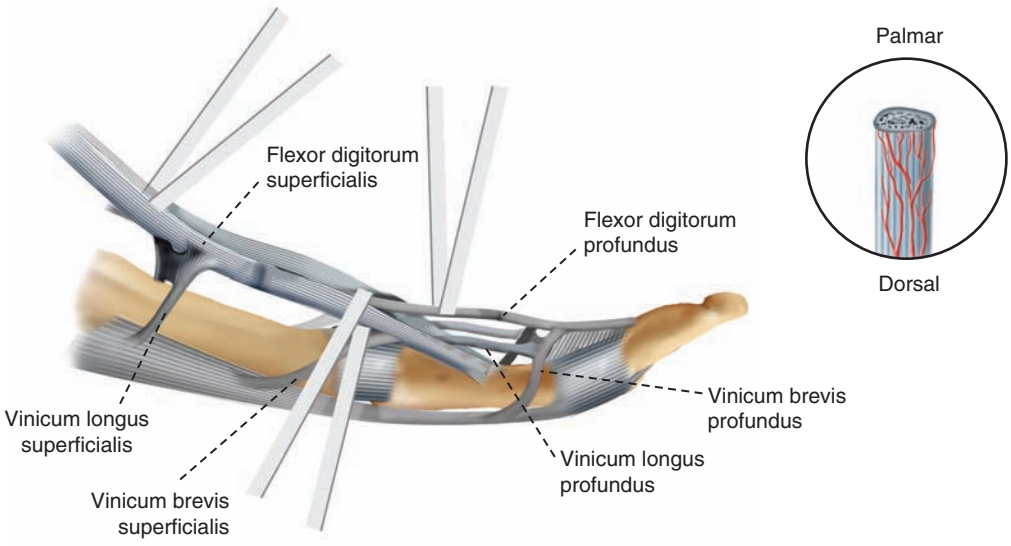


FIGURE 38-1 The anatomy of the FDS and FDP tendons.

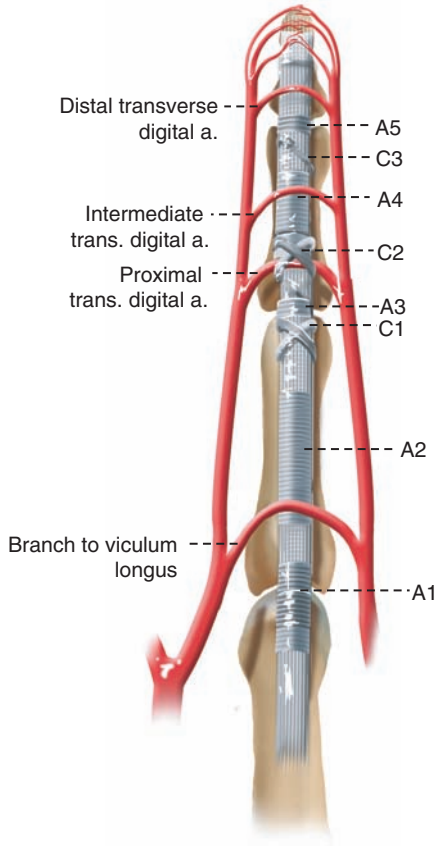


FIGURE 38-2 Schematic diagram of the annular and cruciate pulley system.

Clinical Evaluation

Clinical evaluation begins with a good history. Information regarding the acuity of injury and the mechanism is most important. In older patients, additional questions may be asked about subjective numbness or tingling of the affected digit(s) as well as the quality of bleeding at the time of injury, which suggest concomitant injury to the adjacent neurovascular bundle. (Given the anatomic relationship between the more volar digital nerve and more dorsal digital artery, any volar finger laceration with profuse bright red bleeding should raise concern for a digital nerve laceration.) Chronicity is important, particularly after closed tendon ruptures, as long-standing injuries are associated with greater tendon retraction, myostatic contractures, and the potential need for single- or two-stage flexor tendon grafting and pulley reconstruction.

Physical examination should note the location, orientation, and quality of all lacerations and wounds, however small. Remember that small superficial lacerations may mask larger tendon and soft tissue injuries beneath. The vascularity of the digits should be assessed to determine the integrity of the digital arteries and guide surgical timing. Sensibility can be evaluated using light touch (threshold) or two-point discrimination (innervation density) testing. Discriminatory sensibility is usually present in patients older than 5 to 7 years of age. In rare situations, in a young child, the warm water immersion test can be performed to assess digital nerve function; if after soaking the affected hand in lukewarm water there is no wrinkling

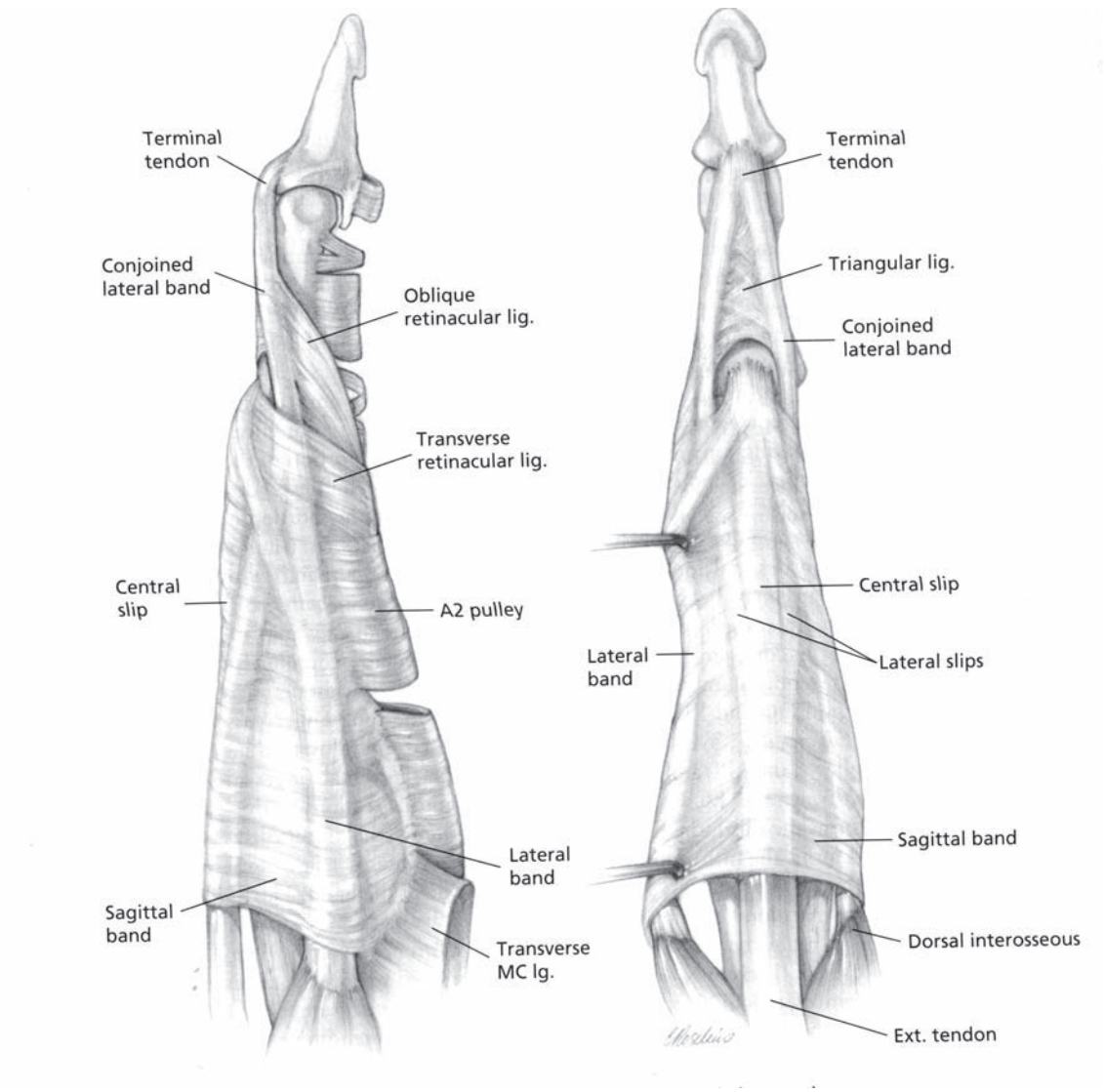


FIGURE 38-3 The extensor tendon apparatus of the hand and digits.

Table 38.1

Zones of flexor tendon injury

Zone	Location
I	Distal to insertion of FDS
II	Distal to leading edge of tendon sheath, proximal to zone I
III	Distal to carpal tunnel, proximal to tendon sheath
IV	Carpal tunnel
V	Proximal to carpal tunnel

Table 38.2

Zones of extensor tendon injury

Zone	Location
I	Over DIP joint
II	Over middle phalanx
III	Over PIP joint
IV	Over proximal phalanx
V	Over MCP joint
VI	Over metacarpal
VII	Dorsal extensor retinaculum
VIII	Distal forearm
IX	Mid and proximal forearm

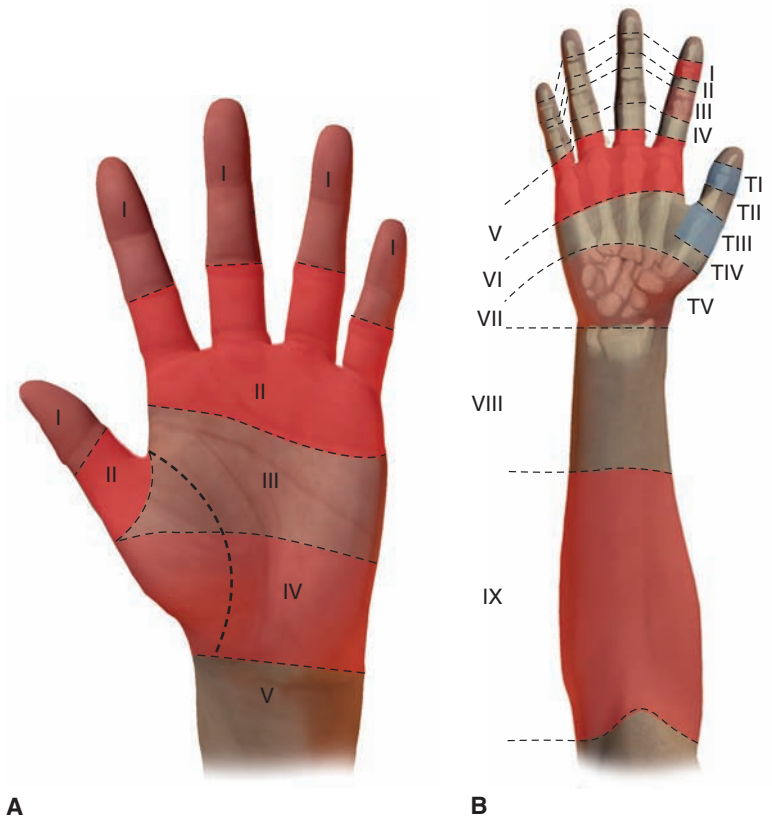


FIGURE 38-4 **A:** Zones of flexor tendon injury. **B:** Zones of extensor tendon injury.

FIGURE 38-5 The warm water immersion test. This is a 3-year-old male with a transverse laceration through the palm. After warm water immersion, note is made of wrinkling of the thumb, small, and ring fingers but absent wrinkling of the index and long fingers. At the time of surgical exploration, confirmation was made of common digital nerve injuries to the index and long fingers.

of the glabrous skin, a digital nerve injury should be suspected (Figure 38-5).

Assessment of flexor tendon integrity is performed by observation, passive motion, and active motion. Disruption of the normal digital cascade—in which each digit is slightly more flexed at rest than the adjacent radial digit—suggests flexor tendon laceration. This may be highlighted using the tenodesis effect, whereby passive wrist extension causes obligate passive digital flexion (Figure 38-6). In the young uncooperative or anxious child, compression of the FDS and FDP muscle bellies in the forearm, away from the zone of injury, is a helpful maneuver; again, absence of passive digital flexion should alert the examiner to a flexor tendon disruption. Finally, active distal interphalangeal (DIP) joint and proximal interphalangeal (PIP) joint flexion of each digit should be specifically assessed. Isolated DIP flexion is performed to test FDP function. For FDS testing, isolated PIP flexion with the other digits held in an extended position is needed to prevent the FDP—with its shared muscle belly—from flexing the tested digit. In cases of partial tendon lacerations, active flexion may be intact, but there will be pain with flexion against resistance.

Extensor tendon injuries are similarly assessed by observation and passive and active motion. Tenodesis

FIGURE 38-6 Disruption of tenodesis, indicative of a flexor tendon injury. Note the abnormally extended position of the long finger, combined with the small, seemingly innocuous laceration in the palm. Subsequent exploration confirmed flexor tendon injury to the long finger.

and passive wrist extension are helpful, as is specific testing of metacarpophalangeal (MCP) joint (sagittal bands), PIP (central slip), and DIP (terminal tendon) extension. Furthermore, it is important to recognize that in the case of an isolated central slip injury (the boutonniere deformity), the digit can still be actively extended, due to the pull of the extrinsic extensors through the lateral bands to the terminal tendon. To specifically test central slip integrity, the so-called Elson's test is used.[3] The PIP joint is flexed, and the patient is then asked to extend the PIP joint. In cases of central slip injuries, the DIP joint goes into rigid extension prior to attempted PIP joint extension.

The diagnosis of tendon disruption is made clinically, though radiographic imaging may be helpful. Both ultrasound and magnetic resonance imaging (MRI) scans may be used to assess tendon integrity as well as the degree of retraction (Figure 38-7). This is particularly helpful in chronic injuries or postsurgical patients with limited motion in whom rerupture is suspected.

Surgical Indications

Surgical repair is indicated in all patients with open extensor tendon injuries and acute complete flexor tendon lacerations. Furthermore, flexor tendon repair or reconstruction is indicated in chronic flexor tendon disruptions in patients with significant functional limitations who are willing and able to comply with postoperative rehabilitation and activity restrictions.

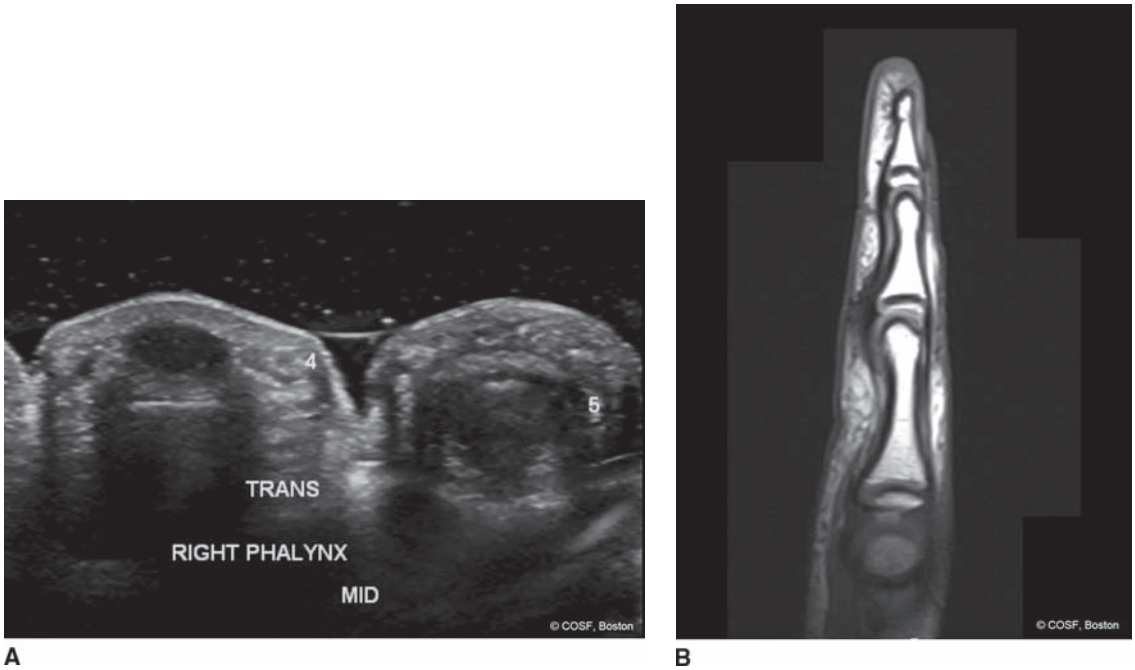
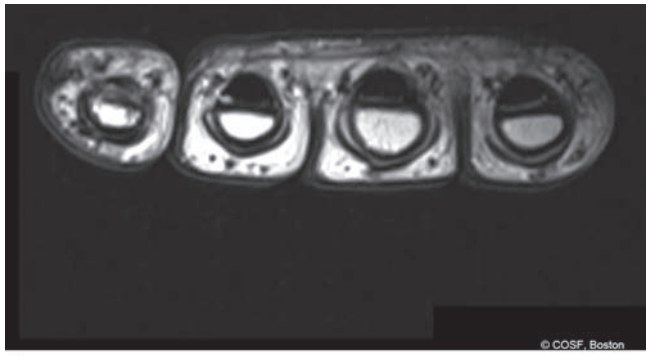


FIGURE 38-7 Radiographic imaging of a suspected flexor tendon rerupture after attempted primary tenorraphy in an 8-year-old male. **A:** Transverse (axial) ultrasound images depicting normal flexor tendon within the ring finger sheath (left) but absence of flexor tendon within the small finger fibro-osseous canal. **B:** Sagittal proton density MRI images depicting absence of the flexor tendon in zone II.



C

FIGURE 38-7 *(continued)* **C:** Corresponding axial images, depicting absence of tendon within the small finger (far left) flexor tendon sheath.

SURGICAL PROCEDURES

Hitting is timing.
—Warren Spahn

Treatment of flexor tendon injuries is dependent upon the timing from injury to surgery. In acute flexor tendon lacerations, primary tenorrhaphy is performed using minimum four-strand core suture repair supplemented by an epitendinous suture repair. When surgery is delayed >4 weeks from injury, the myostatic contractures and tendon retraction may not allow for primary repair; in these cases, surgical treatment options include single-stage tendon grafting or staged flexor tendon reconstruction, depending upon the status of the fibro-osseous canal.

Closed Treatment of Mallet Fingers and Open Mallet Finger Extensor Repair

Mallet finger refers to the characteristic extensor lag associated with disruption of the terminal tendon's insertion onto the dorsal distal phalanx. In children, due to the presence of the physis, clinical mallet fingers may actually represent Salter-Harris type III fractures of the dorsal epiphysis of the distal phalanx. Radiographs of the affected digit are needed to distinguish fractures (bony mallet finger) from true soft tissue extensor tendon injuries. The standard of care for closed soft tissue mallet fingers is continuous extension splinting of the DIP joint for 6 weeks; the PIP joint is left free and PIP motion encouraged to avoid lateral band and PIP joint adhesions and stiffness, respectively. After 6 weeks, part-time extension splinting is recommended for an additional 4 weeks during sleep and sporting activities.

Occasionally, patients will present late with chronic mallet injuries. This situation is commonly seen in pediatric patients, due to either missed diagnosis or failure to comply with acute splinting. Usually, this is not painful or functionally limiting, and observation alone may be recommended. In the rare situation of the painful or functionally limiting chronic mallet finger, soft tissue reconstruction by tenodermodesis technique may be performed (Figure 38-8).[4,5]

Open mallet fingers are an indication for surgical treatment. After formal irrigation and debridement of the traumatic wound, the extensor tendon ends are mobilized, with care being taken to avoid iatrogenic injury to the germinal matrix during exposure and soft tissue dissection. The tendon ends are then reapproximated with interrupted figure-of-eight, cruciate, or core-grasping sutures; due to the thin, flat, often diaphanous consistency of the terminal tendon, traditional core-grasping sutures with heavy (3-0) braided nonabsorbable suture material may not be technically feasible. Tenodermodesis sutures may similarly be used in acute open mallet injuries if the quality of the tendon stumps is insufficient. After tendon repair, a single retrograde percutaneous pin is placed into the distal phalanx and across the DIP joint, holding the fingertip in full extension. A mallet splint or cast is applied. The pin is removed and splinting and therapy are initiated as described above 4 weeks postoperatively.

Primary Tenorrhaphy of Acute Flexor Tendon Laceration

Under loupe magnification, flexor tenorrhaphy begins with adequate exposure. Although a variety of incisions have been advocated, we favor a volar zigzag Bruner approach, which is extensile, allows access to the radial and ulnar neurovascular structures, and can easily incorporate traumatic wounds.[6] This is particularly useful, as both the distal and proximal flexor tendon stumps may retract and reside far from the initial traumatic laceration. For example, when a flexor tendon laceration is caused

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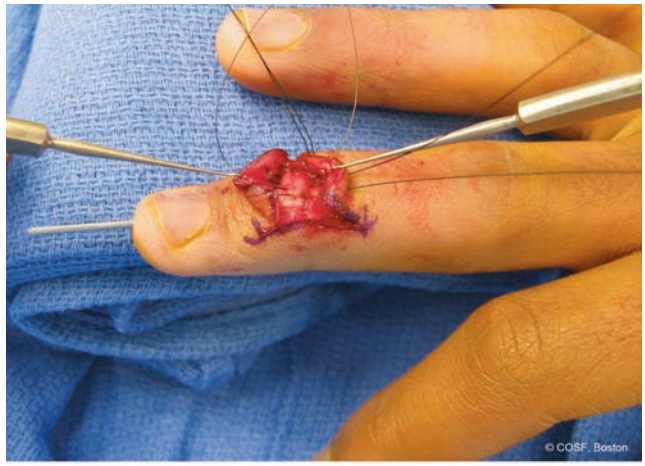

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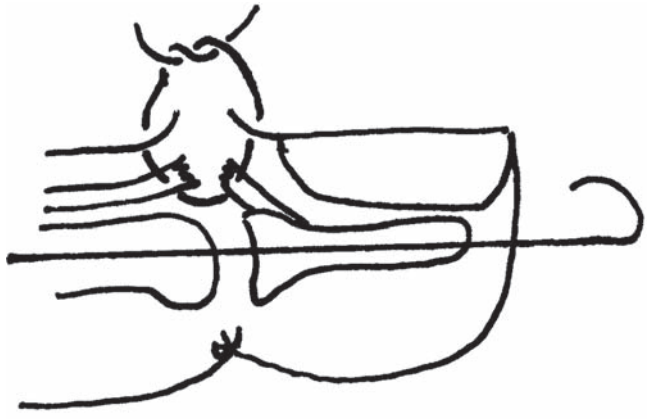

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FIGURE 38-8 Tenodermodesis for chronic soft tissue mallet fingers. **A:** Clinical photograph of a chronic, severe long finger mallet digit. **B:** Intraoperative photograph depicting suture passage for tenodermodesis reconstruction. **C:** Schematic diagram of the tenodermodesis reconstruction.

by a child grasping a knife with a closed fist, the position of the tendon laceration is digital flexion; during surgery, as the finger is extended, the distal stump will lie more distal than the original wound, and the proximal tendon will retract due to the effect of the proximal muscle bellies. Skin flaps are carefully raised, and the tendon sheath and adjacent digital arteries and nerve are exposed.

Access to the flexor tendon is achieved by judicious opening of the flexor tendon sheath using the A1, C1–A3, and C3–A5 windows (Figure 38-9). Even prior to opening the sheath, tendon stumps may be localized by the characteristic hematoma that forms in the zone of injury and at the tendon ends. The A2 and A4 pulleys are preserved in an effort to avoid subsequent bowstringing. Working within these intervals, the flexor tendon stumps are identified.

One of the first intraoperative challenges is reapproximating the tendon ends within the same tendon sheath window. If there has been minimal retraction—often the vincula will prevent tendon migration, particularly in the acute setting—reapproximation is straightforward. In cases

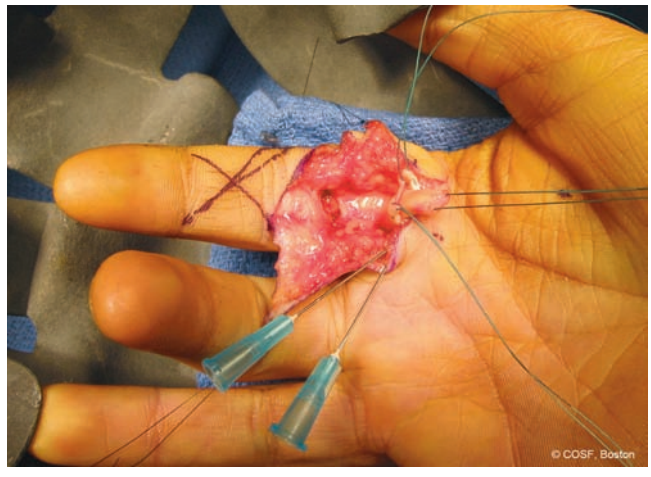


FIGURE 38-9 Clinical exposure of index finger FDS and FDP tendon lacerations. The proximal tendon stumps have been retrieved in the A1 pulley window, and core sutures have been placed. Distally, the C1–A3 interval has been opened and will be used for subsequent tenorraphy.

of greater tendon retraction, a number of retrieval methods have been described. First, a milking maneuver is performed. With the wrist and digit flexed, pressure on the volar surface of the wrist, hand, and digit is applied in a proximal to distal fashion. Often this will provide a glimpse of the proximal tendon stump, which may then be brought into the appropriate tendon sheath window. Second, a single blind pass with a small skin hook may be attempted.[7] The hook is passed into the tendon sheath with the curvature of the hook flat. After the tendon stump is felt, the skin hook is rotated 90 degrees to engage the tendon end and pull it into the window of repair. This technique should be attempted only once, as repeated passes will only increase the local trauma and thus risk of subsequent fibrosis and tendon adhesions. Finally, a pediatric feeding catheter (typically 5 or 8 Fr in diameter) can be used as a tendon shuttle. The catheter is passed retrograde from the tendon gap, through the tendon sheath, proximally, into a region where the flexor tendon is identifiable (usually beneath the A1 pulley).[8] The tip of the catheter is then temporarily sewn to the intact flexor tendon with a fine 5-0 or 4-0 nylon suture. Once secured, the catheter is withdrawn, delivering the flexor tendon into the zone of intended repair. The flexor tendon is held in place by a transverse 25-gauge hypodermic needle passed across the sheath and flexor tendon.

After the tendon stumps have been identified and retrieved, preparations are made for suture passage. It is clear that thicker suture material and a greater number of strands crossing the tenorrhaphy site increase the strength of the repair. While in adults, six- or eight-strand repairs have been performed, our practice is to perform four-strand repairs using either 3-0 or 4-0 nonabsorbable braided core sutures (Ethibond, Ethicon, Inc., Somerville, NJ) supplemented by a running locked, 6-0 monofilament epitendinous stitch (Prolene, Ethicon, Inc., Somerville, NJ). This is in part due to the small size of the tendons in children as well as our choice of postoperative rehabilitation. Currently, we perform a Strickland-type repair, which utilizes a Tajima core suture and horizontal mattress[9] (Figure 38-10). The back wall (dorsal) running epitendinous suture is placed first, followed by the core sutures. Core sutures are then tied at the tenorrhaphy site or outside the zone of injury, and the epitendinous sutures are completed around the front (volar) wall. Epitendinous sutures are critical in tenorrhaphies performed in tendon sheaths, due to the increase in strength and decrease in the friction/work of flexion achieved by the tidying of the repair site.[10,11] In situations where the tendon ends are easily reapproximated without undue tension, an "epitendinous first" repair may be done.

While both the FDP and FDS tendons are repaired in this manner, special considerations are made regarding injuries to the FDS slips distal to their bifurcation within zone II. Anatomically, the FDS slips are smaller, thinner, and flatter than the FDP or more proximal FDS tendon. Furthermore, given the passage of the FDP tendon through

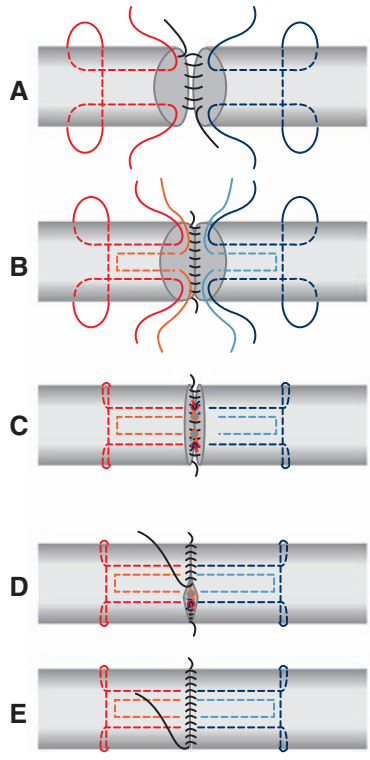


FIGURE 38-10 Schematic diagram of a four-strand core suture repair supplemented by a running epitendinous suture.

the FDS slips, excessive bulk or constriction may lead to limitations in FDP excursion and digital motion. We advocate repair of both the FDS and FDP whenever possible. Due to the small size of the FDS slips, tenorrhaphy is often performed using figure-of-eight or cruciate sutures. If excursion of both tendons is limited after completion of the repairs, a single FDS slip is considered.

After primary tenorrhaphy, every effort is made to avoid tendon gapping at the repair site as well as excessive girth or "bulging" of the repair. With passive digital flexion and extension, there should be no triggering or block to motion.

The wound is then closed using interrupted absorbable simple skin sutures (Chromic, Ethicon, Inc., Somerville, NJ). A bulky sterile bandage is applied, followed by a dorsal splint or more commonly a hand-based cast, holding the wrist in approximately 30-degree flexion, MCP joints at about 70-degree flexion, and IP joints straight. We avoid placement of cast material on the palmar aspect of the hand to prevent giving our pediatric patients a firm surface against which they may grasp and flex, thereby increasing the risk of rerupture.

◆ Flexor Tenolysis

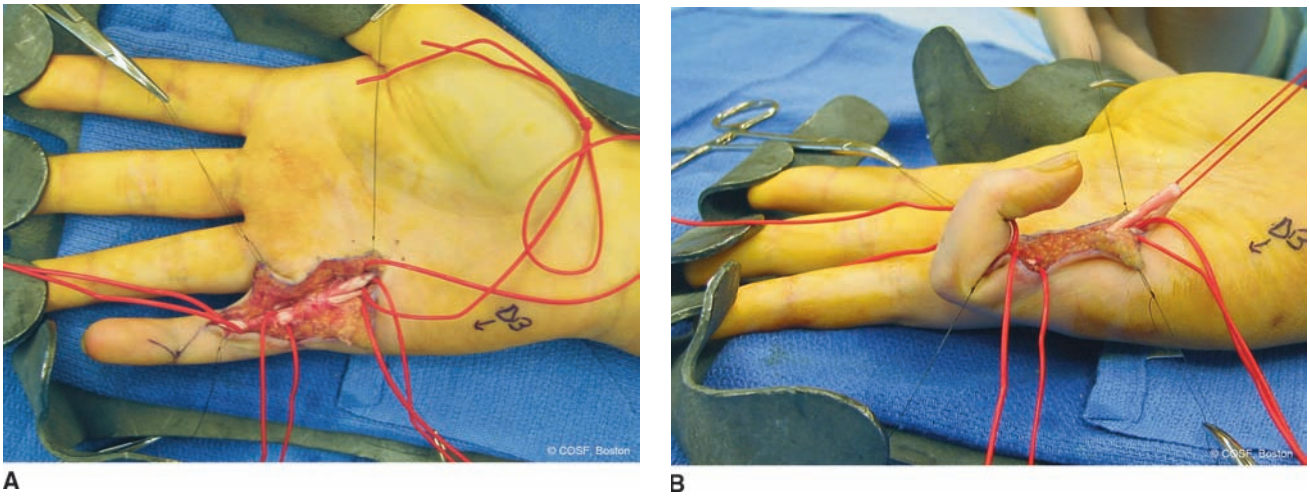
Persistent limited range of motion following flexor tendon repair can be a vexing and challenging problem in children. The differential diagnosis of persistent stiffness following

flexor tenorrhaphy includes tendon rerupture, adhesions, and joint contractures. These three clinical conditions may be distinguished through careful physical examination. If the digit has incomplete passive motion, the presumption is that joint contracture is the cause; indeed, no comment can be made upon tendon adhesions or rerupture in the setting of a rigidly stiff digit. Aggressive therapy is needed to reestablish tissue homeostasis and passive joint motion. If passive motion is intact but active flexion is limited, the distinction should be between rerupture and adhesions. If the patient is able to resist passive flexion or demonstrates isolated active flexion through the allowable arc of motion, the tendon is intact and adhesions are the cause. If no active flexion is noted, rerupture is a concern. As cited above, ultrasound or MRI may be a helpful adjunct to the clinical diagnosis.

Although children generally do not demonstrate the same propensity to postoperative adhesions and long-standing loss of passive digital motion as adults, tendon adhesions do occur. While tenolysis can be performed, the results of tenolysis in children are more unpredictable than in adults.[12–14] This is in part due to limitations in surgical technique (e.g., the need for general anesthesia, small size of the anatomic structures) as well as persistent obstacles in compliance with postoperative therapy, which may result in recurrent adhesion formation. Therefore, the indications are very specific, and tenolysis should not be performed without thorough discussion with both patient and family.

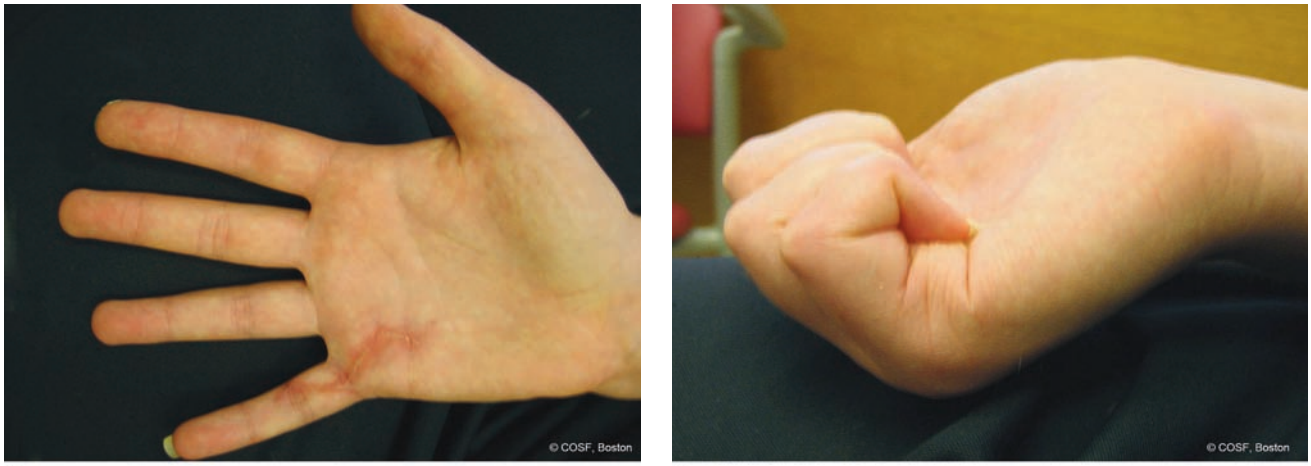
Indications for tenolysis include persistent functionally limiting digital stiffness or contractures despite maximization of hand therapy. Tenolysis should only be performed after wound healing, scar management, and soft tissue homeostasis has been normalized, usually 6 months after the index procedure.[15–17] Furthermore, tenolysis is generally contraindicated in patients <10 years of age, due to the unpredictability of the results.[13]

Despite the advantages of tenolysis under local anesthesia, which have been well documented in adults, release of tendon adhesions is commonly performed under general anesthesia in children[18,19] (Figure 38-11). Under tourniquet control, an extensile volar zigzag Bruner incision is utilized, incorporating prior surgical incisions whenever possible. The tendon sheath is identified, and confirmation is made that the pulley system is intact. (Whenever flexor tenolysis is performed, the surgeon should be prepared for the possible need for pulley reconstruction and/or first-stage tendon reconstruction; care should be taken to have the appropriate equipment and implants available if needed.) The flexor tendons are identified distal and proximal to the zone of prior injury/surgery, typically requiring release of the A1 pulley and identification of the tendon in the palm. A vessel loop or other elastic is placed around the FDS and FDP to provide traction.[20] The A1, C1–A3, and C3–A5 windows within the tendon sheath may be utilized if necessary, but the A2 and A4 pulleys should be preserved and as little surgical dissection and sacrifice of the tendon sheath should be performed as possible. Adhesions between the FDS and FDP and between the tendons and the tendon sheath are released in a gradual, circumferential, and systematic fashion. While tenolysis knives and suture/wire loops have been used, our preference is to use appropriate-size blunt elevators (Freer elevator, Cottle elevator) for adhesion release. Serial dilation of the tendon sheath can also be performed using pediatric feeding catheters ranging from 3 to 8 Fr in caliber. With surgical patience and persistence, adhesions can be released without disrupting tendon continuity or tendon sheath integrity. Confirmation of adequate release is made by proximal traction on the tendons, which should allow for full digital flexion.



A B

FIGURE 38-11 Flexor tenolysis in a 14-year-old female with persistent tendon adhesions following prior zone II flexor tenorraphy. **A:** Surgical exposure via a volar, zigzag incision and preservation of the A2 and A4 pulleys. **B:** After tenolysis and release of all adhesions, passive traction of the flexor tendons allows for full passive digital flexion.



C D

FIGURE 38-11 (*continued*) **C:** Postoperative appearance of surgical incisions in full digital extension. **D:** Postoperative digital active flexion.

Upon completion of tenolysis, the skin is closed using interrupted absorbable (Chromic, Ethicon, Inc., Somerville NJ) or nylon sutures, and a well-padded splint or cast is applied. At present, we do not instill corticosteroids or use any interpositional materials to prevent recurrent adhesion formation. Hand therapy for edema control, scar management, and range-of-motion exercises are started early, usually within a few days of tenolysis.

◆ Single-Stage Grafting of Chronic Jersey Finger

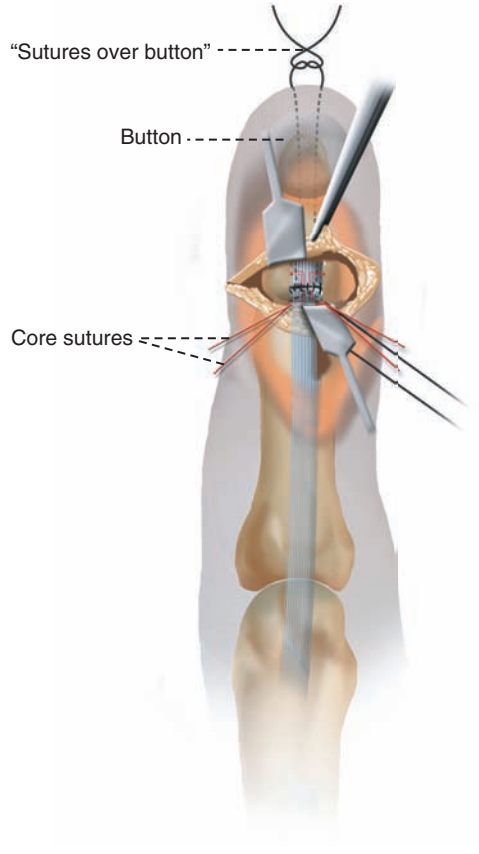
Given the challenges of the diagnosis of closed flexor tendon rupture in children, it is common for patients to present late after injury. This is particularly true of the closed FDP avulsion injury, the so-called jersey finger.[21] Forceful extension on the flexed finger may cause avulsion of the FDP from its insertion on the distal phalanx. The typical mechanism of injury in the child or adolescent is sports related, when the patient is attempting to grab an object or another athlete as it is forcibly withdrawn. The ring finger is most commonly affected, due to the fact that it is the longest and most prominent digit with MCP and PIP flexion, the position of injury. As the FDS and lumbricals remain intact, the digit can still be flexed and the loss of isolated DIP flexion not initially appreciated. For this reason, patients will often present many weeks to months after injury, attributing the initial discomfort and swelling to a "sprain" or "jammed finger."

Patients will present for evaluation of loss of DIP flexion, often but not universally associated with pain or functional limitations. Examination will identify isolated loss of FDP function. Occasionally, a tender, palpable mass can be felt at the base of the digit near the distal volar crease; this coincides with the location of the retracted proximal tendon stump. Diagnosis is made clinically, though radiographs can be obtained to evaluate for associated fracture and advanced imaging considered to confirm the diagnosis. The Leddy classification is applied to children as in adults.[21]

A decision must be made regarding optimal treatment. Given the clinical challenges of late FDP avulsion injuries and often indeterminate results of surgery, careful assessment must be made of the patient's complaints. If there is no pain or functional loss, consideration of observation alone is reasonable, particularly in the older patient with long-standing injury. In cases of acute or subacute injury, in younger patients, and in patients with functional limitations, surgery is indicated.

Primary tenorrhaphy is performed whenever possible, but in late-presenting cases, tendon retraction and myostatic contractures are commonplace. For this reason, if primary repair is not possible, preparation should be made for flexor tendon grafting where appropriate. Indications and prerequisites for single-stage flexor tendon grafting include: (1) a flexor tendon injury in which primary tenorrhaphy is not possible; (2) an intact flexor tendon sheath and annular pulley system; (3) the presence of an appropriate tendon graft donor; and (4) an informed and motivated patient and family.

Surgery is performed under general anesthesia via a Bruner zigzag incision (Figure 38-12). The tendon sheath is exposed and tendon stumps are identified. Often dissection proceeds in this fashion for the entire length of the digit, as the tendon may retract into the palm. If the proximal stump cannot be mobilized to the distal phalanx and the tendon sheath is intact, a single-stage graft can be performed. Typically, the tendon sheath is competent but needs to be serially dilated; we use pediatric



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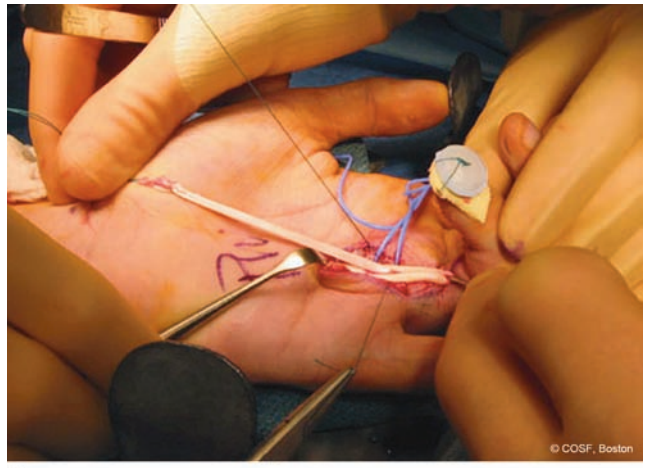

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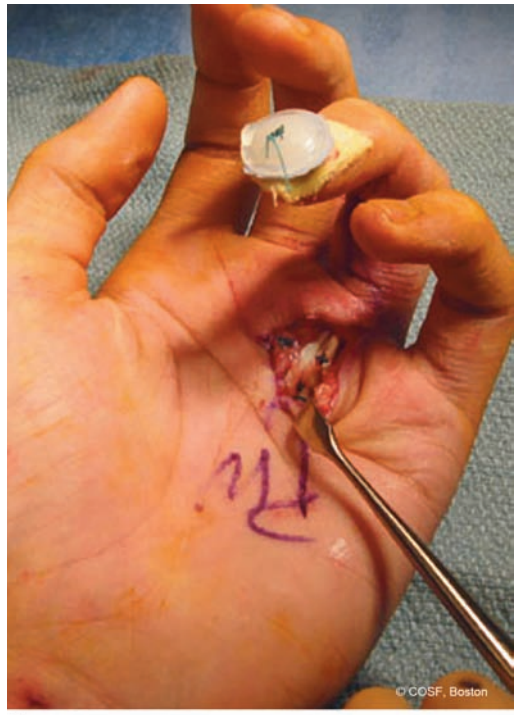


C

FIGURE 38-12 Single-stage flexor tendon grafting. **A:** Illustration depicting tendon graft secured into the distal phalanx using both core sutures and sutures-over-button technique. **B:** The tendon graft is placed within the tendon sheath, and preparations are made for securing the proximal junction. **C:** Upon completion of the Pulvertaft weave proximally, the graft procedure is complete. Note that the affected digits lie equal or slightly more flexed than the adjacent ulnar digit.

feeding catheters of increasing size (usually 3, 5, 8, and 10 Fr) to achieve this goal. The palmaris longus tendon is our preferred choice for a graft. In patients without a palmaris, the extensor indicis proprius, plantaris, or toe extensor tendon may be used depending upon surgeon preference. The graft is placed into the preserved tendon sheath.

Attention is first turned to the distal phalanx. One of two situations is usually encountered. First, rarely there is still some distal tendon stump remaining on the distal phalanx. In these situations, tendon-to-tendon graft repair may be performed. If a standard end-to-end tenorrhaphy cannot be performed, a number of techniques can be used to secure suture repair (Figure 38-13A). After the distal stump is incised longitudinally and opened, the distal end of the tendon graft may be sewn into the base of the tendon stump with side-to-side sutures completing the repair. The second situation, where the FDP has avulsed cleanly from the distal phalanx, is more common. In these cases, the tendon graft must be approximated securely to the distal phalanx. While suture anchors have been used in adults for this situation, we have not used suture anchor techniques due to both the size concerns in pediatric patients, as well as our desire to avoid physeal injury. Instead, we prefer suture-over-button techniques of tendon graft

approximation (Figure 38-13B). A 3-0 or 4-0 sliding core suture (Prolene, Ethicon, Inc., Somerville, NJ) is placed into the distal end of the tendon graft. The proximal volar lip of the distal phalanx is then carefully scored or debrided to punctuate bleeding bone. Two straight Keith needles are then drilled obliquely through the distal phalanx, beginning at the proximal volar lip and passing through the sterile matrix and nail plate. The ends of the tendon graft suture are passed into the eyelets of the needles and brought out over the fingernail. These sutures are tensioned and tied over a sterile button, reapproximating the tendon graft to the distal phalanx. Alternatively, instead of drilling through the distal phalangeal bone, the Keith needles may be passed radial and ulnar to the distal phalangeal diaphysis.

After the distal junction is complete, as much of the digital wound is closed as possible, leaving the proximal wound in the palm open. Preparations are then made for completion of the proximal junction. A simple grasping suture is placed into the proximal tendon graft. Both the proximal intact FDP and proximal tendon graft are isolated. Traction is placed on the tendon graft to restore the normal digital cascade; in general, the affected digit should be equally or slightly more flexed than the adjacent ulnar digit to allow for appropriate tensioning. The proximal junction is completed using a Pulvertaft tendon weave, completing a total of three passes and secured with 3-0 nonabsorbable braided suture (Ethibond, Ethicon, Inc., Somerville, NJ).[22] Confirmation is made of appropriate tension based upon observation of the digital cascade and tenodesis maneuver.

Wounds are irrigated and completely closed. A bulky soft bandage is applied, followed by a hand-based cast similar to that described above.

◆◆ Staged Reconstruction of Flexor Tendon in Child

How long should you try? Until.
—Jim Rohn

The need for staged reconstruction of flexor tendon insufficiency in the child is rare and should be approached cautiously. The challenges of anatomic size, technical skill, patient compliance, and reproducibility of results are compounded by the fact that flexor tendon reconstruction requires two or three procedures, often separated by many months.

Common indications include chronic flexor tendon injuries with delayed diagnosis; flexor tendon rerupture after prior tenorrhaphy; and flexor tendon insufficiency in the setting of prior complex trauma, infection, or tumor excision. As with all reconstructive efforts, surgery should only be considered in patients with well-vascularized and

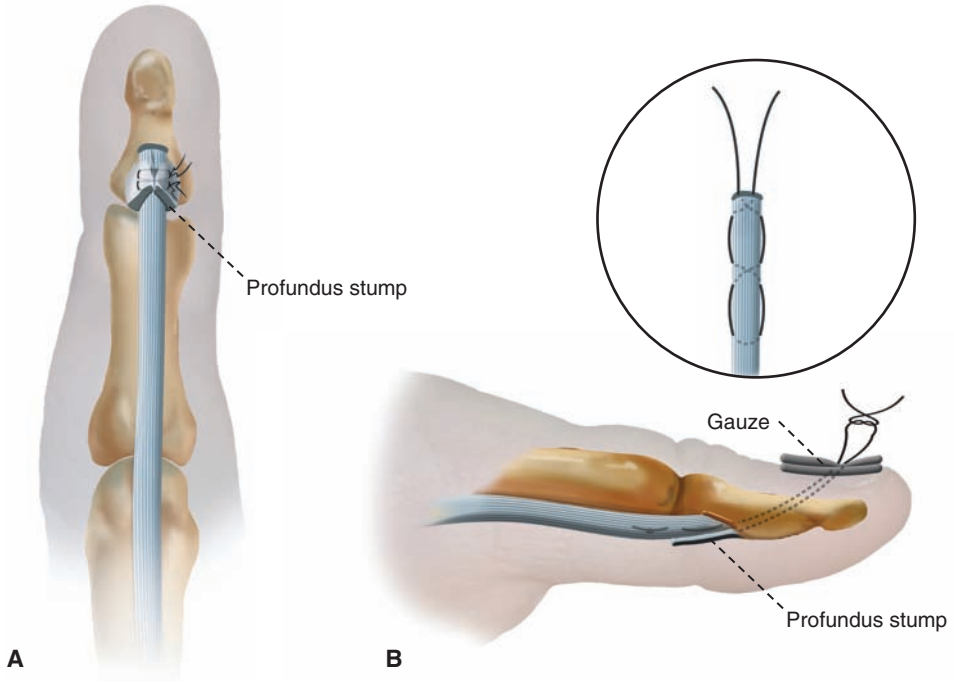


FIGURE 38-13 **A, B:** Schematic diagrams depicting means of securing the distal stump of the FDP tendon to its anatomic insertion on the distal phalanx.

sensate digits with functional compromise and a willingness to comply with postoperative immobilization and therapy.

The strategy of staged reconstruction involves first reconstruction of the pulley system and placement of a biologically inert tendon spacer, followed 3 to 6 months later by free flexor tendon grafting.[23–25] Experienced surgeons acknowledge that often a third procedure—flexor tenolysis—is needed given the propensity for adhesion formation; this is required less frequently in children than in adults.

Stage one begins with an extensile approach to the digit via a volar Bruner incision (Figure 38-14). The tendon sheath is exposed and assessment of the pulley apparatus made. If the tendon sheath is preserved and adequate atraumatic dilation can be achieved to accommodate a tendon graft, a single-stage tendon grafting may be performed. If the canal is obliterated or cannot be reconstituted, pulley reconstruction is performed. Multiple techniques have been advocated, each with its theoretical and practical advantages and disadvantages (Figure 38-14D).[26–34] Most recently, we have used a combined technique of Kleinert and Lister, utilizing a free extensor retinaculum graft secured to the "always-present fibrous rim" of the tendon sheath to reconstruct the pulley system.[32,33] At a minimum, the A2 and A4 pulleys are reconstructed.

Following pulley reconstruction, an appropriate-size silicone tendon rod (Hunter Active/Passive Tendon Implant, Wright Medical Technologies, Inc., Arlington, TN) is placed within the tendon sheath using meticulous technique. The distal stump of the implant is sewn to the periosteum or FDP stump at the level of the DIP joint. The proximal end is brought through the palm into the distal forearm, where it is trimmed and allowed to rest adjacent to the extrinsic digital flexors. We do not typically sew the proximal implant to the flexor tendon, though a nonabsorbable

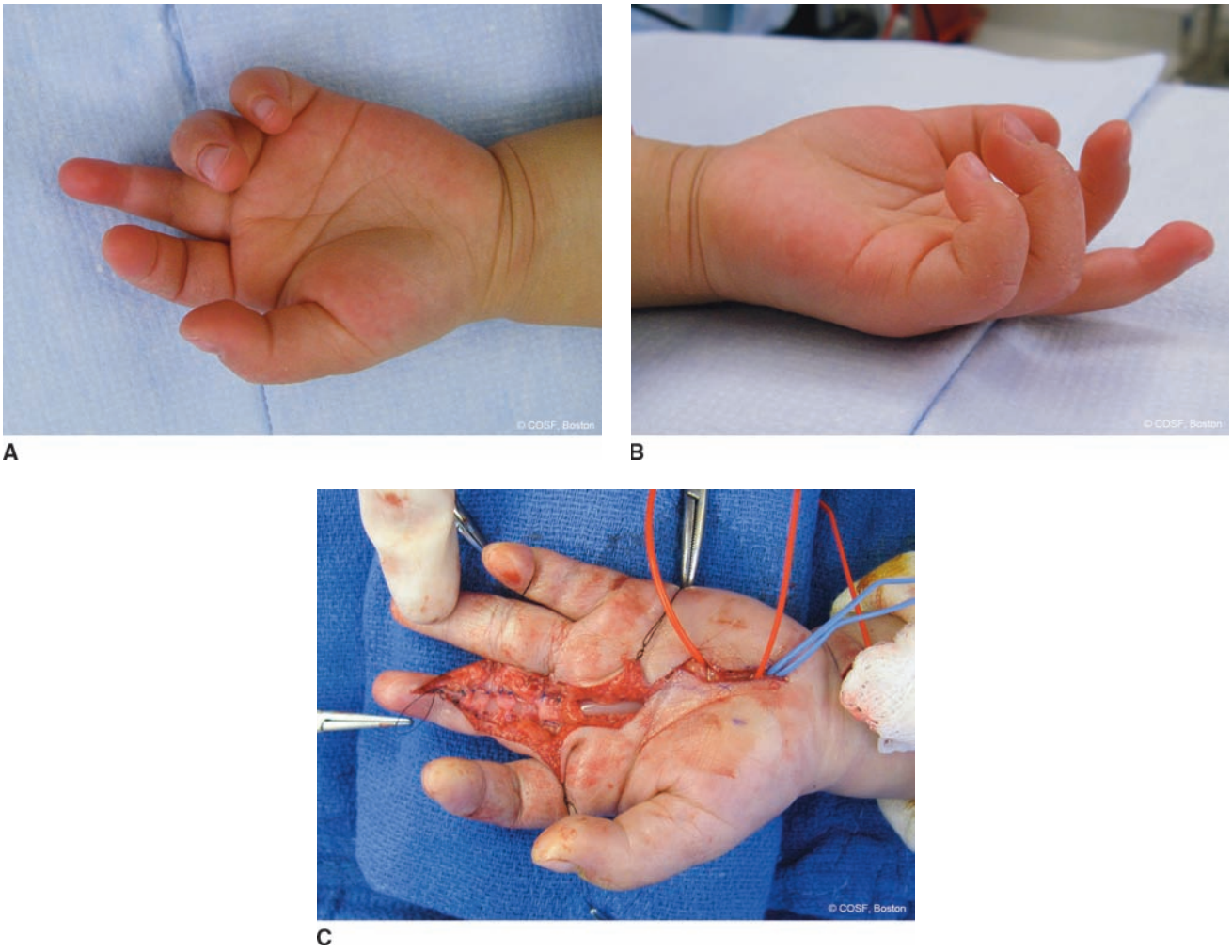
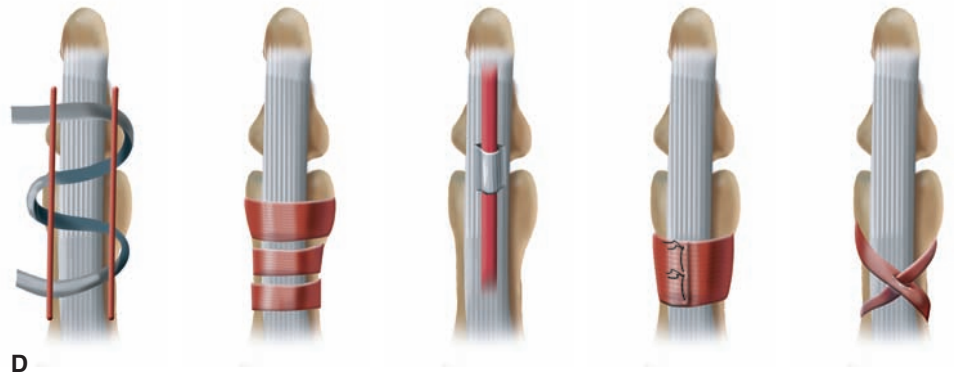


FIGURE 38-14 Staged flexor tendon reconstruction. **A, B:** Preoperative appearance of an 18-month-old female with history of perinatal sepsis and multiple abscesses, one of which resulted in neonatal rupture of the flexor tendons of the long finger. **C:** After exposure, the pulley systems were reconstituted using extensor retinaculum graft.



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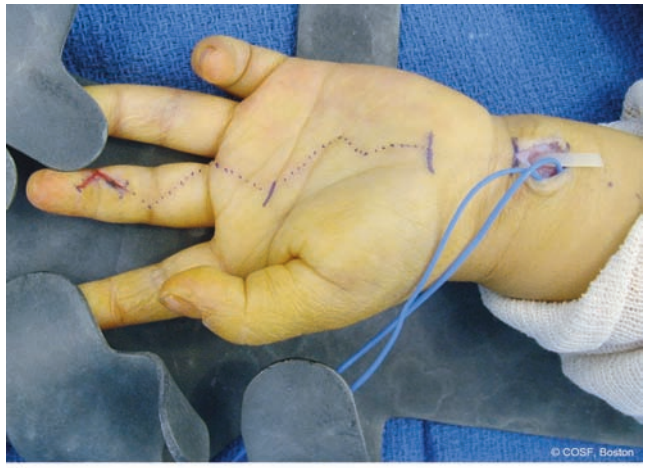

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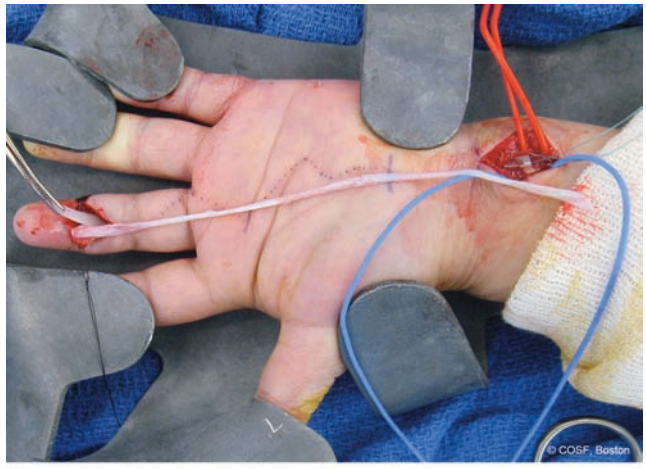

G

H

FIGURE 38-14 *(continued)* **D:** Schematic diagram depicting treatment options for annular pulley reconstruct. **E:** At the time of second stage of reconstruction, the previous suture lines have healed and tissue equilibrium restored. Access to the silicone tendon rod and fibro-osseous canal is achieved through small proximal and distal incisions. **F:** Exposure and traction upon the silicone implant at the level of the wrist allow confirmation of digital flexion and therefore of the silicone implant integrity. **G:** Autogenous plantaris tendon is harvested for subsequent grafting. **H:** Final appearance after single-stage grafting is complete.

colored suture (Prolene, Ethicon, Inc., Somerville, NJ) may be used to tag the corresponding FDP tendon in the distal forearm to facilitate later identification and grafting. The wound is irrigated and closed, followed by application of the splint or cast. After wound healing, hand therapy is reinitiated for edema control and scar management, and passive range-of-motion exercises are started.

After 3 to 6 months of therapy, the second stage is performed. Scar healing, restoration of passive digital motion, and soft tissue homeostasis are prerequisites to second-stage reconstruction. Again under general anesthesia, preparations are made for tendon grafting. The distal forearm incision is opened first. The proximal end of the silicone tendon spacer is identified, and gentle traction should result in easy digital flexion, confirming silicone rod continuity and digital motion. A small portion of the prior digital incision is then opened in the region of the DIP joint. The junction between the distal FDP stump and silicone spacer is identified. The tendon graft is then harvested. Due to the length required for this graft (which will span from the DIP joint to the distal forearm), the palmaris longus tendon may be too short and the plantaris tendon is needed.[35–38] The palmaris may be used if the proximal junction will lie in the palm. The tendon graft is secured to the proximal or distal end of the silicone implant using core-grasping sutures; graft passage through the tendon sheath is then performed by pulling on the silicone spacer and delivering the attached tendon graft through the reconstructed pulley system. Distal and proximal tendon graft junctions are then completed using the techniques described above. Patients are casted after wound closure.

POSTOPERATIVE

In golf and in life, it's the follow-through that makes the difference.
—Anonymous

There are clear advantages of early motion protocols after flexor tendon repair in adults, and many of these principles have been applied to the pediatric patient.[39–41] At present, however, we still utilize cast immobilization for 4 weeks after flexor tendon repairs or reconstructions in children <15 years of age[12,14,42,43] (see Sidebar).

After 4 weeks, casts are discontinued. Dorsal splints are utilized for an additional 2 weeks, during which scar management, edema control, and supervised motion (passive flexion, active extension) are performed. Splinting is discontinued after the sixth postoperative week, with advancement of range-of-motion and strengthening exercises as tolerated. Sports participation is restricted until there is return of near full motion and strength.

SIDEBAR

Postoperative Rehabilitation of Pediatric Flexor Tendon Injuries

We cast immobilize pediatric patients following flexor tendon repair or reconstruction. While theoretically increasing the risk of tendon adhesions in the short term, casting for 4 weeks postoperatively confers a number of practical advantages. First, children do not generally demonstrate the same propensity for long-term stiffness as adults. Second, cast immobilization allows the child to return to school and other daily activities without the need for constant supervision or parental and surgeon anxiety. Furthermore, the use of early mobilization and splinting protocols, while effective, depends entirely on the compliance and constant diligence of the patient, be it a young child or active teenager. Lastly, the potential morbidity and complications of rerupture in our opinion outweigh the temporary stiffness encountered with postoperative casting.

ANTICIPATED RESULTS

With timely diagnosis, meticulous technique, and appropriate postoperative rehabilitation, good-to-excellent functional results may be anticipated after primary tenorrhaphy of flexor (and extensor) injuries. O'Connell et al.[42] previously reported on the results of 95 flexor tendon lacerations in 78 patients <16 years of age. All zone I injuries returned to 90% or greater total active motion (TAM). In patients with single or combined zone II injuries, 70% or greater TAM was seen across all age groups, with no significant difference in patients managed with early motion versus postoperative cast immobilization for 4 weeks. Interestingly, patients who had somewhat limited TAM at 6 months postoperatively were observed to have improved 12 to 18 months later, suggesting that TAM indeed increases over time.

Following tenolysis procedures, patients may expect improved but often still imperfect restoration of digital active motion. As in adults, a 50% or greater improvement in TAM is expected in the majority of patients.[16,44] Results have been less encouraging in patients <10 years of age; for this reason, many still advocate observation in younger children with tendon adhesions, with the understanding that tenolysis can be considered later if functional limitations persist.[13]

Staged reconstruction can offer similarly good results.[43,45] Although the risks of persistent stiffness and incomplete return of TAM persist, with proper patient selection, surgical technique, and postoperative rehabilitation, 140 to 200 degrees of TAM can be expected in the majority of patients.

COMPLICATIONS

Complications occur following tendon injuries of the hand in children. As postoperative infection and neurovascular injury are rare, the majority of suboptimal or unexpected outcomes related to final digital motion.

As discussed above, failure of acute diagnosis resulting in delayed presentation and potentially more complex reconstructions occurs with great frequency. Careful history and physical examination are needed with a high index of suspicion to make appropriate acute diagnoses.

Tendon rerupture can occur following primary tenorrhaphy. Often this results in the need for additional surgery and even staged tendon reconstruction. Proper surgical technique—including minimum four-strand core suture repair supplemented by an epitendinous suture—and cast immobilization for 4 weeks postoperatively will serve to minimize this risk.

Stiffness remains the bane of the flexor tendon surgery. Tendon adhesions, even in technically successful acute repairs, are the rule rather than the exception. Continued investigation of biological solutions may provide future improvements in our ability to prevent postoperative adhesion formation. At present, meticulous surgical technique and appropriate postoperative rehabilitation remain the mainstays of prevention. Tenolysis should be entertained cautiously, particularly in the young child, but it can be helpful in cases of considerable functionally limiting stiffness.

CASE OUTCOME

This patient was diagnosed with a subacute closed FDP avulsion, or "jersey finger." After extensive discussion with the patient and family, the decision was made to proceed with attempted repair. Through a volar approach, considerable tendon retraction was apparent. As primary tenorrhaphy was not feasible but a competent tendon sheath remained, a single-stage tendon graft was performed (Figure 38-12). Hand therapy was begun after 4 weeks of postoperative casting. At 6 months postoperatively, the patient demonstrated a return of isolated FDP function and was able to appose the tip of the ring finger to the distal volar crease.

SUMMARY

Acute and chronic tendon injuries of the hand are common injuries. The pediatric hand and upper extremity surgeon should be adept not only in diagnosis and surgical treatment of acute sharp lacerations but also familiar with the principles and techniques of chronic reconstruction. With careful evaluation, meticulous surgical technique, appropriate surgical decision making, and frank communication with patients and families regarding results of treatment, hand function may be successfully restored and complications avoided for the vast majority of patients.

COACH'S CORNER

Glass Lacerations

Glass injuries are commonly seen in the hand, particularly in the pediatric and adolescent age group. Despite the frequency with which these injuries occur, often the injuries imparted are unrecognized or underappreciated. A few points bear mention.

First, the often innocent appearance of the skin laceration belies the scope of trauma beneath. Shards of glass may inflict tremendous injury to multiple anatomic structures through a very small traumatic wound.[46,47] Indeed, even experienced hand surgeons may be unable to accurately identify injured structures (tendons, nerves, vessels) based upon physical examination alone. A high index of suspicion is required in the evaluation of glass injuries.

Second, standard radiographic imaging is insufficient. As lead-based glass is no longer used in most contemporary objects, retained glass may not be readily apparent on plain x-rays. Other imaging modalities, such as ultrasound or MRI, may be helpful but incur cost and result in delays to treatment. Ultimately, surgical exploration is the best way to assess for foreign bodies.

In patients with glass injuries to the upper limb, a low threshold should exist for surgical exploration and repair of any injured structures. This is particularly true in the young, nonverbal, or noncompliant child, or in any patients with the suggestion of nerve or tendon injury. For us, the dictum of glass injuries is to explore early and expect the unexpected.

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CHAPTER 39

Overuse Injuries of the Upper Limb

INTRODUCTION

Sports are inseparably woven into the fabric of our lives. Be it as recreational participants, serious competitors, supportive parents, professional coaches, backyard teachers, or avid fans, all of us are directly or indirectly involved in sporting activities. And it is no different for our children.

While the physical, emotional, and developmental benefits of physical activity are well established, life is full of risks.[1] Inherent in any sports participation is the risk for traumatic or overuse injury. Given the spectrum within which these sports-related injuries affect the upper limb, it is common for these conditions to present to the pediatric hand and upper extremity surgeon. Although the vast majority of sports injuries may be managed via nonoperative means, often surgical treatment is required to alleviate pain, restore function, and allow return to prior levels of participation.

The purpose of this chapter is to describe the evaluation and treatment of sports-related injuries. While this chapter focuses on several common overuse conditions amenable to nonoperative care, the ensuing chapters discuss injuries of the upper extremity commonly requiring surgical treatment.

YOUTH SPORTS PARTICIPATION AND INJURY

I'm tired of hearing about money, money, money, money, money. I just want to play the game, drink Pepsi, wear Reebok.
—Shaquille O'Neal

The number of children and adolescents involved in sports continues to grow. While it is estimated that 32 million were involved in organized sports in the United States in 1997, it is now believed that over 44 million US children and adolescents participate in organized sporting activities.[2] As the enthusiasm for youth athletics grows, so too will participation rates among children and adolescents.

With this increased participation has come an increased incidence of sports-related injuries. An estimated 2.5 million emergency room visits are due to sports-related injuries each year in the United States.[3] Furthermore, it is estimated that sports-related injuries account for up to 20% of all primary care physician evaluations for injuries in the pediatric population.[4] Prior epidemiological studies have demonstrated an incidence of 2.51 injuries: 1,000 athlete exposures among US high school students alone, accounting for approximately 1.5 million injuries per year.[5,6]

Skeletally immature athletes are particularly vulnerable to sports-related injury due to a variety of physiologic and environmental factors. Growing athletes are growing children, and physiologically their bodies are changing. Bones are lengthening and muscles are maturing, leading to an inherent imbalance between strength and flexibility, predisposing to injury.[7] Open physes are also susceptible to traumatic and overuse injuries, as they are less resistant to compression and shear forces than the adjacent bone.[8,9] Furthermore, the extremities in young athletes may be subjected to greater forces given the changes in body composition. The increased obesity seen in the United States and other developed nations is further cause for concern.

In addition to these physiologic factors, a number of societal and environmental trends may be raising the frequency of youth sports injuries. The age of first sports participation is becoming younger and younger. Youth athletes are now raised in an era of specialization, in which sports participation is year-round, with few breaks between seasons or opportunities to pursue varied physical activities.[10] In addition, the financial investment and rewards of youth sports participation continue to increase. Scholarships are given, television contracts are negotiated, and money is made in the industry of youth sports. (e.g., every game of the Little League World Series was televised in

2010. For the 2009 financial year, Little League Baseball reported net revenues of over $21 million and had net assets worth over $70 million!) Given the social climate, families and coaches are now pushing their young athletes to participate at unprecedented levels. All of these factors are leading to startling increases in repetitive, overuse injuries and more violent acute injuries at a young age. The extreme sports are at an entirely different level of concern.

COMMON OVERUSE INJURIES BY ANATOMIC REGION

I've come to accept that the life of a frontrunner is a hard one, that he will suffer more injuries than most men and that many of these injuries will not be accidental.
—Pele

SHOULDER: INTERNAL ROTATION DEFICIT AND PHYSEAL STRESS INJURY

Shoulder complaints are common in the youth overhead athlete, particularly in the baseball pitcher and other repetitive overhead athletes. Indeed, in a previous longitudinal study of 298 youth baseball pitchers, for example, approximately one-third developed shoulder pain over the course of two seasons.[11] Epidemiological data like this reinforce the common observation that shoulder pain is a frequent complaint in young throwers and overhead athletes.

The term "Little League shoulder" has often been used to describe shoulder pain in skeletally immature throwers. While this term is liberally used to describe a host of different clinical entities, in most situations it denotes a repetitive stress injury to the proximal humeral physis[12] (Figure 39-1). While the exact mechanism is unknown, it is theorized that repetitive throwing imparts excessive rotational torque and tension to the proximal humeral physis, resulting in pain, tenderness, and characteristic radiographic changes.

Previous biomechanical analyses have demonstrated that external rotation torques approximate 18 Nm during pitching, 400% of the mechanical tolerance of physeal cartilage. Distraction forces may be as high as 200 Nm in the adolescent shoulder, representing 5% of the physeal cartilage strength.[13,14] These forces are thought to be highest during the late cocking to late release phases of the pitching motion. It has been hypothesized that these rotational and tensile forces cause "microfractures" across the physeal zone of hypertrophy, which may be vulnerable to greater injury due to the orientation of the collagen fibers and relatively low mechanical strength.[15,16]

Not surprisingly, this condition is most commonly seen in skeletally immature athletes between the ages of 9 and 15, at a time in which the physis is metabolically active and vulnerable to injury. Additional risk factors include arm pain and fatigue during pitching, pitch counts of higher than 80 per game, and pitching over more than 8 months per calendar year.[17]

Clinical Presentation and Evaluation

Patients will typically present with insidious onset shoulder pain, exacerbated during and after throwing. The pain is usually localized to the anterior and lateral aspect of the shoulder, and there is often tenderness to percussion and deep palpation of the proximal humerus. Abduction and forward flexion motion and strength are frequently unaffected but may be limited at the time of presentation due to pain.

Careful examination of internal and external rotation will often demonstrate greater external rotation and less internal rotation than the unaffected, nonthrowing shoulder, the so-called glenohumeral internal rotation deficit (GIRD).[18–22] Unlike older adults, it should be noted that young overhead athletes may often have GIRD without an associated increase in external rotation.[18] Care should be made during assessment of shoulder rotation to prevent scapular elevation and protraction, which is typically

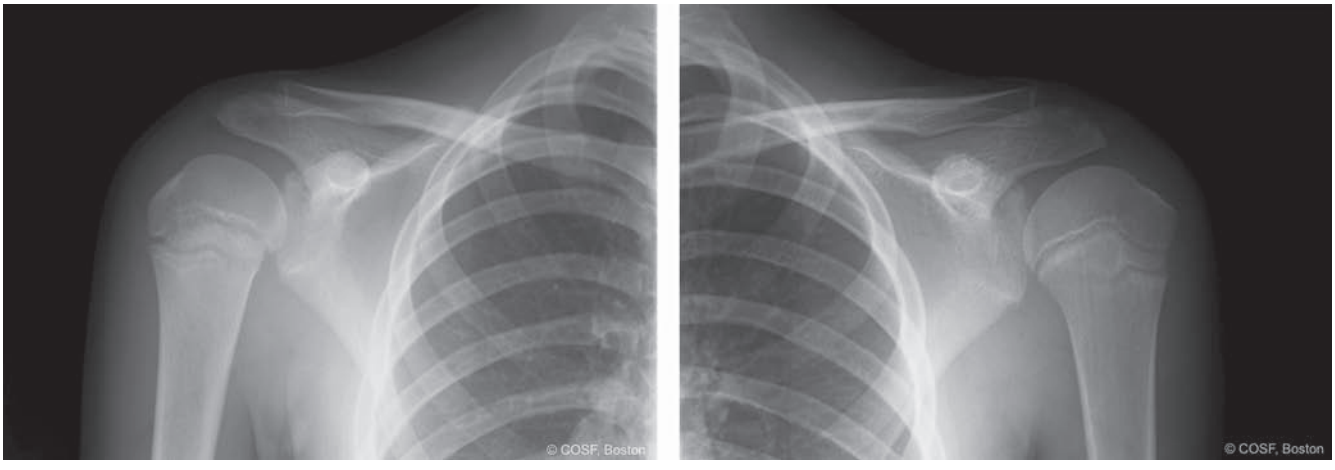

FIGURE 39-1 AP radiographs of the right and left shoulder in an 11-year-old right-handed youth baseball pitcher demonstrating physeal widening and juxtaphyseal sclerosis of the symptomatic right side.

recruited to compensate for loss of glenohumeral joint internal rotation. This may lead to scapulothoracic dyskinesis and asymmetric scapulothoracic motion during shoulder range-of-motion testing. If the GIRD and/or scapulothoracic dyskinesis are severe, provocative testing for internal impingement and superior labral/long head of biceps pathology may be positive.

Radiographic Evaluation

Plain radiographs of the shoulder should be examined in patients with significant pain and tenderness, even in the absence of an obvious traumatic event. Standard anteroposterior (AP), scapular Y, and axillary views are sufficient, though an AP in external rotation may allow for better visualization of the undulating proximal humeral physis. Characteristic findings consistent with epiphysiolysis include physeal widening, cystic changes, juxtaphyseal sclerosis, or periosteal reaction.[23] As these findings are often subtle and difficult to distinguish from the normal physis, contralateral comparison radiographs are helpful (Figure 39-1).

Magnetic resonance imaging (MRI) may assist in diagnosis, particularly in cases where plain radiographs appear normal. Physeal widening and abnormal signal within the juxtaphyseal-metaphyseal region may be seen.[24–26]

Treatment

As with all overuse sporting injuries, prevention remains the key to treatment. For youth baseball pitchers, a number of formal guidelines have been developed to regulate the quantity and quality of throwing allowed to young throwers (Tables 39.1 and 39.2). Derived from epidemiological data of shoulder injuries in youth throwers and formulated by a consensus of baseball and medical experts, these guidelines attempt to minimize the risk of overuse injury.[27,28]

In addition to rules and guidelines, efforts should be made to educate young throwers on proper pitching mechanics, appropriate warm-up and cool-down activities, and pertinent stretching and strengthening regimens to avoid injury due to mechanical failure.

However, further work needs to be done. Guidelines are helpful and applicable to the general population, yet to date they are mostly based upon chronological age rather than physiological status. (While some 12-year-olds are shaving, others have yet to begin their preadolescent growth spurt.) In addition, there is little oversight and monitoring of athletes involved with multiple teams in multiple leagues during the same season, an increasingly common phenomenon in today's highly competitive climate. Furthermore, though great attention has been paid to youth baseball pitchers, little scientific information exists on the risks and recommendations for other position players or other overhead sports (e.g., softball, tennis). Finally, in the era of specialization and earlier sports participation, better guidelines need to be created regarding the optimal time spent away from throwing and baseball between seasons.

In patients with established proximal humeral physeal stress injury, treatment is predicated on rest until there is resolution of pain and tenderness. While highly variable, this typically involves cessation of all throwing activities for 6 to 12 weeks. After the acute pain—and presumably physeal stress injury—has resolved, physical therapy is initiated for range of motion and strengthening. Particular attention is given to "sleeper stretches" to improve internal rotation and periscapular strengthening to address scapulothoracic dyskinesis, hyperangulation, and internal impingement. Advancement to an interval throwing program with attention to pitching mechanics is then begun, adhering to the "soreness rules"[23,29,30] (Tables 39.3 and 39.4). Patients and families should be counseled that this process is dynamic and may indeed take months to complete.

Table 39.1

Youth baseball pitching guidelines

Age	Pitches Per Game	Pitches Per Week
17–18 y	105	2 games/wk
13–16 y	95	
11–12 y	85	100
9–10 y	75	75
7–8 y	50	

Number of Pitches Thrown	Days of Rest After Pitching
61+	3 d
41–60	2 d
21–40	1 d

Table 39.2

Age at which pitches should be learned

Pitch	Age
Fastball	8
Change-up	10
Curveball	14
Knuckleball	15
Slider	16
Splitter	16
Screwball	17

Table 39.3

Interval throwing program for youth baseball (age 10–12 y)

Following injury, athletes are started at phase 1. Two days of rest are allotted between each phase of the program, which is advanced according to the "soreness rules."

Phase 1
Short toss 20 ft, 2 sets of 15 throws, 1 set of 20 throws
Rest 10 min
Long toss 50% target distance, 25 throws

Phase 2
Short toss 30 ft, 2 sets of 15 throws, 1 set of 20 throws
Rest 10 min
Long toss 70% target distance, 25 throws

Phase 3
Short toss 40 ft, 2 sets of 15 throws, 1 set of 20 throws
Rest 10 min
Long toss 75% target distance, 25 throws

Phase 4
Short toss 46 ft, 1 set of 15 throws, 2 sets of 20 throws, 50% intensity
Rest 10 min
Long toss 80% target distance, 25 throws

Phase 5
Short toss 46 ft, 1 set of 15 throws, 2 sets of 20 throws, 75% intensity
Rest 10 min
Long toss 85% target distance, 25 throws

Phase 6
Short toss 46 ft, 3 sets of 20 throws, from mound at up to 100% intensity
Rest 10 min
Long toss 90% target distance, 25 throws

Phase 7
Short toss 46 ft, 2 sets of 20 throws, 1 set of 25 throws, from mound at 100% intensity
Rest 10 min
Long toss 95% target distance, 25 throws

Phase 8
Short toss 46 ft, 2 sets of 20 throws, 1 set of 25 throws, from mound, at 100% intensity
Rest 10 min
Long toss 100% target distance, 25 throws

Phase 9
Simulated game

Adapted from Axe MJ, Snyder-Mackler L, Konin JG, et al. Development of a distance-based interval throwing program for Little League-aged athletes. *Am J Sports Med.* 1996;24:594–602 and Axe MJ, Wickham R, Snyder-Mackler L. Data-Based Interval Throwing Programs for Little League, High School, College, and Professional Baseball Pitchers. *Sports Med Arthrosc.* 2001;9:24–34.

Table 39.4

Soreness rules

Soreness Rules
1. If no soreness, advance one step every throwing day.
2. If sore during warm-up but soreness is gone within the first 15 throws, repeat the previous workout. If shoulder becomes sore during this workout, stop and take 2 d off. Upon return to throwing, go back one step.
3. If sore more than 1 h after throwing, or the next day, take 1 d off, and repeat the most recent throwing program workout.
4. If sore during warm-up, and soreness continues through the first 15 throws, stop throwing and take 2 d off. Upon return to throwing, go back one step.

Adapted from Axe MJ, Snyder-Mackler L, Konin JG, et al. Development of a distance-based interval throwing program for Little League-aged athletes. *Am J Sports Med.* 1996;24:594–602 and Axe MJ, Wickham R, Snyder-Mackler L. Data-Based Interval Throwing Programs for Little League, High School, College, and Professional Baseball Pitchers. *Sports Med Arthrosc.* 2001;9:24–34.

ELBOW: MEDIAL EPICONDYLE APOPHYSITIS

Elbow pain is an equally common complaint in the young athlete. As described earlier, previous longitudinal studies of youth baseball pitchers have demonstrated that 26% will develop elbow pain in-season.[11] Elbow pain is not limited to the pitcher or thrower, however. Repetitive stress and overuse will cause elbow pain and functional limitations in a host of athletes, including gymnasts, tennis and other racquet sports players, wrestlers, and football players, among others.

Medial elbow pain is particularly prevalent, due to the valgus stresses imparted on the elbow during overhead and weight-bearing activities. In addition, there is repetitive eccentric loading of the flexor-pronator mass during many sports. These tensile forces on the medial elbow will often result in a stress injury of the medial epicondylar apophysis, which is the "weak link" in the chain of medial-sided structures (ulna, ulnar collateral ligament, medial epicondyle, medial epicondylar apophysis, and distal humerus). Repetitive submaximal stress may result in mechanical failure and apophyseal widening. Medial epicondylar avulsion fractures may be seen in athletes resulting from high-energy injuries, particularly in the setting of repetitive overuse and an already weakened apophysis.

Clinical Presentation and Evaluation

Patients will typically present with medial elbow pain, localized to the medial epicondyle and flexor-pronator origin. Pain occurs during and/or after sports activities such as throwing. The patient's history should be carefully obtained, not only to assess the character of the pain but also to get information regarding the inciting activities. In the young thrower, questions are asked regarding the number, frequency, and types of pitches thrown.

Direct palpation of these structures will elicit tenderness, and occasionally swelling is present. In rare situations, there may be objective signs of ulnar nerve irritation about the cubital tunnel. Valgus stress testing may elicit pain but rarely demonstrates frank instability. Careful examination of elbow motion will reveal full motion or subtle elbow flexion contractures.

As this condition is often seen in throwers, careful examination of the rest of the kinetic chain is critical.[31] Evaluation of the shoulder will often reveal scapulothoracic dyskinesis or asymmetry and GIRD. Identification of these additional features and education of the athletes and families regarding their significance is critical to ensure adequate comprehension of the scope of the problem and treatment.

Radiographic Evaluation

Standard AP and lateral radiographs of the elbow are obtained to assess the morphology of the medial epicondyle. Oblique views put the medial epicondyle in profile. Comparison views of the unaffected contralateral elbow are helpful to distinguish subtle irregularities. Findings include widening of the medial epicondylar apophysis, with both acute and chronic features (Figure 39-2). In cases in which ulnar collateral ligament insufficiency is suspected, a gravity stress radiograph may be performed. This is taken with the patient supine, shoulder abducted 90 degrees, elbow extended, and forearm supinated. An AP x-ray of the elbow is taken by directing the beam parallel to the floor. Gravity provides a mild valgus stress, which results in medial joint space widening of >3 mm.

An MRI scan may be obtained to further assess the extent of bony and soft tissue injury and rule out other associated pathology. Increased T2-weighted signal around the medial epicondyle and medial apophysis in the absence of associated ulnar collateral ligament injury is diagnostic.

Treatment

Treatment of medial epicondylar apophysitis begins with patient and family education regarding the nature of the injury. It is emphasized that the cause is overuse, and guidelines are provided regarding age-appropriate activities (e.g., pitch counts, types of pitches). Furthermore, information regarding the role of trunk, scapulothoracic, and shoulder strength and mechanics is provided, particularly in patients with GIRD.

Rest is initially prescribed. While most will have resolution of symptoms with 6 to 12 weeks of rest, in some athletes more time is required. After the pain and tenderness have subsided, physical therapy is instituted to address

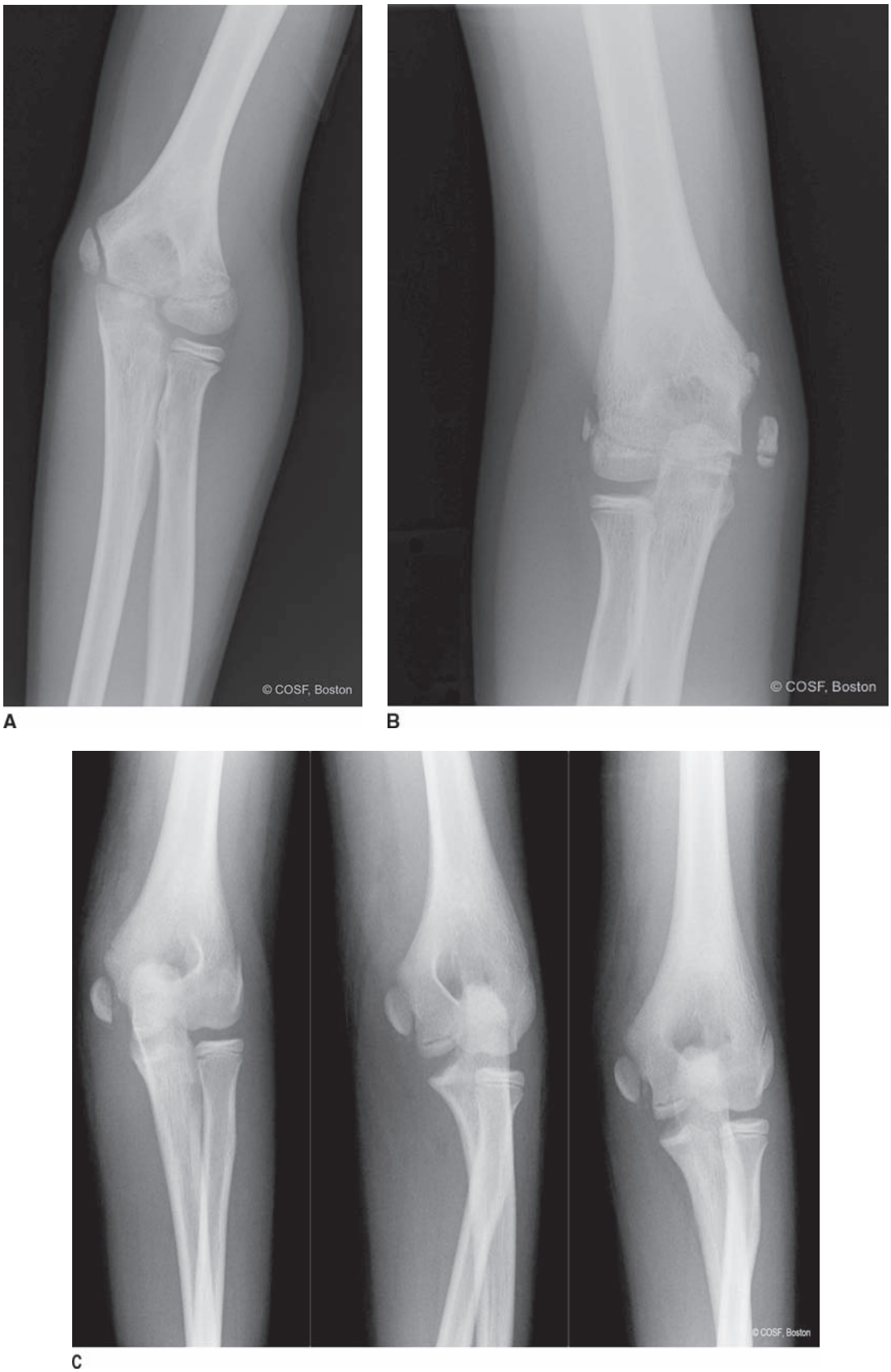

FIGURE 39-2 Radiographs of medial epicondylar apophysitis. **A:** Mild widening in a 10-year-old baseball pitcher with medial elbow pain and bony tenderness. **B:** Widening and displacement in a former pitcher with persistent pain, ulnar nerve symptoms, and mild valgus instability. **C:** Acute or chronic injury with a displaced medial epicondyle fracture sustained during gymnastics in a 10-year-old female.

scapulothoracic dyskinesis, posterior capsular contracture of the shoulder, and flexor-pronator stretching and strengthening. Once pain-free motion and strength have returned, an interval throwing program may be initiated, adhering to the "soreness rules."

WRIST: GYMNAST'S WRIST

Hard work is always hard work, for young gymnasts and old gymnasts. Whoever can handle this will be a champion.
—Svetlana Boginskaya

Few sports impart as much repetitive stress on the wrist as gymnastics.[32] With tumbling, vaulting, bar work, pommel horse, and balance beam activities, the wrist is subjected to intense static and dynamic forces, often at high rates of loading in extreme positions. Indeed, the wrist sees 2.4 times body weight (BW) during back handsprings and pommel horse activities, with loading rates of up to 200 times BW per second.[33,34]

For these reasons, wrist pain is extremely common, affecting approximately 45% to 80% of young gymnasts.[35–39] In addition to fractures, sprains, tendinosis, and triangular fibrocartilage complex (TFCC) tears, one common cause of pain in these young athletes is the so-called gymnast's wrist. *Gymnast's wrist* is a colloquial term used to describe repetitive stress injury to the distal radial physis. It is believed the incidence of gymnast's wrist is approximately 2:100 gymnast seasons.[40,41]

Clinical Presentation and Evaluation

The pain is typically dorsocentral in location and is often described as a vague, achy pain localized to the distal radial metaphysis and radiocarpal joint, which may occur both during and after gymnastics activities. Prior studies have suggested that it most commonly occurs in gymnasts between the ages of 10 and 14 years. Risk factors include older age at initiation of gymnastics training, higher gymnastic skill levels, and higher intensity training.[36,37]

In addition to pain and tenderness, careful physical examination will often demonstrate subtle loss of wrist extension. While many gymnasts are ligamentously lax, gross carpal and distal radioulnar joint (DRUJ) instability are uncommon. In advanced cases with ulnocarpal impaction due to distal radial growth retardation and ongoing normal distal ulnar growth, there may be restrictions in ulnar deviation. Tenderness over the ulnar aspect of the wrist—particularly in the ulnar fovea—may similarly be indicative of ulnar overgrowth and possible TFCC injury.

Radiographic Evaluation

Radiographs, while not always positive, will often exhibit characteristic features consistent with distal radial physeal stress injury, including physeal widening, cystic or sclerotic changes of the metaphysis, beaking of the epiphysis near the radial styloid, and even premature physeal closure (Figure 39-3). Indeed, a classification scheme has been

FIGURE 39-3 Radiographic images of the gymnast's wrist. **A:** AP radiograph of the left wrist in a 12-year-old female demonstrates physeal widening, cystic changes, and metaphyseal sclerosis. **B:** AP radiograph of the same wrist after 3 months of rest from gymnastics, demonstrating incomplete resolution of the physeal changes.

Table 39.5

Radiographic grades of the gymnast's wrist

Radiographic Grade	Findings
0	Normal plain radiographs
1	Physeal haziness, irregularity of physeal borders
2	Cystic changes, metaphyseal sclerosis, metaphyseal beaking
3	Physeal widening

Adapted from DiFiori JP, Puffer JC, Aish B, et al. Wrist pain, distal radial physeal injury, and ulnar variance in young gymnasts: does a relationship exist? *Am J Sports Med.* 2002;30:879–885.[36]

developed based upon the severity of radiographic findings and physeal involvement[36,42] (Table 39.5). Correlations between radiographic grade and wrist pain have been noted.

While the etiology of gymnast's wrist remains unknown, it is hypothesized that repetitive compressive loads across the physis lead to vascular insufficiency as well as mechanical failure. Previous animal studies have demonstrated that disruption of the vascularity to the metaphysis and epiphysis interferes with the mineralization in the zone of provisional calcification, resulting in persistence of chondrocytes in the physis.[43] As these chondrocytes proliferate and hypertrophy, the physis appears to widen, and characteristic radiographic changes ensue. If unrecognized and untreated, continued gymnastics participation may lead to physeal arrest. The resulting changes in distal radial morphology and progressive ulnar positive variance can lead to worsening pain, ulnocarpal impaction, TFCC tears, DRUJ instability, and articular cartilage damage.[39,44–53]

While ulnar positive variance has been proposed to be more common in young gymnasts than age-matched nongymnasts, the clinical significance and etiology of these associations remain unknown.[36,44,46,54–57] First, it is unclear whether the relative ulnar positivity seen in gymnasts is an independent cause of wrist pain or result of abnormal distal radial growth due to repetitive compressive loading. Second, radiographic evaluation of ulnar positive variance remains challenging. There can be side-to-side differences, as well as changes in ulnar variance based upon the position of the forearm (pronation, supination, neutral). Standardization of views for variance need to have the shoulder abducted 90 degrees, elbow flexed 90 degrees, and wrist and forearm neutral on the cassette. In addition, assessment of ulnar variance on plain radiographs may underestimate the true length of the distal ulna, as the cartilaginous epiphysis is not completely visualized. Therefore, in skeletally immature children, variance is measured off the proximal epiphysis or metaphysis depending on the age of the patient. It has been demonstrated that ulnar positive variance is not seen in every gymnast, nor is it seen in every case of gymnast's wrist.[36,44,54] However, there are gymnasts with longitudinal laxity of the forearm in which the plain radiographs will reveal normal variance, but athletic loading of the wrist will result in dynamic positive ulnar variance and ulnar carpal impaction.

Treatment

An ounce of prevention is worth a pound of cure. Perhaps the best treatment of gymnast's wrist is to prevent its occurrence, particularly given the insidious nature of its development, detection, and treatment. While little scientific information exists to demonstrate that preventative measures can decrease the incidence or prevalence of distal radial physeal injury in young gymnasts, a number of concepts continue to be advocated.[32,58,59] While all training regimens should be individualized, in general, cyclic progressive training cycles (e.g., 1-2-3-2-3-4-3-4-5 as opposed to 1-2-3-4-5-6-7-8-9) are advocated. Alternating loading activities should be implemented (e.g., push one day, pull the next day). Persistent or recurrent wrist pain should be investigated rather than ignored. Advances in training intensity should be gradual during periods of rapid skeletal growth and in other "high-risk" athletes.

It remains controversial whether wrist braces (e.g., "tiger paws" or "lion paws") confer any protective effect in the prevention of gymnast's wrist. The concept is that limiting wrist extension may limit excessive loading of the radial physis. These can also provide some symptomatic relief to athletes returning from injury.

Once the diagnosis of distal radial physeal injury has been made, rest is initiated until tenderness and pain dissipate. Following this, a gradual return to sport-specific training is recommended. In our practice, a typical "prescription" involves 6 weeks of rest, followed by 6 weeks of closed-chain upper extremity activities, and then gradual resumption of open chain activities. More important than the time devoted to each stage of recovery are the "soreness rules," which simply state that if there is recurrent or persistent pain, more rest is needed before progressing to upper limb weight-bearing activities.

Even with resolution of symptoms and successful return to gymnastics, serial radiographic examinations are recommended to confirm resolution of x-ray changes and absence of distal radial physeal arrest.

In cases in which distal radial physeal arrest occurs, and there is symptomatic ulnar positive variance, a host of surgical options exist, depending upon the patient's symptoms, skeletal age, amount of ulnar positive variance, and associated pathology. In general, wrist arthroscopy, TFCC repair, DRUJ stabilization, ulnar shortening osteotomy, distal ulnar epiphysiodesis, or combinations thereof may be considered. Further details of these procedures are provided in Chapter 34.

CONCLUSIONS

Sports-related injuries affecting the upper extremity are increasingly common in children and adolescents. Given the open growth plates in these skeletally immature athletes, repetitive overuse injuries may often result in physeal stress injuries of the shoulder, elbow, and wrist. While prevention remains the ultimate goal, pediatric hand and upper limb surgeons should be aware of the clinical presentation, radiographic evaluation, and treatment principles of these conditions. With timely diagnosis and intervention, irreversible physeal disturbance and associated complications may be avoided.

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CHAPTER

40

Shoulder Instability

CASE PRESENTATION

A 16-year-old right hand–dominant football linebacker presents for evaluation of shoulder instability. One week before, while tackling another player in the first game of the season, the patient sustained a traumatic anterior glenohumeral shoulder dislocation. The shoulder was reduced under conscious sedation in a nearby emergency department, and the affected limb was placed in a sling and swathe. He now presents for his first orthopaedic consultation. The patient denies any distal numbness, weakness, or tingling. He has aspirations of playing football at the collegiate level.

CLINICAL QUESTIONS

- What is the risk of recurrent glenohumeral joint instability after a first-time traumatic dislocation in an adolescent athlete?
- Are there any nonoperative treatments that might reduce the risk of recurrent instability?
- What measures can be taken to allow this athlete to complete the current football season?
- What are the indications for acute surgical treatment?
- What surgical techniques are utilized for shoulder stabilization?
- What different surgical strategies should be employed in the setting of glenoid bony deficiency?
- How is the treatment of atraumatic, multidirectional instability different from traumatic, unidirectional instability?
- What are the surgical techniques for multidirectional instability?
- Should surgery be performed for the adolescent, first-time dislocator?

THE FUNDAMENTALS

The glenohumeral joint is one of the most commonly dislocated joints of the human body.[1,2] The same skeletal and soft tissue anatomy designed for a wide range of shoulder joint motion results in inherent instability, particularly in young athletes who subject their shoulders to repetitive and high-energy trauma. As the understanding of the pathophysiology and spectrum of glenohumeral joint instability has increased, so too has the natural history knowledge and treatment expertise expanded. With the advances in surgical techniques and instrumentation come increased demand for appropriate decision making and communication in the treatment of these conditions. This is particularly true in this age of escalating patient/family demands for expedited diagnosis, increasing sports participation, and timely and full functional recovery.

Etiology and Epidemiology

Traumatic anterior shoulder instability typically occurs from anteriorly directed forces imparted upon the shoulder in abduction and external rotation. In these situations, the glenohumeral joint will dislocate with disruption of the anterior-inferior labrum and an obligate capsular stretch. Associated injuries are common, including extension of the labral tear into the superior labrum, Hill-Sachs lesions of the posterior humeral head, and bony fractures of the glenoid rim or greater tuberosity.

In addition to the capsulolabral injury, glenoid bone loss may be seen following traumatic instability events, particularly following multiple dislocations or high-energy injuries.[3–5] This results in reduced bony constraint, increased shear forces, and loss of the normal concavity-compression effect of the joint.[6]

While the exact natural history of the first-time adolescent dislocator has yet to be fully characterized, it is clear that the risk of recurrent instability is high. Hovelius et al.[7] previously reported the 25-year follow-up on 227 patients who sustained 229 traumatic anterior shoulder dislocations between the ages of 12 and 40. Overall, 57% had recurrent instability. However, when patients between the ages of 12 and 22 years at the time of first dislocation were assessed, the recurrent instability rate rose to 72%. Other studies have documented between a 75% and 100% redislocation rate in younger, active patients.[8–14] Therefore, the risk of recurrent instability is high, but not universal.

Clinical Evaluation

Clinical evaluation begins with a careful history and physical examination. Patient-related information—including hand dominance, sports or functional demands, and expectations for a return to activities—is critical at the first consultation. Details regarding the exact mechanism of injury, associated neurological symptoms, and frequency of recurrent subluxation or instability events are obtained. This information provides important insights into the suspected pathoanatomy and helps to guide decision making.

A number of physical examination maneuvers will assist in diagnosis. In addition to standard range-of-motion and strength evaluation, provocative maneuvers such as the apprehension test, apprehension-relocation test, and anterior load-and-shift test are typically positive in cases of anterior instability[15] (Figure 40-1). In patients with multidirectional instability, glenohumeral joint laxity or instability can be exhibited with anteriorly and posteriorly directed stress, in addition to inferior translation with the shoulder adducted, the so-called sulcus sign. Patients with voluntary instability may be able to demonstrate this without assistance from the examiner (Figure 40-2). Finally, superior labral pathology (SLAP tears) is often suggested by pain with O'Brien's maneuver (resistance with downward pressure on the forward flexed, adducted, and internally rotated limb).

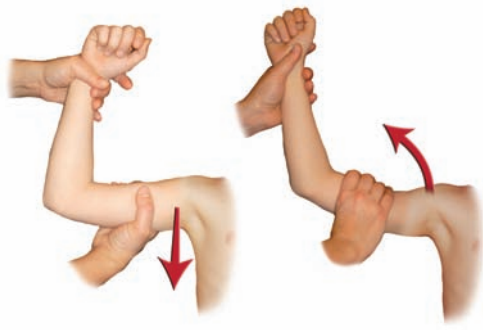


FIGURE 40-1 Schematic diagrams depicting the (**A**) apprehension and (**B**) apprehension-relocation physical examination provocative maneuvers.

Classification of shoulder instability remains descriptive, based upon history, clinical examination, and radiographic

A

B

C

FIGURE 40-2 Clinical photographs of a patient with voluntary multidirectional instability of the left shoulder. **A:** Anterior glenohumeral subluxation. **B:** A prominent "sulcus sign." **C:** View of the subluxed shoulder from the posterior aspect.

findings. Traumatic instability remains the most common in children and adolescents, resulting from a single, identifiable inciting event. Not all traumatic instability, however, results in overt joint dislocation or need for manipulative reduction by an orthopaedic surgeon or emergency room physician. Indeed, a recent study suggests that traumatic subluxation, though subtle, may result in similar pathoanatomic lesions in the glenohumeral joint.[16] Direction of instability similarly provides great insight into the failure of bony or soft tissue restraints, and provocative testing aids in characterizing the problem and predicting surgical findings.[4] Indeed, 90% to 100% of traumatic anterior glenohumeral joint dislocations will result in anterior labral tears and Hill-Sachs deformities of the humerus.[4,17,18] Conversely, multidirectional instability is typically atraumatic and is often seen in patients with repetitive overuse disorders, generalized ligamentous laxity, or systemic connective tissue disorders (e.g., Ehlers-Danlos syndrome, Marfan syndrome).[19,20]

Radiographic evaluation begins with plain films of the shoulder. Anteroposterior and axillary views will confirm dislocation or reduction and detect obvious large bony lesions. MRI will provide additional insights into soft tissue injury involving the labrum, capsule, and surrounding structures (Figure 40-3). We favor the use of MR-arthrography, which may identify subtle injuries not seen on magnetic resonance imaging (MRI) scans performed without intra-articular contrast; arthrography also assists in the assessment of capsular laxity, particularly during the evaluation of the patient with multidirectional instability.[21]

Surgical Indications

The indications for surgical treatment continue to evolve (see Coach's Corner). In general, surgical stabilization procedures are indicated in patients with post-traumatic, recurrent, functionally limiting, or painful glenohumeral joint instability refractory to physical therapy and activity modification. There continues to be enthusiasm and ongoing research into the merits of surgery after a single instability event.

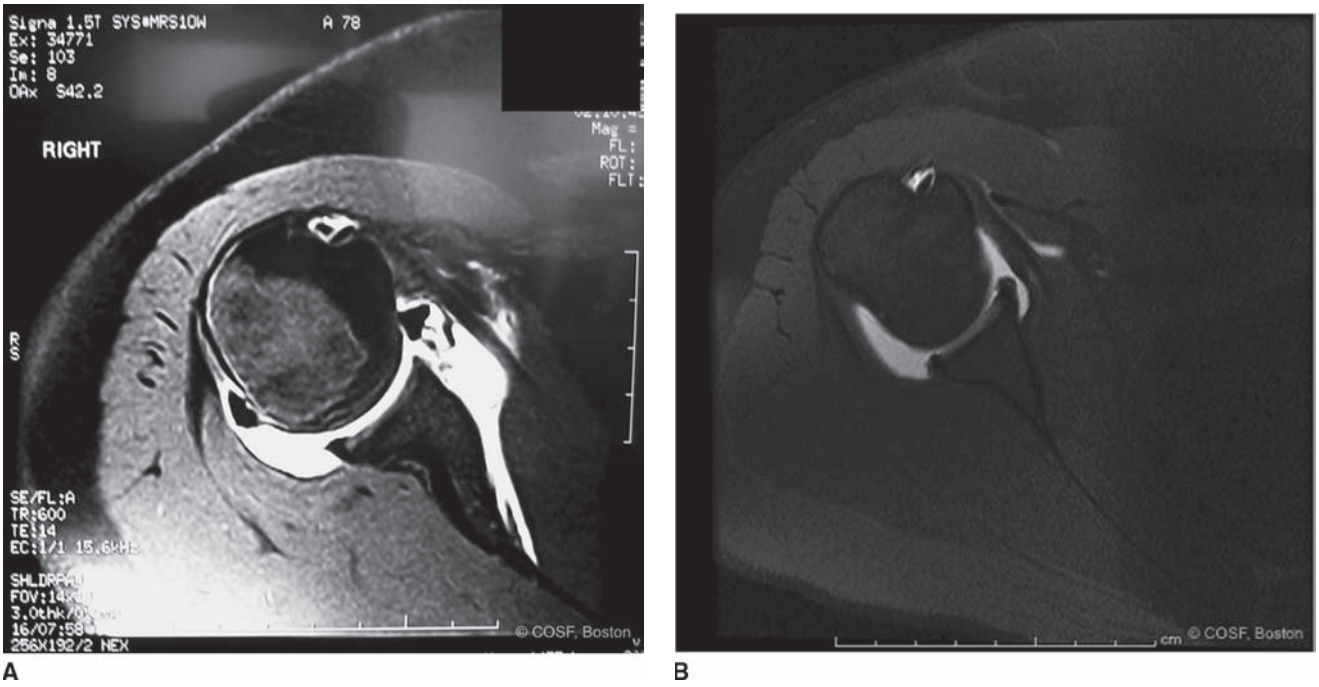
SURGICAL PROCEDURES

Nonoperative Treatment

A pint of sweat will save a gallon of blood.
—General George S. Patton

Following the first traumatic instability event, nonoperative treatment is typically pursued. Following closed reduction of the glenohumeral joint, the shoulder is typically immobilized in a sling for comfort. There is no compelling evidence that prolonged sling immobilization of the shoulder in adduction-internal rotation for longer than what is needed for symptomatic relief lowers the risk of recurrent instability.

Recently, there has been increasing interest in immobilizing the shoulder in external rotation. The rationale is based upon the premise that external rotation



A B

FIGURE 40-3 **A:** Axial MRI arthrography image of an anterior labral tear in the setting of traumatic anterior instability. **B:** Axial MRI arthrography image of a patient with multidirectional instability; note is made of an intact labrum but a capacious and redundant joint capsule anteriorly and posteriorly.

immobilization may tension the anterior soft tissues, thus better reapproximating the torn or avulsed labrum to the glenoid rim. Itoi et al.[22] have demonstrated via dynamic MRI studies that this may be accomplished. Indeed, in a preliminary case-control study and subsequent randomized controlled trial, the relative risk reduction of recurrent instability was 38% in patients treated with external rotation immobilization versus conventional internal rotation sling immobilization.[23–25] The benefit of external rotation immobilization was higher in younger patients. Interestingly, others have not been able to reproduce this experience, suggesting that external rotation immobilization, while theoretically appealing, may not be applicable to all patients.[26,27] Furthermore, external rotation immobilization requires a great deal of patient compliance, given the difficulties in performing everyday activities with the shoulder externally rotated 30 to 45 degrees for 4 weeks.

In general, rehabilitation for the unstable shoulder is based upon progressive resistive strengthening of the dynamic stabilizers of the glenohumeral joint, with emphasis on the rotator cuff and periscapular muscles (trapezius, serratus anterior, rhomboids, levator scapulae)[28,29] (Figure 40-4).

In addition to immobilization and physical therapy, functional bracing may be a helpful adjunct in allowing young athletes to return to higher-risk activities. Buss et al.[30] evaluated the results of 30 adolescent and young adult collegiate athletes who attempted to complete their sports season after a traumatic anterior instability event. Once range of motion and near-symmetric strength were achieved in the affected shoulder, these patients were allowed to participate wearing an orthosis, which prevented hyperabduction and external rotation. Twenty-six of the thirty athletes were able to complete their season, though approximately one-third of the athletes did experience recurrent instability. Interestingly, almost half of the patients in this cohort study elected to pursue surgical stabilization once their season had ended.

Arthroscopic Bankart Repair

In patients with recurrent, functionally limiting or painful instability, surgical stabilization is indicated. Although historically open procedures were safely and effectively performed, arthroscopic stabilization has now become the standard of care. Indeed, comparative studies of open versus arthroscopic stabilization have demonstrated equivalent results and less morbidity with arthroscopic approaches.[31–33]

Arthroscopic anterior stabilization procedures are performed under general anesthesia in the lateral decubitus position. The trunk is allowed to fall back posteriorly approximately 10 degrees to align the glenoid parallel to the floor. An axillary roll is placed on the down side, and care is made to protect all bony prominences, particularly the fibular head and peroneal nerve on the contralateral down leg. Longitudinal and lateral distraction is applied using a traction boom to facilitate positioning and improve visualization; typically 7 to 10 lbs of longitudinal and 7 lbs of lateral distraction are sufficient while avoiding the complications associated with excessive traction. The limb is placed in approximately 40 degrees of abduction and 30 degrees of forward flexion.

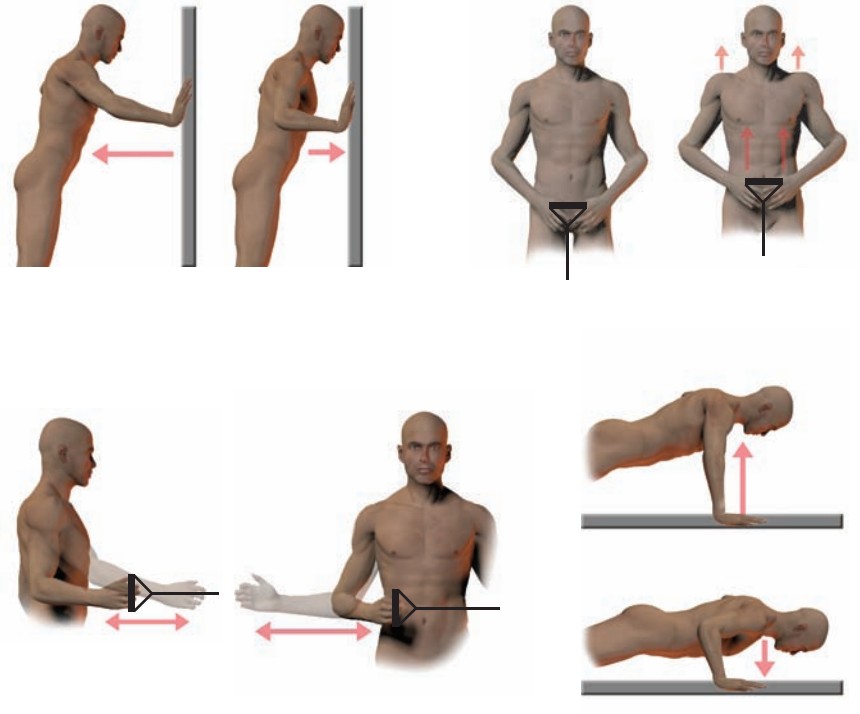


FIGURE 40-4 Illustrations of exercises used during nonoperative treatment for shoulder instability. Emphasis is placed on strengthening deltoid, rotator cuff, serratus anterior, rhomboid, levator scapulae, and trapezius muscles, with appropriate proprioceptive retraining and biofeedback to educate the patient regarding provocative positions.

After the glenohumeral joint is insufflated with 20 mL of saline solution, the skin is incised and a 4.0-mm, 30-degree arthroscope is inserted through a standard posterosuperior portal (Figure 40-5). Arthroscopic survey is performed, and the extent of the labral tear and anterior capsular injury evaluated. Anterosuperior and anteroinferior portals are then placed through the rotator interval using an outside-in technique. In general, the anteroinferior portal is placed more laterally to provide the appropriate "angle of attack" on the glenoid during suture anchor placement. Conversely, the anterosuperior portal is placed more medially to facilitate suture passage and manipulation tangential to the glenoid face. An arthroscopic probe is utilized to confirm the initial survey findings.

Soft tissue preparation is critical to ensure biological healing, regardless of the type of implants or sutures used. In a sequential fashion using arthroscopic elevators, rasps, and shavers, fibrous tissue binding the anterior labrum and capsular tissue is removed, and a bleeding bony surface is created on the anterior glenoid neck. Adequate soft tissue mobilization can be confirmed by the "float" or "suction reduction" sign.[34] With gentle suction from the posterior viewing portal, the anterior capsulolabral tissue should appear to "float" to its anatomic position on the anterior

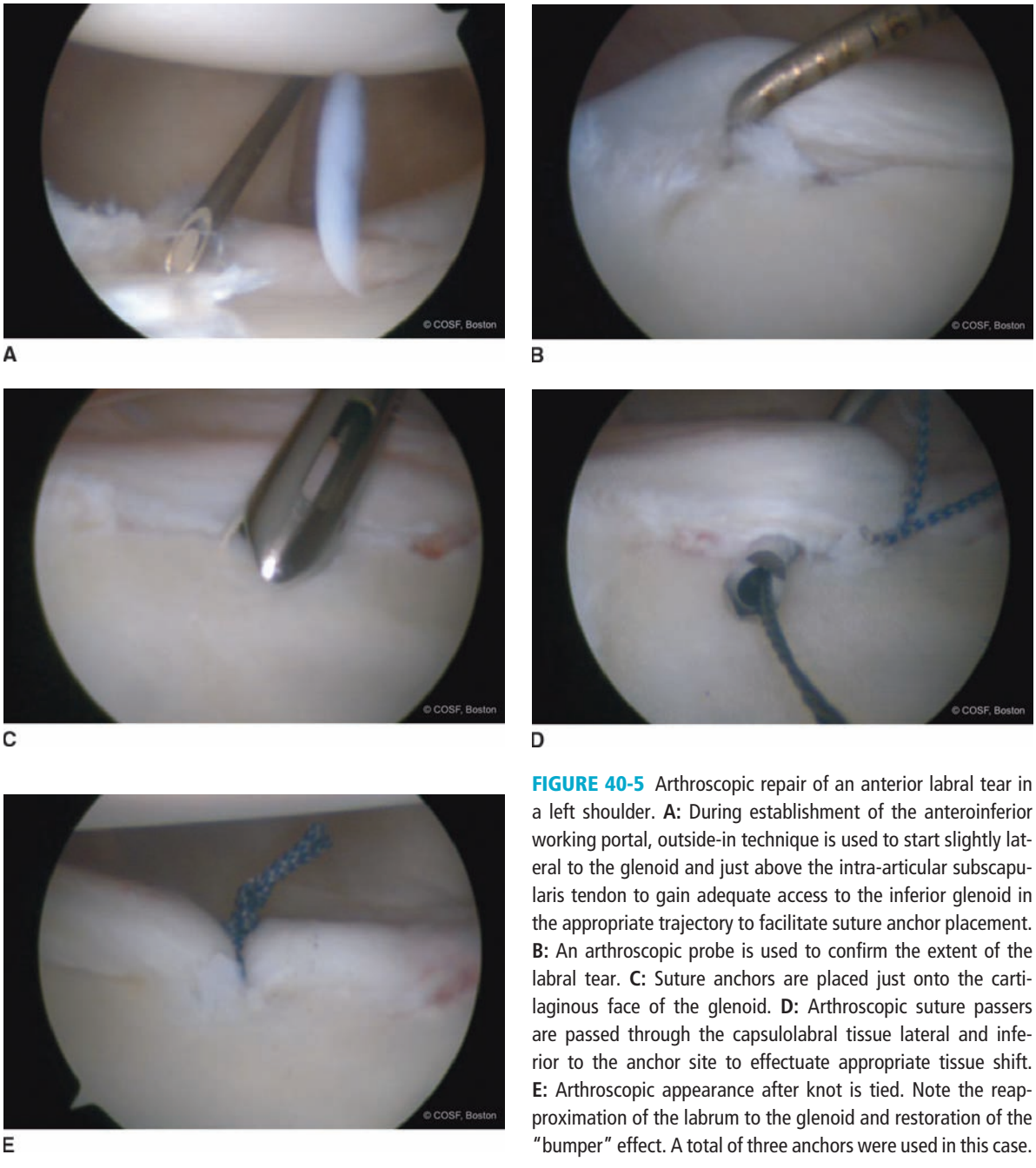


FIGURE 40-5 Arthroscopic repair of an anterior labral tear in a left shoulder. **A:** During establishment of the anteroinferior working portal, outside-in technique is used to start slightly lateral to the glenoid and just above the intra-articular subscapularis tendon to gain adequate access to the inferior glenoid in the appropriate trajectory to facilitate suture anchor placement. **B:** An arthroscopic probe is used to confirm the extent of the labral tear. **C:** Suture anchors are placed just onto the cartilaginous face of the glenoid. **D:** Arthroscopic suture passers are passed through the capsulolabral tissue lateral and inferior to the anchor site to effectuate appropriate tissue shift. **E:** Arthroscopic appearance after knot is tied. Note the reapproximation of the labrum to the glenoid and restoration of the "bumper" effect. A total of three anchors were used in this case.

rim of the glenoid; failure to do so indicates inadequate soft tissue release and persistent medialization of the capsulolabral sleeve.

Once the soft tissues have been adequately prepared, the repair is performed. Biocomposite suture anchors (Bio-SutureTaks, Arthrex, Inc., Naples, FL) are placed just on the chondral face of the glenoid, beginning in the most inferior position (typically 5:00 or 7:00). Sutures are passed through the adjacent capsulolabral tissue just medial and inferior to the anchor, thereby effectuating both an "east-to-west" and a "south-to-north" shift. Knots are tied in the standard fashion, and the process is repeated superiorly until the labral repair is complete.[35] In many situations, placing the camera in the anterosuperior portal and using the posterior portal for suture shuttling will improve visualization and facilitate accurate anchor placement and suture passage, particularly in anterior labral periosteal sleeve avulsion (ALPSA) lesions.[36,37] In cases where the anterior labral tear extends to the level of the biceps root, a superior labral repair is performed as well.[38] At the conclusion of the procedure, a soft tissue "bumper" should be restored, and the previously noted "drive through" sign obliterated. Skin portals are closed using interrupted nylon sutures, and the limb is placed in a sling and swathe.

Patients remain sling immobilized for the first 4 weeks postoperatively, doing pendulum exercises only. After postoperative week 4, gentle range-of-motion exercises are initiated. An example of our current postoperative rehabilitation protocol is seen in Figure 40-6.

Posterior Instability

Pure posterior instability is much less common than anterior instability, representing 5% of shoulder instability in children and adolescents. Traditionally, traumatic posterior instability was thought to be seen only in patients with a history of epilepsy or electrocution. Given the dramatic increase in high-energy sports participation in younger children, however, posterior glenohumeral joint instability is becoming more common (e.g., football, weightlifting, gymnastics, cheerleading, skateboarding). In cases where posterior instability causes pain or functional limitations refractory to physical therapy and activity modification, arthroscopic stabilization may be performed.[39]

While posterior stabilizations may be performed via open, anteroinferior capsular shift or posterior capsulorrhaphy procedures, arthroscopic stabilization may provide the best visualization and access for appropriate soft tissue reconstruction. Patients are placed in the lateral decubitus position with the affected limb suspended in overhead longitudinal and lateral distraction. While similar to positioning for anterior arthroscopic labral repairs, judicious adjustment of shoulder position (e.g., more lateral

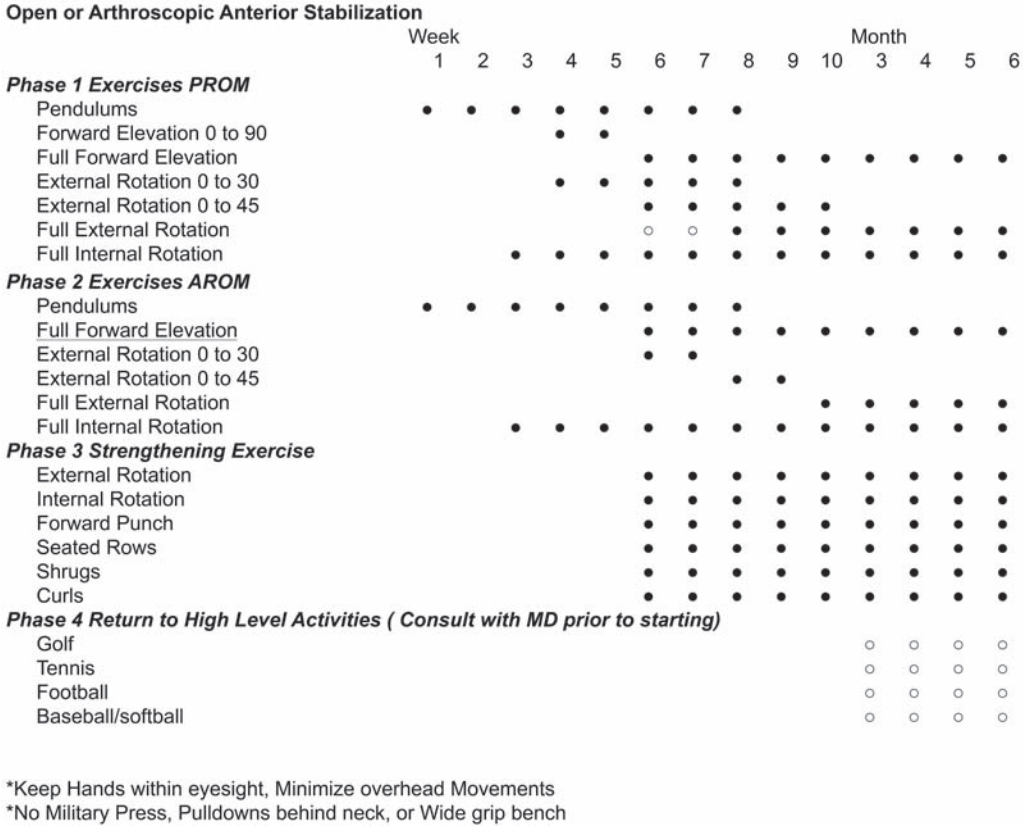


FIGURE 40-6 Example of a rehabilitative protocol following arthroscopic anterior shoulder stabilization.

distraction, less forward flexion) may improve visualization of the posterior joint space. After arthroscopic survey and establishment of anterosuperior and anteroinferior portals within the rotator interval, the camera is moved to the anterosuperior portal. Soft tissue preparation is performed in the standard fashion. Capsulolabral tissue is mobilized and the bony glenoid prepared as in anterior Bankart repairs. In cases where the labrum is intact and a capsulorrhaphy is to be performed, the capsule is "roughened" using arthroscopic rasps or shavers run in reverse without suction to stimulate punctate bleeding and a healing response. Suture anchors are placed sequentially from inferior to superior, and sutures are shuttled in the standard fashion through the capsulolabral tissues to effectuate an inferior-to-superior and medial-to-lateral shift of tissue. (In cases of posterior capsulorrhaphy without labral repair, plication "pinch-tuck" sutures are placed from inferior to superior and "parked" in the anteroinferior working portal.) After all sutures are placed, they are tied sequentially from inferior to superior, completing the soft tissue repair.

Two technical points are worth noting. First, we do not typically utilize a posteroinferior 7:00 portal; adequate access to the posteroinferior glenoid and capsule can be achieved via the posterosuperior and anteroinferior portals without conferring additional risk to the axillary nerve. Second, sutures are passed but *not tied* until all planned anchors/sutures have been placed. This prevents the frequent difficulties in both visualization and intra-articular maneuvering that occur if the posterior capsule is closed prior to the placement of all sutures.

Postoperatively patients are placed in sling immobilization, and the rehabilitation protocol is similar to anterior instability reconstruction.

◆ Latarjet Procedure

If you are going to be a successful duck hunter, you must go where the ducks are.
—Paul "Bear" Bryant

While arthroscopy is a powerful tool, open surgical reconstruction remains the standard for shoulder instability associated with significant glenoid deficiency. The answer to the question, "How much bone loss is too much?" however, continues to be investigated. Lo et al.[40] initially proposed that loss of 25% to 27% of the glenoid width constituted a glenoid defect worthy of bony augmentation. Itoi et al.[41] proposed that an osseous defect in which the width was 21% of the glenoid length was of sufficient magnitude to result in persistent instability after Bankart repair alone. Gerber and Nyffeler[42] had similar conclusions, demonstrating that loss of more than half of the glenoid width resulted in marked decrease in resistance to dislocation. Finally, Yamamoto et al.[43] demonstrated in a cadaveric model that an anterior defect of 20% of the glenoid length (6 mm) resulted in dramatically decreased joint stability.

In cases of critical glenoid deficiency, bony augmentation procedures are indicated. While there have been a plethora of techniques proposed, the Latarjet procedure remains our current operation of choice.[44,45] This procedure utilizes the coracoid process with attached conjoined tendon as a bone graft affixed to the anterior-inferior glenoid. Stability is imparted by the increased articular arc of the glenoid as well as the "sling effect" of the conjoined tendon across the anterior-inferior glenohumeral joint (Figure 40-7).

Patients are placed in the modified beach chair position; an arm holder or positioner is used if available. Initial arthroscopic evaluation is performed to assess for associated pathology and to confirm the severity of bone loss. While various measures have been utilized, perhaps the easiest and most reliable is measuring the distance from the "bare spot" of the glenoid to the anterior glenoid rim. If this distance is <4 to 6 mm, consideration should be made for Latarjet reconstruction. (Alternatively, the percentage of bone loss may be estimated as 1 – (distance from bare spot to posterior rim + distance from bare spot to anterior rim/2 × distance from bare spot to posterior rim) (Figure 40-8).

After arthroscopic confirmation, an open Latarjet procedure is performed. The shoulder is approached via an anterior incision, based medially over the coracoid process. After the deltopectoral interval is developed and cephalic vein taken laterally, the coracoid process is identified. A spiked Hohmann or Cobra retractor is placed superiorly over the coracoid in the region of the coracoclavicular ligaments. With abduction and external rotation of the shoulder, the coracoacromial ligament is divided, leaving a 1-cm cuff of tissue attached to the bone for later use. The shoulder is then adducted and internally rotated, and the pectoralis minor insertion is released off the coracoid. Repeat abduction and external rotation will then allow for easy division of the coracohumeral ligament. Blunt dissection with the assistance of a peanut is then performed to free up adjacent adhesions. The entire coracoid must be easily visualized, often more proximally than initially believed.

A 90-degree-angled saw is then used to osteotomize the coracoid from lateral to medial, just distal to the coracoclavicular ligament insertions. The length of coracoid bone should be approximately 3 cm. Once the bony cut is completed, the osteotomy fragment is mobilized, preserving the conjoined tendon attachment and protecting the musculocutaneous nerve, which enters the coracobrachialis approximately 4 to 5 cm distal to the coracoid tip. With a hemostat or Kocher clamp placed and the coracoid reflected inferiorly, the deep surface is exposed and may be decorticated and flattened with the microsagittal saw. Two drill holes are created from the deep to superficial surface for subsequent screw fixation; electrocautery or marking pen is used to mark the exit holes on the superficial surface.

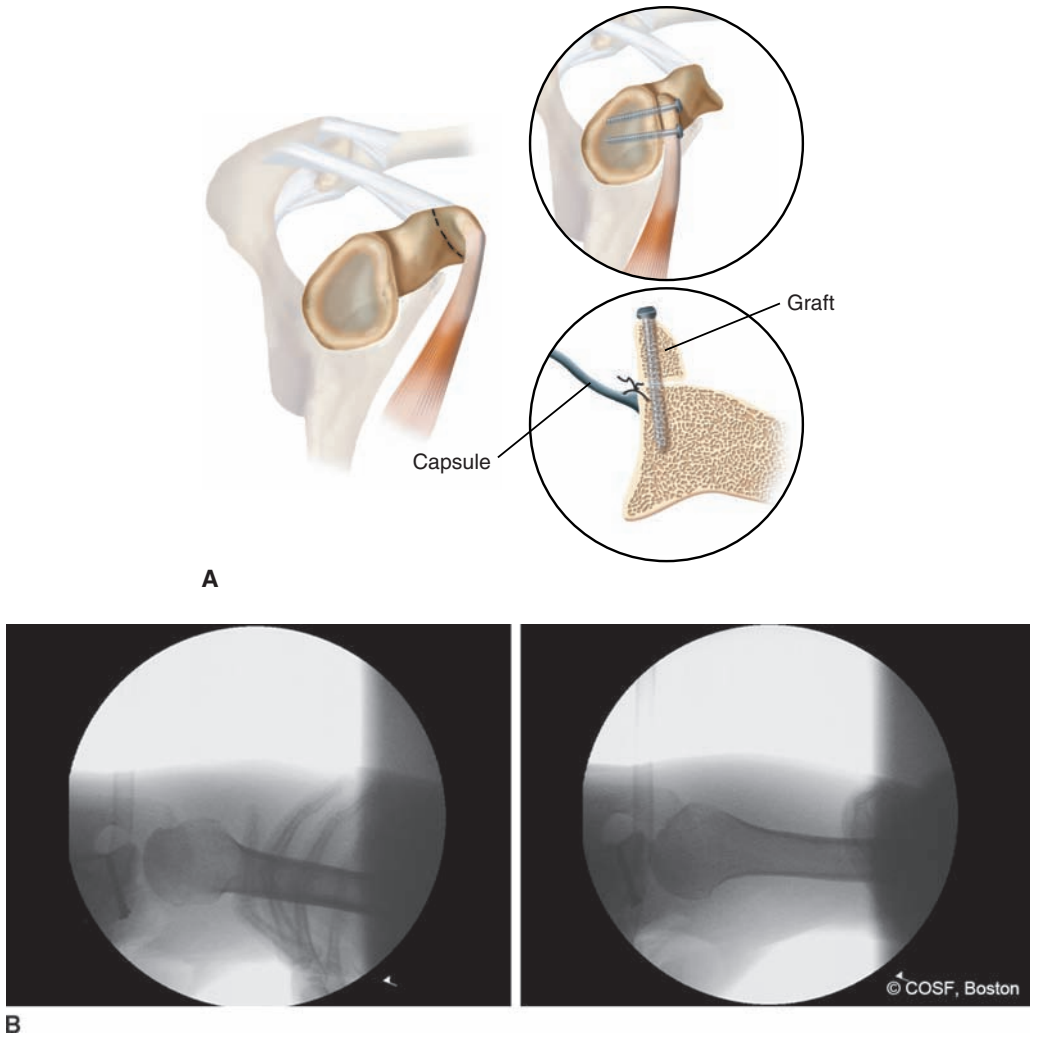


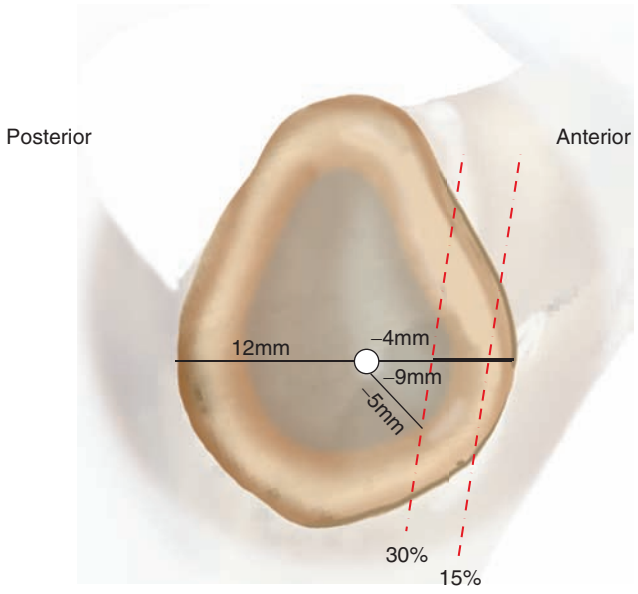
FIGURE 40-7 The modified Latarjet procedure. **A:** Schematic diagram depicting use of the coracoid process and attached conjoined tendon to augment the anterior glenoid. **B:** Intraoperative fluoroscopic images following Latarjet procedure. Note is made of appropriate screw fixation and precise placement of the coracoid bone block.

The glenoid is then exposed with the shoulder in maximal external rotation. A transverse split in the subscapularis is made between the superior two-thirds and inferior one-third. Dissection is performed in the plane between the subscapularis and joint capsule, medially to the subscapularis fossa and laterally to the lesser tuberosity. A spiked Hohmann or similar retractor is then placed in the subscapularis fossa. The shoulder is moved back to neutral rotation, and a vertical capsulotomy is made. Typically, the deficient anterior capsule and labrum, if present, is debrided, and the recipient bed is prepared until bleeding bone is seen.

With the humerus in internal rotation, the graft is positioned with *great care* taken to make the lateral border flush with the articular surface. Lateralization of the graft will result in articular incongruity and subsequent arthrosis; medial placement will result in suboptimal augmentation of the glenoid joint surface. Using the previously placed drill holes in the coracoid, guide pins from 3.5- or 4.0-mm cannulated headed screws are placed. The guide pins are overdrilled and screw fixation performed. Screws are typically 34 to 36 mm in length in older adolescents and young adults. If desired, intraoperative anteroposterior and axillary fluoroscopic imaging is used to confirm appropriate graft placement and screw length, and stability is confirmed (Figure 40-7B). The previously incised capsule is then sewn to the coracoacromial ligament stump with the shoulder placed in external rotation. The wound is then closed in layers.

◆◆ Multidirectional Instability

Historically, nonoperative treatment in the form of physical therapy and activity modification has been the standard of care for patients with atraumatic, multidirectional glenohumeral joint instability.[29,46–48] However, changes in the understanding of the characteristics of, natural history



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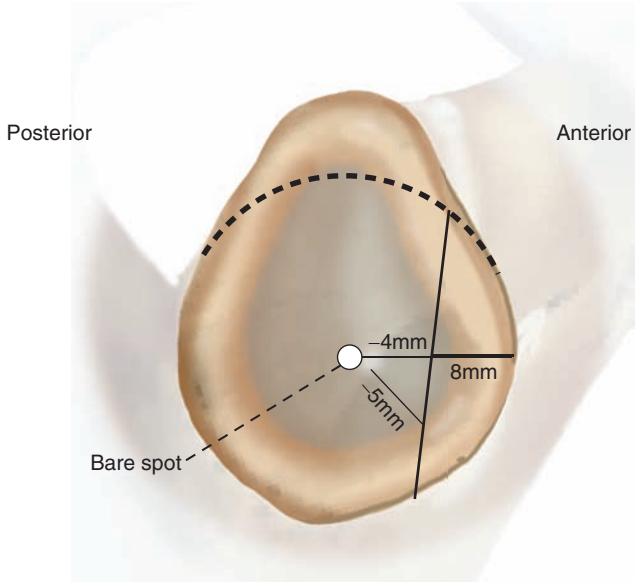

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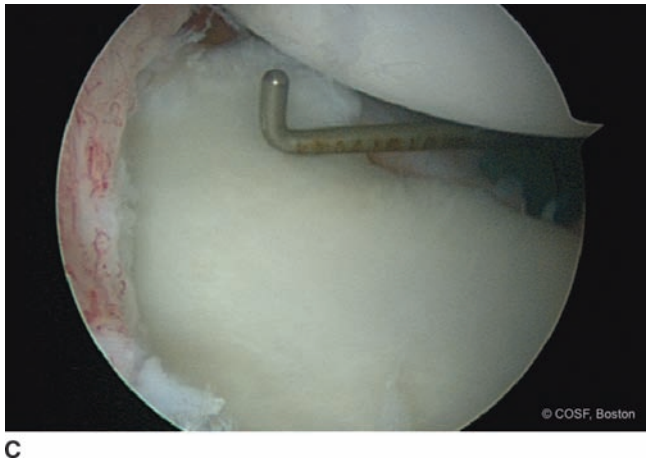

C

FIGURE 40-8 **A:** Schematic diagram depicting measurements of "critical" bone loss of the anterior glenoid. **B:** Schematic diagram illustrating arthroscopic measurement of anterior glenoid bone loss from the "bare spot" of the glenoid. **C:** Intraoperative arthroscopy image of a left shoulder viewed from the posterosuperior portal. The tip of the calibrated probe is placed on the glenoid "bare spot." Note is made of obvious anteroinferior glenoid insufficiency.

of, and potential surgical options for multidirectional instability have altered treatment considerations.

First, not all multidirectional instability is the same. Patients with generalized ligamentous laxity and a predominant direction of *in*voluntary instability are very different patients from voluntary multidirectional instability or patients with multidirectional instability in the setting of connective tissue disorders (e.g., Ehlers-Danlos syndrome). Careful history and physical examinations at multiple office visits over time will allow for characterization of the type of multidirectional instability in each individual patient.

Second, not all patients with multidirectional instability respond adequately to nonoperative treatment. Misamore et al.[49] have previously published a longitudinal cohort study of young athletic patients with multidirectional instability. In their series, 19 of 36 patients had poor results according to the modified Rowe scale with nonsurgical treatment at midterm follow-up. Interestingly, those patients who responded to physical therapy did so rapidly, within 3 months of initiation of treatment.

Finally, advances in surgical techniques have allowed for improved surgical outcomes, even in cases of multidirectional instability.[50,51] Arthroscopy allows the ability to visualize the entire glenohumeral joint and surrounding soft tissue structures, without the morbidity of traditional open anterior or posterior approaches. Increasing understanding of the anatomy and biomechanics of the shoulder, combined with newer generation suture anchors and suture passage devices, has allowed for selective stabilizing procedures aimed at the cause of instability; gone are the days of the anteroinferior shift for posterior or multidirectional instability.

Given these considerations, surgical treatment of multidirectional instability is most likely to "succeed" in patients with the following: (1) involuntary instability, (2) unilateral involvement, (3) radiographically confirmed anatomic pathology (e.g., labral tears, capsular redundancy), (4)

diffuse laxity with a predominant direction of instability, (5) absence of secondary gain, and (6) lack of underlying connective tissue disorder.

While open approaches to multidirectional instability are effective, arthroscopic treatment has increasingly become the current standard of care.[52–55] Arthroscopic techniques allow for greater visualization of the glenohumeral joint and surrounding soft tissue structures and avoid the morbidity associated with dividing or splitting the subscapularis. Furthermore, selective tightening of the offending structures may be done in an anatomically rigorous fashion.

Arthroscopic stabilization of multidirectional instability is performed in the lateral decubitus position, as described above. Judicious positioning of the traction boom during the case will allow for improved visualization of the anterior and posterior soft tissue structures. The scope is initially introduced through the posterosuperior portal, which is placed more laterally and inferiorly to allow for posterior capsulorrhaphy. After the standard anteroinferior and anterosuperior portals are placed and the joint explored, confirmation is made regarding the presence or absence of associated labral tears.[50] Often a "pedestal" sign is seen in cases of multidirectional instability, indicative of a patulous and redundant capsule (Figure 40-9).

Posterior capsulorrhaphy (or labral repair) is performed first. The camera is switched to the anterosuperior portal. The posterior and posteroinferior capsule is then roughened using arthroscopic rasps placed through the posterosuperior portal; alternatively, an arthroscopic shaver run forward without suction may be used to gently roughen the posterior capsule, stimulating a bleeding response needed for biological healing. In cases without associated labral tears, capsulorrhaphy may be performed using a "pinch-tuck" technique.[56,57] Sutures are placed first through capsular tissue approximately 5 to 10 mm from the labral margin, then passed again through the labrum completing the imbrication of capsular tissue. Once the pinch-tuck suture is passed, the suture ends are brought out and stored in the anteroinferior portal prior to tying. (If knots are tied as sutures are passed, the posterior joint space is progressively obliterated, making it difficult to pass the more superior sutures and often forcing out the posterior cannula.) Sequential imbricating sutures are passed from inferior to superior until all the desired posterior sutures have been placed. Sutures are then tied sequentially from inferior to superior, completing the posterior capsulorrhaphy.

The camera is then switched to the posterosuperior viewing portal. In a similar fashion, the anterior capsule is stimulated with a rasp or shaver, promoting a bleeding response. Sutures are passed and tied sequentially from inferior to superior in a pinch-tuck fashion. Upon completion of the repair, the redundant capsule is imbricated near-circumferentially and stability restored.

POSTOPERATIVE

The secret to winning is constant, consistent management.
—Tom Landry

Patients are typically immobilized in sling and swathe for 4 weeks, during which pendulum exercises are performed in addition to gentle elbow, forearm, and wrist motion (Figure 40-6). Physical therapy is initiated after the fourth postoperative week, beginning with gradual range-of-motion exercises. Forward flexion to 90 degrees, lateral abduction in the plane of the scapula, and external rotation to 30 degrees active exercises are performed from the fourth to sixth postoperative week. After postoperative week 6, motion is advanced and strengthening initiated.

ANTICIPATED RESULTS

There continue to be challenges in the assessment of outcomes following treatment for shoulder instability. The broad spectrum of laxity and instability, varying surgical techniques, and patient-related factors (e.g., age, compliance with rehabilitation, functional or sports-specific demands, etc.) may all cloud reports of anticipated results. Furthermore, patient-based outcome instruments are varied and not universally utilized.[58] Finally, the majority of published information on shoulder stabilization pertains to adults. The applicability of this information to pediatric and adolescent patients is unclear.

The pediatric information available suggests, however, that surgical stabilization of glenohumeral joint instability is safe and effective, with high patient satisfaction and return to sports rates.[33,59] Young, active patients should be counseled that up to a 20% risk of recurrent instability exists, even with contemporary stabilization techniques.

COMPLICATIONS

The difference between failure and success is doing a thing nearly right and doing it exactly right.
—Edward C. Simmons

Despite the advances in knowledge and techniques of surgical stabilization, recurrent instability does occur. In general, recurrent glenohumeral joint dislocations occur for one (or more) of four reasons: (1) poor patient selection (wrong patient); (2) inappropriate procedure, given the etiology of instability (wrong procedure); (3) technical failures (right patient, right procedure, poorly executed); and (4) true traumatic recurrent instability (bad luck).[60–62]

Appropriate patient selection is critical. Careful preoperative history and physical examination, while

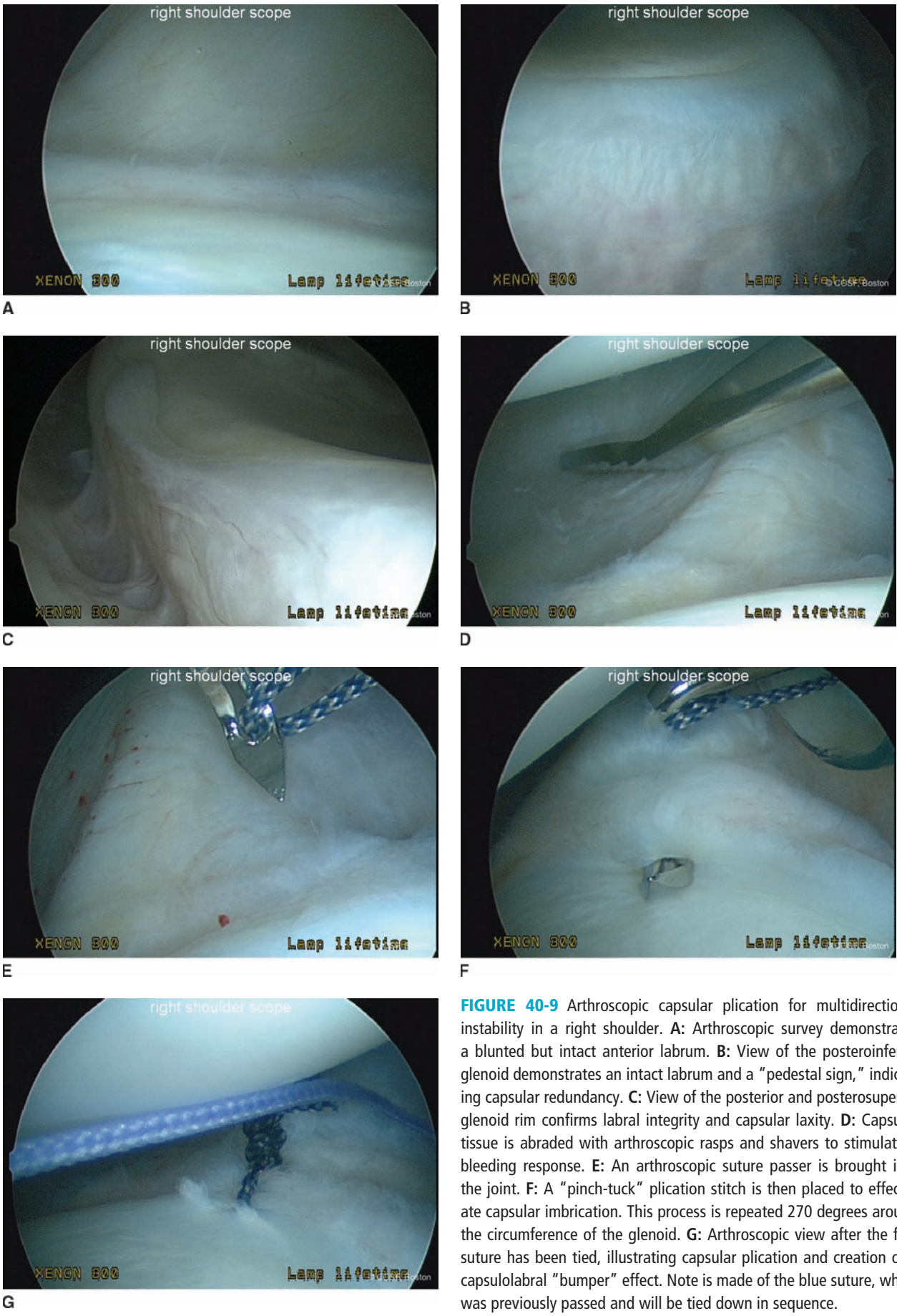

FIGURE 40-9 Arthroscopic capsular plication for multidirectional instability in a right shoulder. **A:** Arthroscopic survey demonstrates a blunted but intact anterior labrum. **B:** View of the posteroinferior glenoid demonstrates an intact labrum and a "pedestal sign," indicating capsular redundancy. **C:** View of the posterior and posterosuperior glenoid rim confirms labral integrity and capsular laxity. **D:** Capsular tissue is abraded with arthroscopic rasps and shavers to stimulate a bleeding response. **E:** An arthroscopic suture passer is brought into the joint. **F:** A "pinch-tuck" plication stitch is then placed to effectuate capsular imbrication. This process is repeated 270 degrees around the circumference of the glenoid. **G:** Arthroscopic view after the first suture has been tied, illustrating capsular plication and creation of a capsulolabral "bumper" effect. Note is made of the blue suture, which was previously passed and will be tied down in sequence.

time-consuming, are essential. As pediatric upper limb surgeons, we take care of patients, not pictures; therefore, decision making based upon anatomic imaging only can lead to suboptimal results. Great care should be taken prior to operating on any patient with voluntary instability, diffuse ligamentous laxity or collagen disorders, psychological or secondary gain issues, and inability to comply with appropriate postoperative rehabilitation and activity modification.[63,64] This is particularly relevant in the young adolescent patient population.

Once appropriate patient selection is achieved, it is imperative to tailor the surgery to the pathoanatomy. Arthroscopic labral repair is not applicable to all patients. In patients with true functionally limiting posterior or multidirectional instability, a posterior or 270-degree capsulorrhaphy should be done. Similarly, in patients with glenoid bone loss, Latarjet or other bone grafting procedures should be done to address the bony deficiency. Finally, in cases of humeral avulsions of the glenohumeral ligament, appropriate humeral-sided repairs, be they arthroscopic or open, are needed to address the underlying pathoanatomy. Failure to do so will result in recurrence.

Technically, a number of intraoperative maneuvers bear mention. In cases of labral repairs or capsulorrhaphy, adequate soft tissue and bony preparation is far more important than the number or type of anchors or sutures used. A bleeding glenoid neck must be prepared to allow for biological healing. Adequate release and mobilization of the capsulolabral tissue are needed, particularly in ALPSA lesions in which the labrum is scarred and medialized. The arthroscopic "float" or "suction reduction" sign can provide confirmation of adequate soft tissue liberation. In addition, suture anchors must be positioned just onto the chondral surface of the glenoid and sutures passed in a way to promote an inferior-to-superior as well as medial-to-lateral shifting of tissue. The current standard is to use bioabsorbable or biocomposite anchors, avoiding metallic implants or tacks. In general, three or more points of suture fixation are needed to promote adequate repair security.[65,66] Thermal capsulorrhaphy and the use of intra-articular pain pumps are to be discouraged, due to the risk of early recurrent instability and chondrolysis.[67–69] Awareness of the proximity of the axillary nerve to the inferior glenohumeral capsule is important to avoid iatrogenic nerve injury during suture passage.[70,71] Finally, judicious capsulorrhaphy will avoid excessive tightening of the anterior tissues and persistent postoperative stiffness.[72]

Finally, despite correct patient selection, choice of procedure, and technical excellence, recurrent instability does occur in up to 20% of patients.[59] Certainly this is common in the young, high-risk, athletic patient population. In these situations, careful clinical and radiographic evaluation is needed to ascertain the etiology of recurrent instability and the best strategy of revision reconstruction.

CASE OUTCOME

After extensive discussion with the patient and family regarding treatment options, including attendant risks and benefits, the decision was made for surgical intervention. Arthroscopic Bankart repair was performed, with anatomic repair of the capsulolabral complex (Figure 40-5). Following immobilization and rehabilitation, the patient returned to full sports participation, including weightlifting and football, by 6 months postoperatively. To date, there have been no recurrent instability events.

SUMMARY

Shoulder instability remains a common condition cared for by the pediatric hand and upper extremity surgeon. Careful history, physical examination, and radiographic interpretation will allow for characterization of the etiology, direction, and severity of instability. In cases of failed nonoperative care, surgical treatment results in successful stabilization in the majority of patients. Surgical techniques should be tailored to the direction (anterior, posterior, multidirectional) and pertinent pathoanatomy (labral tear, capsular redundancy, glenoid deficiency) to maximize outcomes.

SIDEBAR

Arthroscopic Setup, Portals, and Techniques

For glenohumeral joint instability surgery, shoulder arthroscopy is performed in the lateral decubitus position. Advantages of this include the ability to impart longitudinal and lateral distraction without an assistant, and thus easy visualization throughout the shoulder joint, including the axillary pouch and posterior joint space. The thorax is stabilized with a beanbag, rolled posteriorly approximately 10 degrees to flatten the glenoid face parallel to the floor. Care is taken to adequately pad the contralateral lower limb, particularly around the fibular head and peroneal nerve, to avoid compression neuropathy. An axillary roll is also placed to protect the brachial plexus. The operative limb is typically positioned in approximately 40 degrees of abduction, 20 to 30 degrees of forward flexion, and neutral rotation.

We typically begin with a standard posterosuperior viewing portal, placed 2 to 3 cm inferior and 1 to 2 cm medial to the posterolateral angle of the acromion, in the "posterior soft spot." After the arthroscope is introduced into the joint, outside-in technique is utilized to create an anterosuperior and anteroinferior portal through the rotator interval. For the standard labral repair, the anteroinferior portal is created to allow a lateral-to-medial angle to facilitate anchor

placement on the glenoid face. Conversely, the anterosuperior portal is made in a trajectory parallel to the glenoid face to allow for easy suture shuttling. During capsulolabral preparation and anchor placement, the camera may be placed in the anterosuperior portal to provide a more direct "bird's eye" view of the anterior glenoid.

As cited above, we typically utilize a single posterior portal, even in cases of 270-degree capsulorrhaphy or posterior labral repairs. A low posterior portal is unnecessary in our experience and only increases the risk of iatrogenic axillary nerve injury.

COACH'S CORNER

Surgery for the First-time Dislocator? The Art and Science of Pediatric Orthopaedic Surgery

There continues to be great controversy regarding the optimal management for the first-time dislocator. In general, there are early operators and late operators.

Early operators advocate surgical stabilization for the first-time adolescent dislocator, typically via arthroscopic Bankart repair. Early operators contend that the risk of recurrent instability is too high to warrant nonoperative treatment. They further argue that repeated instability events result in more time out of sports and may lead to greater severity of labral, capsular, chondral, and even bony injury. Early operators point to the published randomized studies, which suggest that surgery after the first dislocation is safe, effective, and leads to greater function and quality of life.[11,73–76]

Late operators support nonoperative treatment for the adolescent first-time dislocator, typically in the form of physical therapy and activity modification. Late operators contend that while the risk of recurrent instability exists, between 20% and 50% of patients will never go on to request or benefit from surgical stabilization.[7,12] Indeed, it is difficult to predict which adolescent will go on to develop recurrent instability, and the existing literature does not provide clear risk factors.[7–10] Late operators also argue that if surgical stabilization is performed on every first-time adolescent dislocator, thousands of unnecessary procedures would be performed on growing children and adolescents for no potential gain. Late operators also point out that arthroscopic Bankart repair, while safe, is not a panacea, citing the 7% to 20% risk of recurrent instability after labral repair.[59]

Wise, experienced coaches provide additional insights into this ongoing debate, understanding the psyche of the young athlete. These surgeon-coaches tell us that if a stabilization procedure is performed shortly after the first dislocation and there is recurrence, the patient will blame the surgeon for technical failure. Conversely, if an adolescent is initially treated nonoperatively and sustains a recurrent dislocation—particularly after returning to sports—there is an epiphany. The patient realizes that he/she has a real, anatomic injury. The patient takes greater ownership of his/her injury and the steps required to get better. The patient, parents, trainers, and athletic coaches understand the risks and benefits of surgical intervention and are more invested in and dedicated to the postoperative rehabilitative process.

We believe in both the conclusions of science and the wisdom of experience. In general, we advocate for initial nonoperative care for the adolescent first-time dislocator, providing counsel about the natural history and risk of recurrent instability. In patients who are particularly at risk, who cannot afford the morbidity or time out from potential future dislocations, and who understand the risks and benefits of early surgery, arthroscopic stabilization after the first dislocation is offered. For example, early surgery might be offered to a motivated and compliant nationally ranked basketball player in his junior year, given the desire to win an athletic scholarship for collegiate participation.

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CHAPTER

41

The Thrower's Elbow

CASE PRESENTATION

A 12-year-old youth baseball pitcher comes for evaluation of lateral elbow pain. He reports having soreness when pitching for the past 6 months but continued to participate in both school and town baseball teams. At his last outing, he reports having sudden onset of increased lateral elbow pain associated with swelling and elbow stiffness. He denies distal numbness, weakness, or tingling. He now presents for first clinical evaluation. Radiographs were interpreted as normal. Magnetic resonance imaging (MRI) studies are shown in Figure 41-1.

CLINICAL QUESTIONS

- What are the causes of medial and lateral elbow pain in the young throwing athlete?
- What is "osteochondritis dissecans (OCD)"? What causes it? How is it different from Panner disease?
- Is pitching causative? What guidelines can be offered regarding how much pitching/throwing is safe and appropriate?
- How do these patients present?
- How is OCD classified?
- What are the indications for surgical treatment?
- What are the anticipated results of surgery for OCD?

THE FUNDAMENTALS

Sooner or later the arm goes bad. It has to. …Sooner or later you have to start pitching in pain.
—Whitey Ford

As participation in youth sports has increased, so too, it seems, has the prevalence of overuse injuries of the elbow. Among the various causes of lateral elbow pain in the young athlete is OCD of the capitellum. Most commonly seen in young throwers and gymnasts, OCD of the elbow is a common cause of pain, disability, and long-term impairment in the young, growing athlete.[1,2] Medial elbow pain is also common and may be due to medial epicondylar apophysitis (see Chapter 39), ulnar collateral ligament (UCL) insufficiency, flexor-pronator tendinosis, and ulnar neuritis.

Etiology and Epidemiology

In general, OCD of the elbow results from excessive and repetitive compressive and shear forces across the radiocapitellar (RC) articulation in young, skeletally immature athletes. In the preadolescent and adolescent elbow, the vascular supply to the capitellar chondroepiphysis is tenuous, arising mainly from posterior perforating vessels and supplemented by limited terminal branches of the interosseous recurrent, middle collateral, radial collateral, and radial recurrent arteries (Figure 41-2).[3–8] Given the forces imparted across the lateral elbow—during late cocking and early acceleration phases of throwing in the pitcher, for example, or during handsprings and vaulting in the young gymnast—limitations in vascularity result in the inability to heal after repetitive microtrauma.[9] The subchondral bone fails, and the overlying cartilaginous articular surface is compromised. When left unchecked, this may lead to fragmentation and structural failure of the capitellar cartilage, resulting in loose body formation.[10,11] Despite its name, inflammation does not play a role in the pathophysiology of elbow OCD.[12]

Panner disease refers to an "osteochondrosis" of the capitellum. Similar to the other osteochondroses of the femoral head (Legg-Calve-Perthes disease), navicular (Kohler disease), and scaphoid (Preiser disease), Panner disease typically affects the entire capitellar ossification center in boys under the age of 10 years.[4,13–17] The clinical presentation suggests that Panner's may be due to repetitive microtrauma to the immature capitellar secondary center of ossification, which is vulnerable due to a host of hormonal, nutritional, and mechanical factors.[4,5,8]

While the risk factors may be similar, Panner's is distinguished from OCD by a number of clinical differences.[8] First, Panner's tends to affect patients in the first decade of life, whereas the peak age for OCD is typically between 10 and 14 years of age. Second,

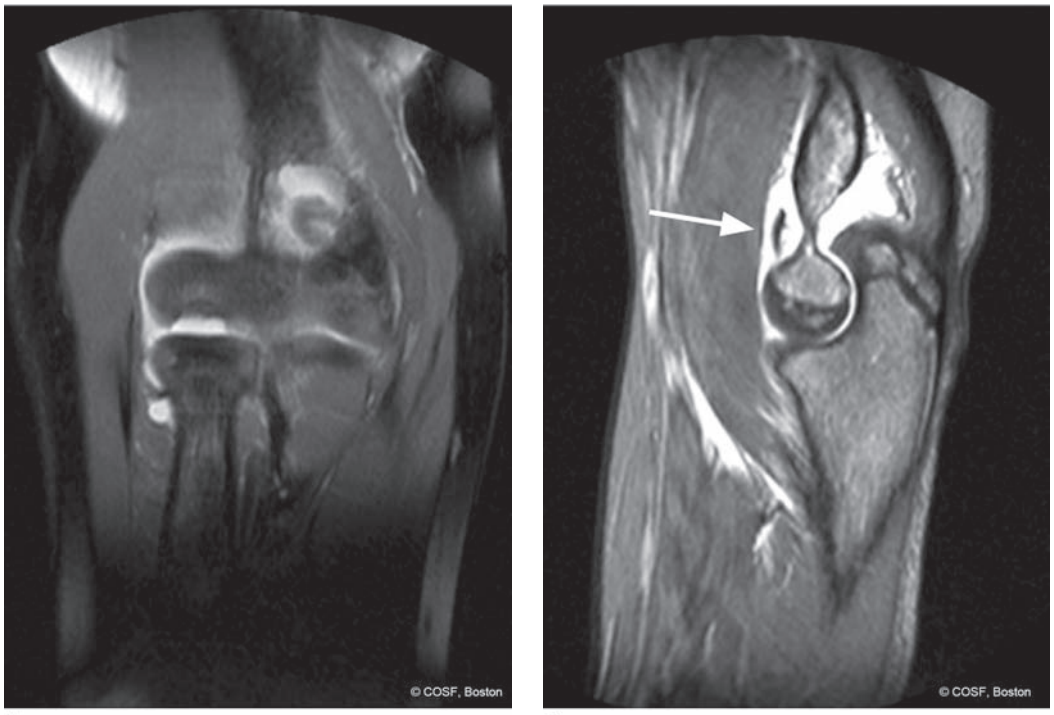


FIGURE 41-1 **A:** Coronal FSE PD MRI image demonstrates a capitellar osteochondral defect. **B:** Sagittal FSE IR MRI image reveals an intra-articular loose body in the anterior compartment of the elbow.

radiographically Panner's involves the entire capitellar ossification center, while OCD lesions of the capitellum are more anatomically distinct, involving a specific part of the articular surface.[18] Finally, Panner's is thought to be a self-limited, self-resolving disease process, in contrast to OCD lesions, which when allowed to progress to fragment instability, have poor healing potential. Despite these distinct clinical features, many still believe that Panner's and OCD represent different aspects of the same clinical entity.[19]

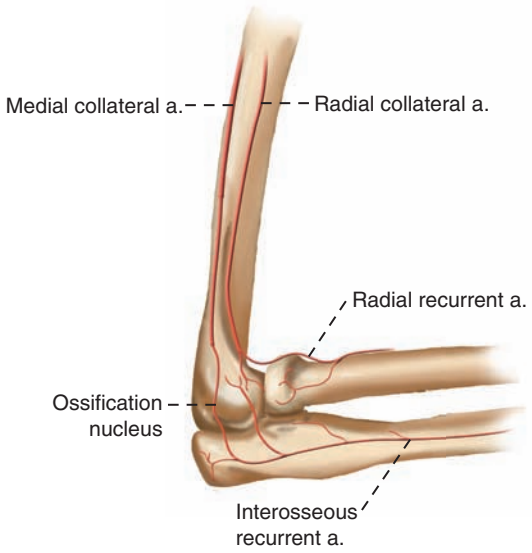


FIGURE 41-2 Schematic diagram of the vascular anatomy to the lateral elbow.

Little epidemiological data are available regarding the true incidence or prevalence of OCD. Prior studies by Lyman et al.[20] have clearly demonstrated that approximately a quarter of all youth baseball pitchers will report elbow pain during a baseball season. Presumably, a considerable proportion of these complaints will be due to OCD.[21] Until more thorough screening and longitudinal observational studies are performed, the exact frequency with which OCD occurs will remain unknown.

Clinical Evaluation

Over 90% of patients with OCD will present with lateral elbow pain. While often casually attributed to lateral epicondylitis or "Little Leaguer's elbow," careful history and examination will elucidate that the location of the pain is in the capitellum, not the lateral epicondyle or extensor-supinator mass (Figure 41-3). Direct palpation over the capitellum, which can only be performed with the elbow hyperflexed, will elicit tenderness. While usually present only during or immediately after provocative activities (e.g., pitching, gymnastics), often patients will develop continuous pain even at rest in advanced situations.

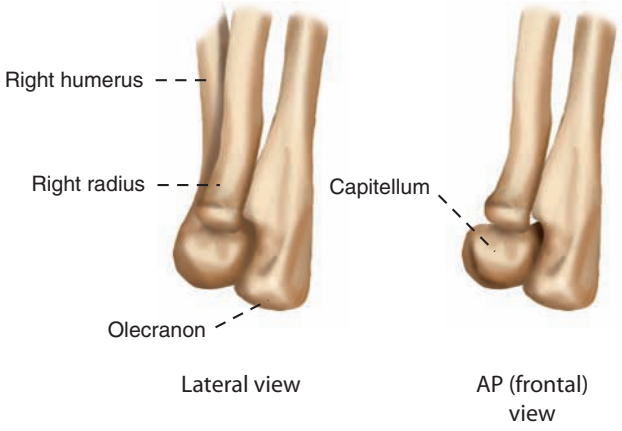


FIGURE 41-3 Schematic diagram demonstrating hyperflexion of the elbow, uncovering the capitellum in the typical region of OCD involvement. Direct palpation in this area with the elbow flexed will elicit tenderness in patients with OCD.

Up to half of patients will demonstrate subtle loss of elbow motion, typically an elbow flexion contracture. This is often the first clinical sign of internal derangement of the elbow. An elbow effusion may or may not be detectable. Similarly, RC crepitus or instability may be elicited in those patients with unstable lesions. Neurovascular examination is usually normal.

In the young thrower or overhead athlete, careful examination of the shoulder will invariably detect an internal rotation deficit (see Chapter 39). Identification of this is critical in the rehabilitation of elbow OCD. As the patient tries to impart more angular velocity during throwing, the presence of an internal rotation deficit will often result in a lower arm-trunk angle ("dropping down") and greater valgus and lateral compression forces across the elbow, thereby increasing the risk for OCD.

Finally and perhaps most importantly, up to 20% of patients will present with mechanical symptoms of locking, catching, or giving way of the elbow. These symptoms should alert the examiner of the possibility of an intra-articular loose body and advanced stage of OCD.

In patients with medial elbow pain, tenderness with direct palpation of the medial epicondyle should alert the examiner to the possibility of medial epicondyle apophysitis. Tenderness more distally over the proximal flexor-pronator mass and pain with resisted wrist flexion are consistent with flexor-pronator tendinosis. In patients with suspected UCL insufficiency, a number of provocative maneuvers will elicit pain and/or instability, including: (1) valgus stress at 30 degrees of elbow flexion, (2) positive modified milking test, and (3) positive moving valgus stress test.[22–24] Finally, all patients with medial elbow pain should be assessed for ulnar nerve instability and ulnar neuritis. Ulnar nerve subluxation may be palpated with elbow flexion and extension. A Tinel's sign, positive elbow flexion test, diminished sensation in the ulnar two digits, or any evidence of adductor pollicis or intrinsic weakness should raise the question of ulnar neuropathy.

Plain radiographs should be obtained during the initial evaluation, including anteroposterior (AP) and lateral views. Contralateral elbow radiographs may be helpful for comparison, particularly in the more skeletally immature. Takahara et al.[25] have also highlighted the utility of the 45-degree flexion AP view, which may better bring an OCD lesion into profile given its characteristic posterior location within the capitellum (Figure 41-4). In cases of suspected UCL insufficiency, a gravity stress radiograph can be obtained. This view is performed with the patient supine, shoulder abducted 90 degrees, and forearm maximally supinated (thumb pointed to the ground). An AP view of the elbow is then taken with the beam directed parallel to the floor. Medial joint space opening of ≥3 mm is indicative of valgus instability.

Increasingly, MRI is becoming the standard imaging modality of choice, given its ability to localize and stage the OCD lesion, as well as identify associated pathology, including intra-articular loose bodies.[26] T2-weighted coronal and sagittal reconstructions are particularly helpful in identifying adjacent signal abnormalities or fluid undercutting of the lesion, radiographic features suggestive of fragment instability. Also, MRI may be helpful in identifying flexor-pronator tendinosis, medial epicondyle apophysitis, and UCL tears.

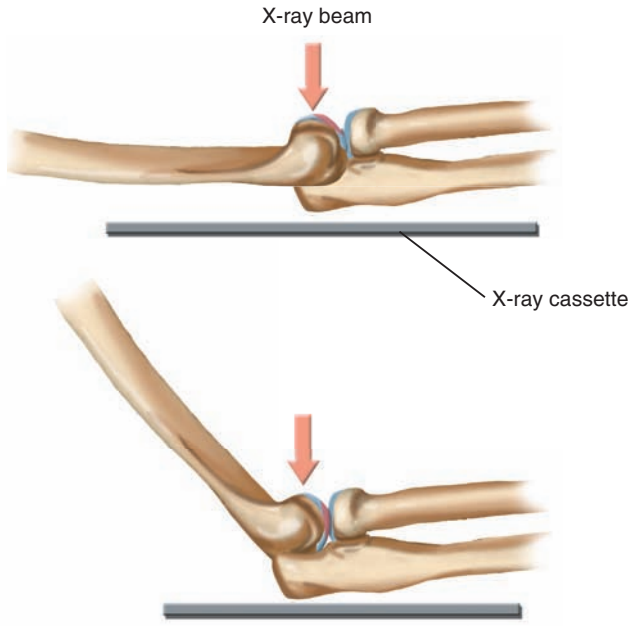


FIGURE 41-4 Schematic diagram depicting use of the 45-degree flexion AP view of the elbow to allow radiographic visualization of OCD lesions.

Currently, a host of classification systems exist for elbow OCD. Most are based on either radiographic or arthroscopic findings and divide lesions according to overlying cartilage integrity and fragment stability. Baumgarten et al.[27] proposed an arthroscopic classification based upon that used to assess talar dome lesions. Grade 1 lesions had smooth but ballotable articular cartilage. Grade 2 lesions had cartilage fibrillations or fissures. In grade 3 lesions, there was exposed bone by stable osteochondral fragments. Grade 4 lesions were loose but undisplaced. Grade 5 lesions were displaced with intra-articular loose bodies.

Difelice et al.[28] proposed a similar classification system, also based upon cartilage integrity and fragment stability (Table 41.1). Type 1a lesions have intact articular cartilage and fragment stability. Type 1b lesions have intact articular cartilage but unstable subchondral bone with impending collapse. Type 2 lesions demonstrate cartilage fracture with collapse or displacement of subchondral bone (e.g., unstable but in situ). Type 3 lesions denote intra-articular loose bodies. This classification system is similar to that of the International Cartilage Research Society classification of osteochondritis dissecans. Grade 1 lesions denote softened but intact cartilage surfaces. Grade 2 lesions have cartilage fissuring but are stable upon probing. Grade 3 lesions demonstrate complete discontinuity of cartilage but remain localized ("dead in situ"). Grade 4 lesions describe displaced lesions. All these classification systems are helpful not only to describe radiographic or arthroscopic appearance but also in guiding treatment. As with many upper limb conditions, however, clinical symptoms often do not correlate with radiographic findings.[1]

Surgical Indications

Surgical treatment is indicated in cases of symptomatic elbow OCD with fragment instability or intra-articular loose bodies. Furthermore, surgical treatment is also relatively indicated in cases of stable OCD lesions with persistent functionally limiting pain despite "adequate" rest and rehabilitation.

SURGICAL PROCEDURES

The downside isn't really injury, fear of injury, or the process of fighting injury. The downside, the very worst thing in the world, is surgery.
—Greg Rusedski

Nonoperative Treatment of Elbow OCD

Nonoperative treatment is recommended for the intact, stable elbow OCD lesion, particularly in the young, skeletally immature athlete. Complete rest of the affected elbow is initiated for 6 weeks, followed by physical therapy to work on posterior capsular stretching of glenohumeral internal rotation deficit, strengthening of the rotator cuff and periscapular muscles, strengthening of the flexor-pronator mass, and special attention to throwing mechanics. Core strengthening is a major part of their rehabilitation, as most of those young athletes need to transition from using their arm to using their core (knees to chest) musculature to increase throwing velocity. While advocated by some, we do not typically utilize hinged or varus elbow braces, given that the upper limb is a non-weight-bearing joint. This is reserved for the hyperactive child who just will not or cannot slow down. Typically, throwing is resumed once the patient demonstrates no pain, even with direct palpation over the capitellum, and full elbow motion symmetric to the opposite side. An interval throwing program is initiated, with emphasis on the "soreness rules," which limit progression or advancement through pain. Patients and families are counseled that it may be many months until vigorous throwing (or gymnastics, etc.) can be resumed.[29] This is not always an easy "sell," but the risk of long-term arthritis needs to be kept in mind.[30]

Medial Epicondyle Avulsion Fracture

While further details regarding medial epicondylar fractures in children are provided in Chapter 29, a brief discussion is warranted here. In addition to the valgus compression forces on the lateral elbow resulting in elbow OCD, tensile forces on the medial elbow may result in avulsion fractures

Table 41.1

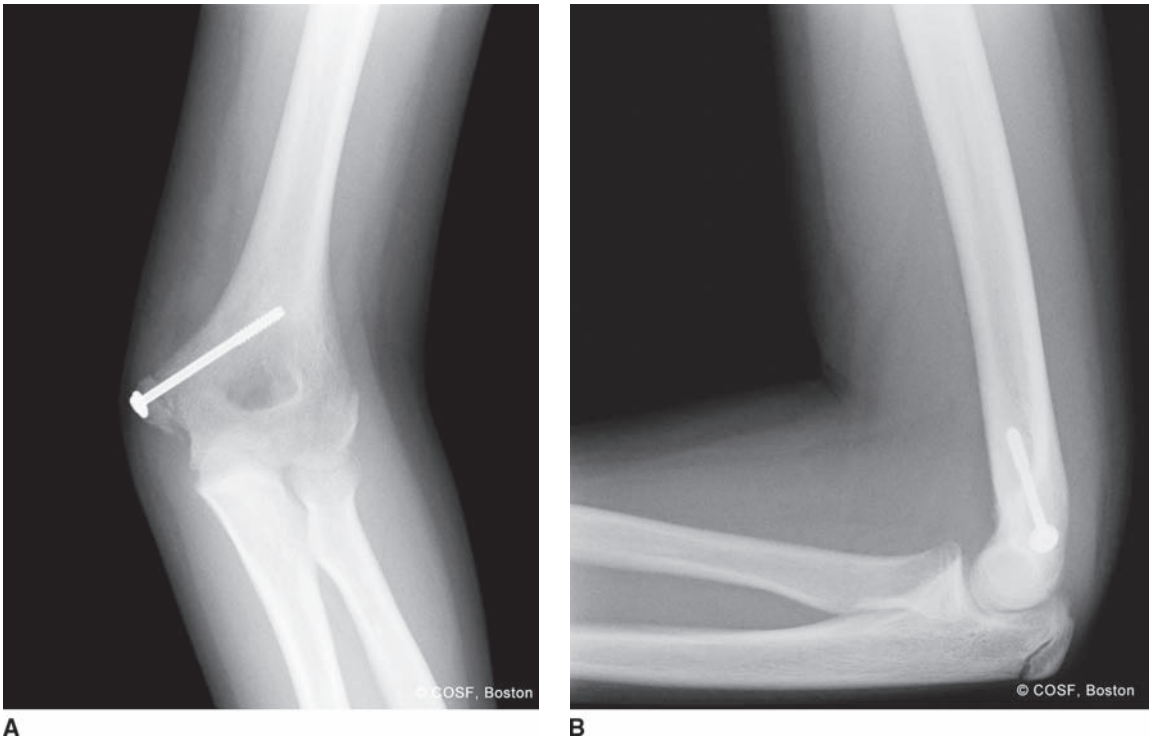
Classification of elbow OCD lesions

Type	Features	Description
1a	Intact/stable	Cartilage intact; Subchondral bone stable
1b	Intact/unstable	Intact articular cartilage; Subchondral bone unstable, impending collapse
2	Open/unstable	Articular cartilage fissures/fractures Subchondral bony collapse and instability
3	Detached	Intra-articular loose osteochondral fragment

of the medial epicondyle in young throwers, gymnasts, wrestlers, cheerleaders, and other overhead athletes. With small avulsion fractures, the athlete will often indicate a particular moment (e.g., "sixth inning, clean-up batter at the plate for the other team, tying run on third, and I threw my best fastball and felt immediate pain") that resulted in the injury. These fractures will heal with nonoperative management. Complete displacement of the entire medial epicondyle comes with macrotrauma (doing a floor routine in gymnastics with a fall). The displaced fractures may result in symptomatic valgus instability and altered flexor-pronator function in these high-demand athletes. For this reason, surgical reduction and fixation are recommended for displaced medial epicondyle fractures in young overhead or upper limb–weight-bearing athletes.

While surgery may be performed in the prone position with the shoulder internally rotated to impart a varus-producing force on the elbow, our preference is to perform these procedures in the supine position with the limb supported by an operating hand table if the patient has enough external rotation at the shoulder to allow easy access to the posteromedial elbow. Positioning this way makes fluoroscopy a bit easier than prone or "sloppy lateral" positioning. We check for the shoulder passive range of motion under anesthesia before a final positioning decision is made. A nonsterile tourniquet is utilized. A longitudinal incision based upon the medial epicondyle and medial column of the distal humerus is made. Skin flaps are carefully raised, understanding that the course of the medial antebrachial cutaneous nerve (MABCN) is quite variable. The MABCN often runs with the more easily identifiable basilic vein and should be protected to avoid symptomatic numbness or neuroma formation. Deep dissection will allow for identification of the ulnar nerve. While it is unnecessary to dissect the ulnar nerve circumferentially, it is critical to localize and gently retract the nerve during bony fixation, particularly as a high percentage of young patients will exhibit asymptomatic ulnar nerve subluxation.[31]

Once the ulnar nerve is retracted and protected, direction is turned to the fracture. The medial epicondyle fragment is identified along with the attached origin of the flexor-pronator muscles. A 2-0 suture (Ethibond, Ethicon, Inc., Somerville, NJ) may be placed through the superior periosteum overlying the displaced fracture fragment to be used for traction during the case. The bony donor site is similarly identified and fracture hematoma and fibrous tissue are debrided. Under direct visualization, the fracture is reduced. This typically requires flexing the elbow and imparting varus stress while the forearm is pronated to relax the deforming forces. A threaded guide pin from the 3.5- or 4.5-mm cannulated screw set (Synthes, West Chester, PA) is placed into the medial epicondyle, across the fracture site, and up the medial column of the distal humerus; care is taken to place this guide pin in the center of the fracture fragment to avoid fragmentation of the typically small displaced epicondyle (Figure 41-5). A slick way to do this is drill the center of the medial epicondyle in the displaced position; with the drill bit just protruding



A B

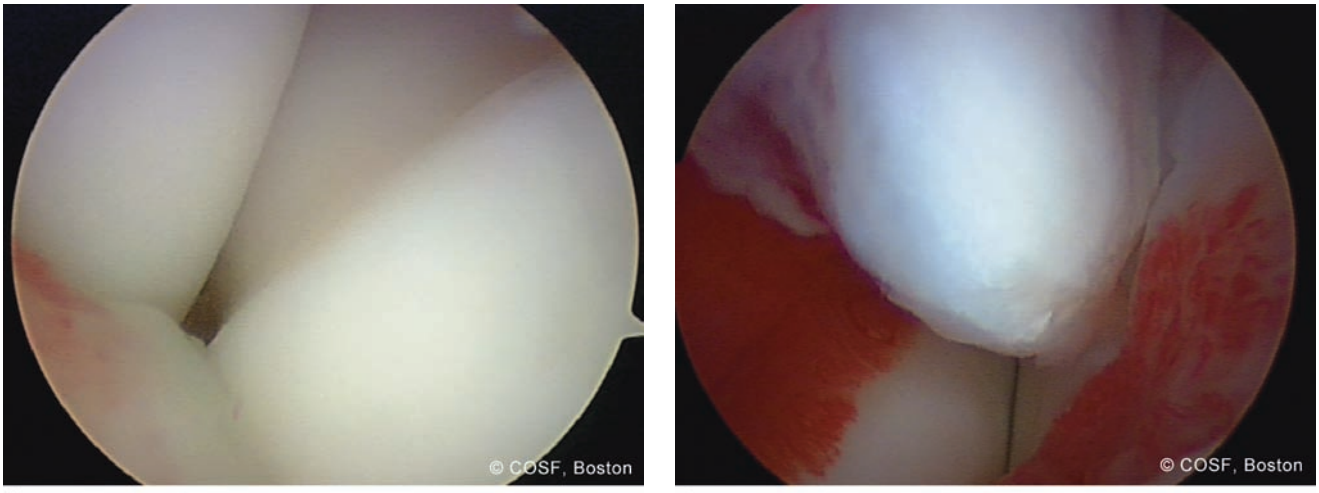
FIGURE 41-5 Postoperative anteroposterior (**A**) and lateral (**B**) radiographs following open reduction and internal fixation of a displaced medial epicondyle fracture.

from the fragment, anatomically reduce the fracture fragment; and then drill up the humerus obliquely avoiding the olecranon fossa. A second guide pin can be placed for temporary rotational control. Either a partially threaded cancellous screw or a fully threaded cortical screw can be used successfully. If a cancellous screw is used, and the fragment is big enough, then the central guide pin is overdrilled, and a partially threaded cannulated screw with a washer is placed, providing compression across the fracture site. Screw length is typically between 35 and 50 mm, and purchase of the far cortex is not necessary for adequate compression and fixation. If the fragment is smaller and there is concern about fragmentation with fixation, then a cortical screw and washer can be used. Cortical purchase is advised, but the screw needs to be removed sooner to prevent complications. Intraoperative fluoroscopy will confirm reduction, implant placement, and elbow stability. Suture repair of the flexor-pronator origin and periosteum increases stability and rotational control. The wound is closed in layers, and a long arm-bivalved cast is applied. Patients are transitioned into a hinged elbow brace by the second postoperative week to begin gentle range-of-motion exercises.

A couple of technical pearls bear mention. First, anatomic fracture reduction can be challenging when performing the surgery in the supine position. The valgus-extension position needed for visualization often impedes anatomic reduction. In addition to elbow flexion, forearm pronation, and varus stress, a dental pick or fracture reduction clamp may be helpful. (In our operating room, we have used a sterilized dinner fork with the central tines removed to facilitate fracture reduction and placement of the central guide pin). Alternatively, the drill hole in the epicondylar fragment and the medial column may be predrilled *prior* to reduction. Once the cannulated screw is placed into the fracture fragment, the screw tip may be inserted into the drilled medial column, using the screw itself to facilitate reduction. Second, it is important to remember that the medial epicondyle is a posterior structure. For this reason, the screw trajectory should be slightly posterior to anterior, and the lateral fluoroscopic image should demonstrate the posterior position of the screw head once fixation is complete. Failure to do so will result in nonanatomic fixation and suboptimal results.

◆ Arthroscopy and Drilling

In patients with unstable OCD lesions with intra-articular loose bodies, arthroscopic loose body removal and drilling may be considered.[1,32,33] Under general anesthesia in the supine position, the affected limb is suspended using either a commercially available limb positioning device or finger trap overhead traction (see Sidebar). After the elbow is insufflated with 10 to 15 mL of sterile saline solution via the direct lateral soft spot, a short 2.7-mm arthroscope is introduced into the joint via a proximal anteromedial portal. Arthroscopic survey is performed, and typically the loose body is immediately visualized in the anterior compartment (Figure 41-6A, B). Via an outside-in technique after first localizing with an 18-gauge spinal needle, an anterolateral portal is created just superior to the RC articulation (Figure 41-6C). An arthroscopic grabber is introduced and the loose body removed (Figure 41-6D, E). Following this, with varying degrees of elbow extension, the OCD lesion may be "unroofed" from the overlying radial head and probed. In cases in which inadequate visualization is achieved from a proximal anteromedial viewing portal, a direct lateral portal is created for viewing of the lesion.



A B

FIGURE 41-6 Arthroscopic treatment of an unstable OCD lesion. **A:** The lateral aspect of the elbow joint is visualized from the proximal anteromedial viewing portal in a right elbow. The trochlea is seen in foreground, the capitellum to the right, and the radial head to the left. **B:** A large intra-articular loose body is seen in the anterior compartment of the elbow.

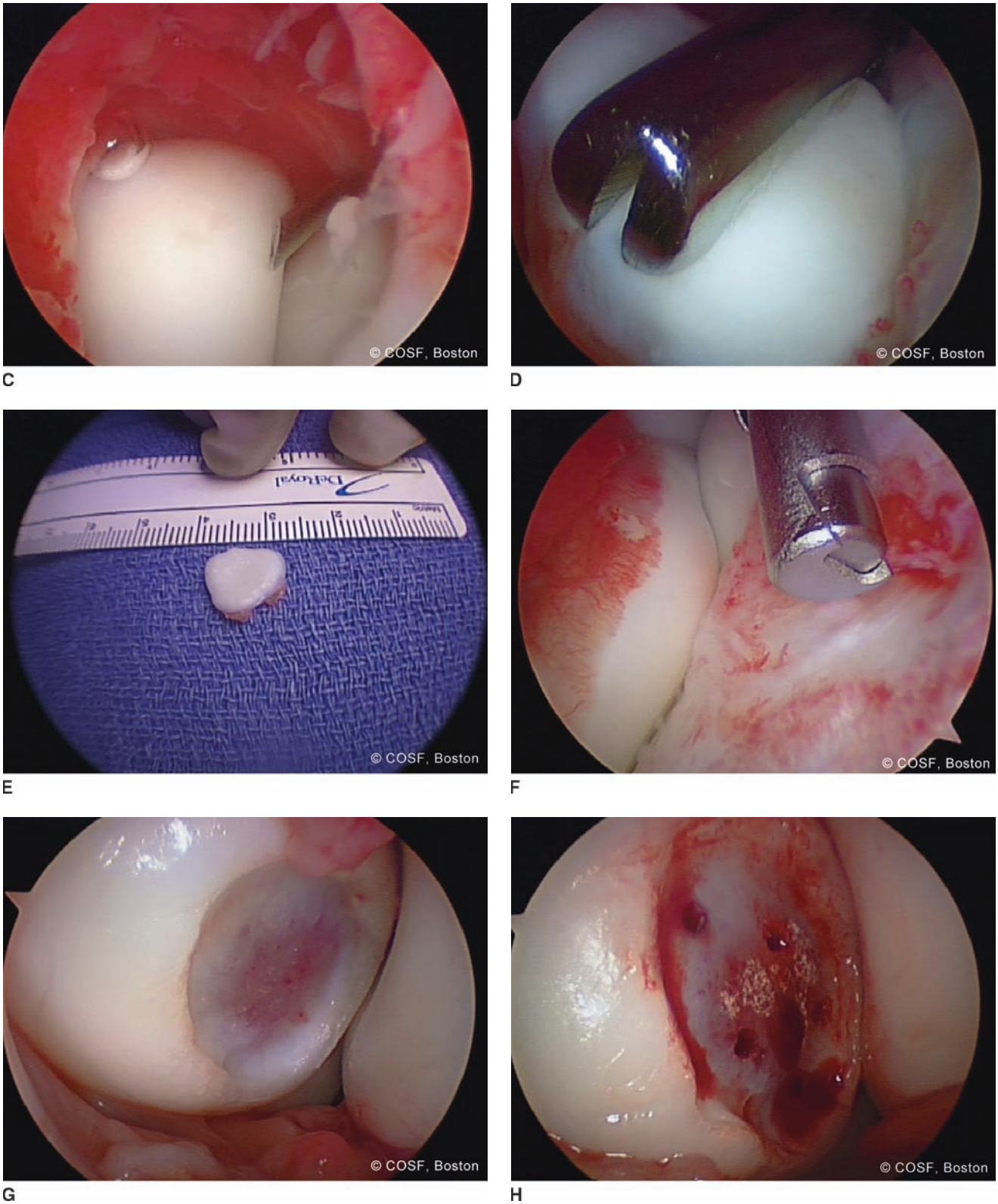


FIGURE 41-6 *(continued)* **C:** A spinal needle is used to localize an anterolateral working portal in an outside-in fashion. Note the surrounding synovitis of the anterior compartment. **D:** An arthroscopic grabber is used to remove the loose body. **E:** The loose body photographed after removal. **F:** Limited joint debridement is performed. **G:** The OCD lesion is easily visualized via an anconeus-splitting small arthrotomy. **H:** Following drilling/microfracture of the donor site, appropriate bleeding is seen.

SIDEBAR

Arthroscopy Setup, Portals, and Techniques

Arthroscopy is an invaluable tool for the pediatric hand and upper limb surgeon. While conceptualized almost 100 years ago, only with increased understanding of anatomy and surgical techniques has elbow arthroscopy become safe, reliable, and accepted in modern-day orthopaedics.[64–66] Traditional indications for elbow arthroscopy included removal of intra-articular loose bodies, osteophyte debridement, and synovectomy. Over time, indications have expanded to include debridement of lateral epicondylitis, contracture release, drainage of infections, and treatment of OCD lesions. Further investigation has evaluated the role of arthroscopy in arthroscopic-assisted fracture reduction, nerve decompression, as well as instability surgery.

In general, elbow arthroscopy may be done in the supine, lateral, or prone positions. For most pediatric indications, in which the pathology lies in the anterior compartment, supine positioning confers a number of advantages (Figure 41-7). Anesthesia is more readily administered and monitored. Portal placement and instrumentation of the anterior compartment are easier in the supine patient. Furthermore, supine positioning allows for easy conversion to arthrotomy and open surgical reconstructions, particularly if a graft is to be harvested from the iliac crest or lower extremities. Prone positioning may be advantageous in the less frequent situations in which all work is to be done in the posterior compartment (e.g., posterior ulnohumeral impingement or valgus-extension overload in the throwing athlete).

While many have been proposed, a few workhorse portals are utilized in elbow OCD and other pediatric elbow conditions (Figure 41-8). The proximal anteromedial portal of Poehling serves as the primary viewing portal and is the first to be created.[64] This portal is created 2 to 3 cm proximal to the medial epicondyle and just anterior to the palpable medial intermuscular septum. After skin incision, careful blunt dissection and spreading are performed in the subcutaneous tissues, with tactile confirmation that dissection proceeds anterior to the intermuscular septum to avoid iatrogenic injury to the ulnar nerve. A small joint arthroscope is then inserted, directed toward the radial head, and skived along the anterior surface of the distal humerus. This portal allows excellent and immediate visualization of the RC joint and OCD lesions.

A

B

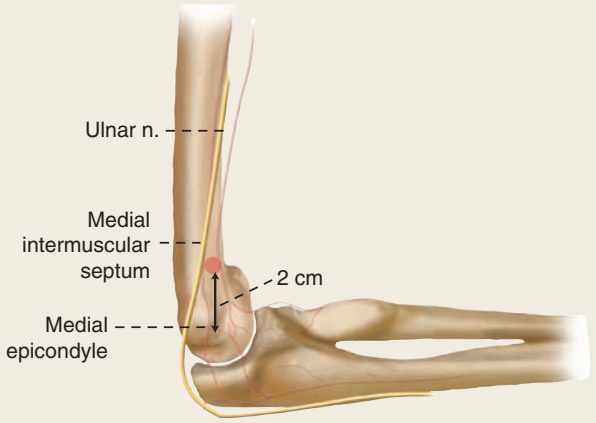
FIGURE 41-7 Supine positioning for elbow arthroscopy. **A:** The limb may be supported via finger trap suspension over an operating hand table. **B:** Alternatively, arthroscopy may be performed without the hand table present, which allows for closer proximity and easier maneuvering about the elbow. An arm board or hand table may be placed later if an open procedure is to be performed.

(continued)

SIDEBAR (*continued*)

The anterolateral portal is typically created in an outside-in fashion, first by localization with a spinal needle placed just superior/proximal to the RC joint. Judicious portal placement will allow for access to the anterior compartment as well as the RC joint itself, critical in the management of elbow OCD.

The direct lateral portal—which lies in the center of the isosceles triangle created by the radial head, lateral epicondyle, and olecranon tip—may be helpful as well. In addition to providing a reproducible means of joint insufflation, the direct lateral portal may be used for visualization and/or instrumentation of the posterior capitellum and ulnohumeral joint in OCD cases.



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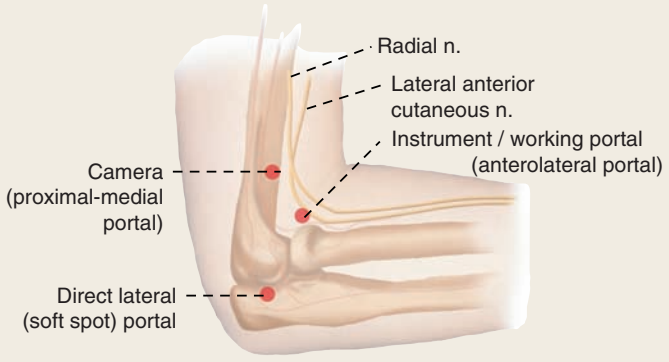

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FIGURE 41-8 Commonly used arthroscopy portals. **A:** Schematic diagram and (**B**) clinical photograph of the proximal anteromedial portal. This is created 2 to 3 cm above the medial epicondyle and just anterior to the palpable medial intermuscular septum. **C:** Schematic diagram and (**D**) clinical photograph of the lateral arthroscopy portals.

At this point, an arthroscopic shaver is introduced, and limited joint debridement and chondroplasty are performed (Figure 41-6F). If an entirely arthroscopic procedure is to be performed, chondroplasty picks may be inserted through the direct lateral or anterolateral portal. The varying angles of these picks will allow for precise placement of microfracture holes orthogonal to the bony surface of the capitellum. Alternatively, 0.045″ smooth K-wires may be utilized to drill the lesion until bleeding is seen. Treating the residual OCD defect is important, as fragment removal alone has been associated with poor long-term outcomes.[34,35]

In cases where suboptimal arthroscopic visualization is obtained, a limited arthrotomy is performed. The limb is taken out of overhead traction and supported on a hand table or arm board. The elbow is hyperflexed, and an oblique incision is created directly over the capitellum. Dissection through the subcutaneous fat will allow for identification of the anconeus fascia. This is incised, and a muscle-splitting approach through the anconeus is made. The joint capsule is then exposed and carefully incised; this is performed delicately, as the cartilaginous surface is immediately beneath the capsule. Self-retaining retractors

are placed, and the entire capitellar lesion is easily seen (Figure 41-6G). Debridement and microfracture or drilling of the lesion are then performed (Figure 41-6H).

While other authors have advocated posterior-to-anterior or "through-the-radius" drilling of the capitellar lesion, we do not currently utilize these techniques.[36] Similarly, we do not currently perform valgus closing wedge osteotomies to treat OCD lesions.[37] There are some instances in which internal fixation of the osteocartilaginous loose body may be performed using buried variable pitch screws or bioabsorbable implants. The best candidates for fragment fixation are patients with large lesions who present with a fresh loose body soon after detachment in which the fragment has some underlying bone attached and/or does not exceed 8 mm in thickness.[38–43] We do not currently utilize staples or "pull-out" wire/suture techniques for fixation of unstable OCD lesions and therefore cannot comment on the utility or results of this technique.[39,40]

Postoperatively, patients with a loose body excision, chondroplasty, and/or microfracture are immobilized in a soft bandage and sling for comfort. Gentle range-of-motion exercises are initiated, though no heavy lifting or resistive strengthening is performed until after the sixth postoperative week. With fragment repair, protected motion in a hinged brace is performed for 6 weeks.

◆ Osteochondral Autogenous Transplantation Surgery (OATS)

The osteochondral autogenous transplantation surgery (OATS) procedure is another treatment option for elbow OCD.[25,44,45] This procedure allows for the replacement of injured bone and cartilage by healthier tissue taken from a less important donor site and offers a number of theoretical advantages over marrow stimulation techniques (see Coach's Corner).

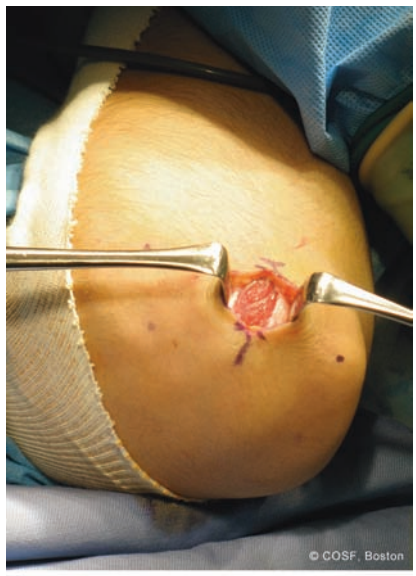
Surgery is initiated as described above, though the ipsilateral lower limb is prepped and draped into the surgical field for anticipated OATS harvest (Figure 41-9). Diagnostic arthroscopy is performed along with loose body removal. The limb is taken out of overhead traction and supported by an arm board or hand table. Tourniquet is inflated, and the elbow hyperflexed. A longitudinal or oblique incision is created directly over the capitellum (Figure 41-9A). In revision cases in which a previous Kocher approach has been used, the posterolateral incision may be extended proximally and distally to facilitate skin flap elevation and exposure of the appropriate deep muscular interval (Figure 41-9B). The anconeus fascia is incised in line with the skin incision and an intramuscular interval developed by bluntly spreading in line with the muscle fibers (Figure 41-9C). The capsule is carefully incised, exposing the capitellar articular surface (Figure 41-9D).

The OCD lesion is inspected and sized. In cases in which a loose body is removed, the dimensions are quite easily defined. In cases of fragment instability in situ, careful probing is performed to identify the transition from injured to healthy cartilage. Once the lesion is identified, a cyclindrical core of injured cartilage and subchondral bone is removed using an appropriately sized cylindrical chisel (Recipient Harvester, OATS Single Use Kit, Arthrex, Inc., Naples, FL); this is typically 10 mm in diameter and 15 mm in depth (Figure 41-9E). Care is taken to stay perpendicular to the articular surface and avoid lateral or posterior "blowout" while creating the recipient defect. Following this, 0.045″ smooth K-wires may be utilized to drill the adjacent cancellous bone from within the lesion to stimulate additional biological healing response.

Although classically OATS has been performed using mosaicplasty to restore articular integrity, we typically replace the articular OCD defect with a single large cylindrical OATS graft. While issues remain regarding matching the radius of curvature from the donor to recipient sites,

A B

FIGURE 41-9 OATS. **A:** Oblique incision created directly over the capitellum with the elbow flexed. **B:** Alternatively, in revision situations after prior Kocher approach, the previous posterolateral incision may be extended.



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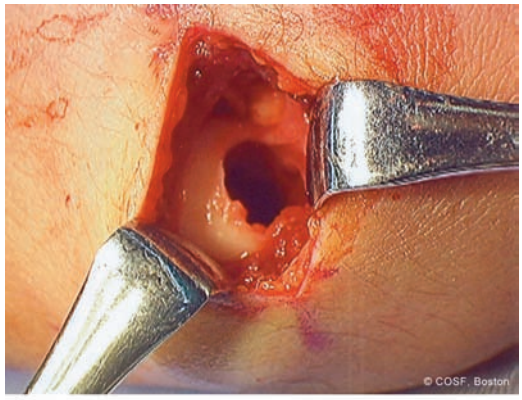

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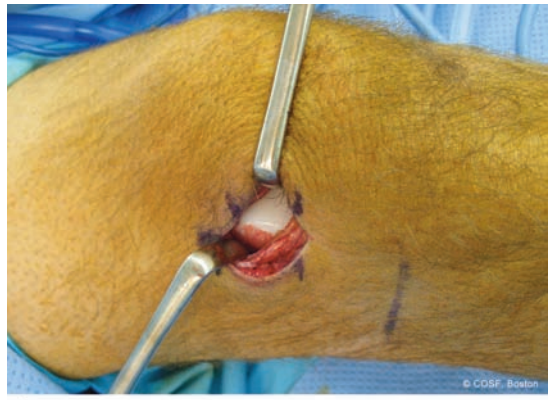

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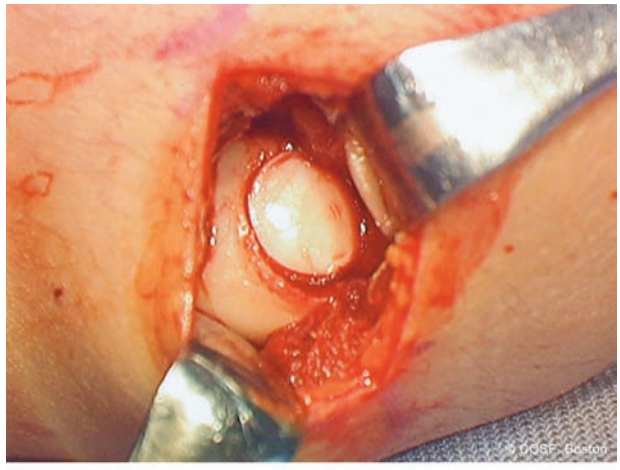

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FIGURE 41-9 *(continued)* **C:** Fascial incision over the anconeus. **D:** The anconeus is split in line with its fibers, and a capsulotomy is performed, exposing the OCD lesion. **E:** The recipient site has been prepared with the appropriate-sized cylindrical chisel. **F:** Intraoperative photograph of the small, lateral parapatellar arthrotomy used to expose the non-weight-bearing portion of the lateral femoral condyle. **G:** The donor osteochondral cylindrical plug has been harvested. **H:** Intraoperative photograph after completion of OATS demonstrating restoration of capitellar surface.

the use of a single plug provides greater stability and technical ease. Furthermore, while appealing in theory, creating a stable and smooth articular surface using multiple smaller OATS grafts can be challenging.

Following recipient site preparation, a donor "plug" of cartilage and bone is obtained. While this may be done arthroscopically, donor harvest may be done quickly, easily, and with minimal morbidity via a small lateral parapatellar arthrotomy. The lower extremity is exsanguinated and tourniquet inflated. A small, 3- to 5-cm longitudinal incision is created lateral to the patella with the knee extended. Dissection is performed in the subcutaneous tissues until the extensor mechanism is identified. A lateral parapatellar arthrotomy is created in line with the skin incision, exposing the lateral condyle of the distal femur (Figure 41-9F). With care being made to stay superior to the sulcus terminalis (and thus the weight-bearing portion of the lateral condyle), an appropriate-size plug of lateral condylar cartilage and subchondral bone is obtained (Donor Harvester, OATS Single Use Kit, Arthrex, Inc., Naples, FL) (Figure 41-9G). Again, care is taken to stay perpendicular to the articular surface. After successful plug harvest, the knee wound is closed in layers, tourniquet deflated, and a sterile bandage applied.

The donor tissue is brought to the elbow wound within the donor harvester. With care being made to stay aligned with the trajectory of the recipient cylindrical defect, the core of cartilage and bone is then gently impacted in a press-fit fashion into the capitellum (Figure 41-9H). If needed, a slightly oversized tamp may be used to finish the graft placement. Vigorous impaction with a mallet is avoided in an effort to preserve chondrocyte viability and mechanical integrity. Direct visualization and palpation will confirm that the donor graft is flush with the surrounding articular surface. The elbow is ranged to confirm full motion without crepitus. The capsule and anconeus fascia are reapproximated with 2-0 and 3-0 sutures (Vicryl, Ethicon, Inc., Somerville, NJ), and skin is closed with running subcuticular sutures. A sterile bandage is applied, followed by a long-arm bivalved cast. The cast is removed at 2 to 3 weeks postoperatively, followed by the initiation of gentle range-of-motion exercises in a hinged elbow brace. Full unrestricted weight bearing on the lower extremity is allowed immediately.

◆ UCL Reconstruction

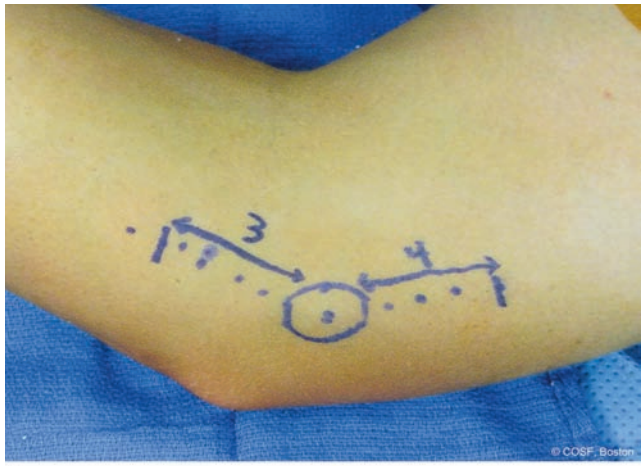
When they operated on my arm, I asked them to put in Koufax's fastball. They did. But it turned out to be Mrs. Koufax.
—Tommy John

In throwing and overhead athletes with UCL insufficiency, every effort is made to alleviate pain, restore function, and return to sports with nonoperative treatment. Nonoperative treatment is typically comprised of initial rest, followed by physical therapy for flexor-pronator strengthening, and an interval throwing program. Historically, nonoperative care is successful in up to half of high-level throwing athletes.[46–49]

In patients with persistent pain or functional limitations despite nonoperative treatment, surgery may be considered. Indications continue to evolve—particularly for the young athlete—in part due to increased expectations regarding expedited return to throwing, improvements in surgical techniques, and the role of the media in popularizing UCL reconstruction. Patients must be committed to the rigorous and lengthy postoperative rehabilitation before surgery is undertaken. We currently favor ligament reconstruction using the "docking technique" via a muscle-splitting approach.[50–53] While direct ligament repair has been advocated by some, the UCL is typically attenuated and of poor quality, resulting in suboptimal outcomes.[46,49,54,55] We currently consider UCL repair only in young, skeletally immature patients with acute UCL ruptures.

Surgery is performed under general anesthesia with tourniquet control. A medial incision extending 4 cm proximal and 4 cm distal to the medial epicondyle is made (Figure 41-10A). Dissection is performed through the subcutaneous tissues, and the MABCN is identified and protected (Figure 41-10B). The deep fascia is identified and incised over the flexor carpi ulnaris muscle, typically at the posterior one-third and anterior two-thirds junction of the flexor-pronator mass. The muscle is then split in line with its fibers exposing the underlying joint capsule and UCL. A longitudinal incision is created in the joint capsule and the ulnohumeral joint inspected. Medial joint space widening of ≥3 mm with valgus stress will confirm UCL insufficiency. Careful subperiosteal dissection is performed over the sublime tubercle. Once the sublime tubercle is exposed, drill holes are created using a 3.2- mm drill bit anterior and posterior to the sublime tubercle; a bone bridge of 5 to 10 mm between drill holes is critical to avoid subsequent breakout during graft passage (Figure 41-10C). A suture is then passed from posterior to anterior through the ulnar tunnels, to be used for subsequent graft passage.

The anterior-inferior aspect of the medial epicondle is exposed by careful flexor-pronator muscle reflection. Often the footprint of the native ligament can be seen, allowing identification of the appropriate site for humeral bone tunnel creation. The ends of the previous passing suture may be snapped and placed on the medial epicondyle, forming an isosceles triangle. With elbow flexion and extension, the suture may be used to confirm that the planned site of humeral graft passage results in isometry of the reconstructed ligament. A 4.5-mm drill bit is then used to create a 15-mm tunnel up the medial column of the humerus, with care taken to avoid posterior or medial cortical breakout (Figure 41-10C). More proximal on the medial column of the humerus, subperiosteal dissection is performed to expose the medial and anterior metaphyseal



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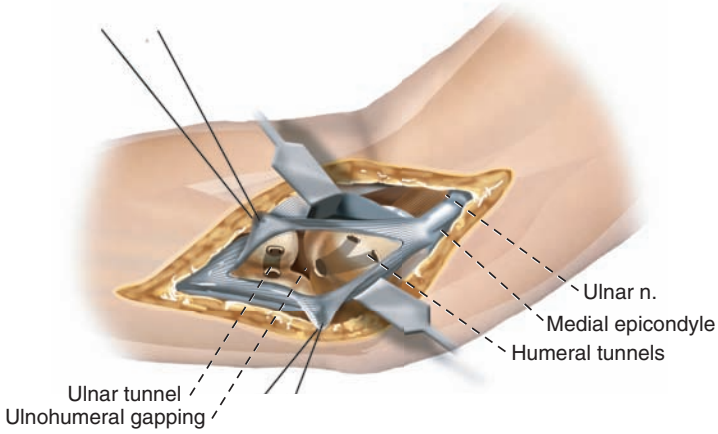

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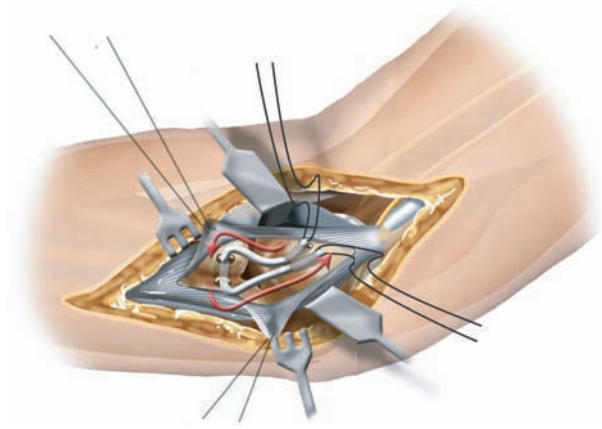

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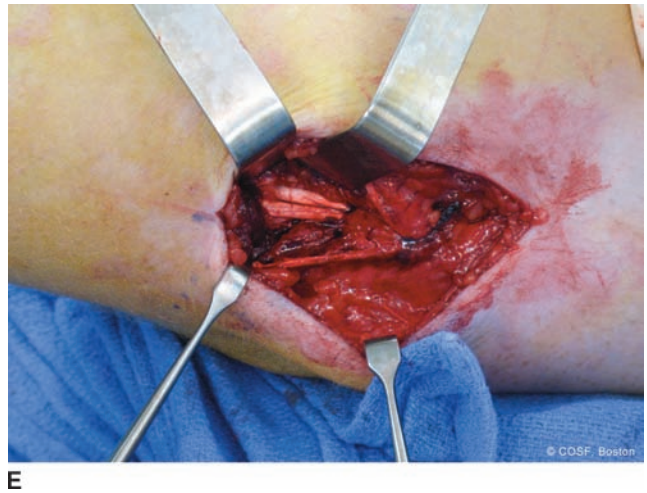

E

FIGURE 41-10 UCL reconstruction. **A:** Clinical photograph of a right elbow depicting the medial incision centered on the medial epicondyle. **B:** Intraoperative radiograph demonstrating the MABCN running through the operative field. **C:** Schematic diagram depicting the bone tunnels utilized with the docking technique. **D:** Schematic diagram following graft passage, illustrating how the sutures are brought out through the docking tunnels and tied over a humeral bone bridge. **E:** Intraoperative photograph of the completed reconstruction.

cortex. (Posterior dissection is not performed to avoid iatrogenic ulnar nerve injury.) Then 2-mm drill bits are used from the medial and anterior metaphysis from proximal to distal, connecting the "docking tunnels" to the previously drilled 4.5-mm tunnel. Placement of a small curette or other instrument will allow for tactile confirmation that the docking tunnels have adequately connected to the 4.5-mm tunnel. Sutures are then passed down the docking tunnels out the hole in the medial epicondyle; Hewson suture passers may facilitate this step.

We favor the use of ipsilateral autologous palmaris longus tendon for ligament reconstruction. (When the

palmaris is absent, autologous hamstring or allograft may be used.) No. 2 Ethibond sutures are passed in a locking Krackow fashion through one end of the tendon graft. This end is passed from anterior to posterior through the ulnar tunnels, into the medial epicondyle tunnel, and out the posterior docking tunnel. With tension on the graft, the elbow is flexed and extended for 20+ cycles to eliminate graft crimp. Following this, the other end of the graft is laid adjacent to the medial epicondyle and cut to allow for 7 to 8 mm of graft in the humeral tunnel. A No. 2 Ethibond suture is again passed in a locking, whipstitch fashion through the freshly cut end, and these sutures are passed into the medial epicondyle and out the anterior docking tunnel. The ulnohumeral joint capsule is now closed with interrupted 2-0 absorbable sutures.

The elbow is placed in approximately 45- to 60-degree flexion with varus stress and forearm supination, and the Ethibond sutures are tied over the humeral bone bridge, completing the repair (Figure 41-10D, E). The wound is closed in layers, and the limb is placed in a posterior splint in 70 degrees flexion and midsupination.

POSTOPERATIVE

It may sound strange, but many champions are made champions by setbacks.
—Bob Richards

Following arthroscopic or open loose body removal and drilling/microfracture, patients are placed in a soft bandage and sling for comfort. Gentle range-of-motion exercises are performed until the sixth postoperative week. Advancement to strengthening is allowed at 6 weeks. An interval throwing program may be initiated 4 to 6 months postoperatively provided there is no pain, motion is restored, and strength is near normal.

After a fragment repair or an OATS procedure, the cast is removed after 2 to 3 weeks, and gentle elbow motion initiated in a hinged elbow brace. Formal physical therapy is similarly initiated at 6 weeks postoperatively for continued motion and advancement to strengthening. Light throwing via an interval throwing program is begun at 4 to 6 months postoperatively.

After UCL reconstruction, the splint is removed and incisions are inspected 2 weeks postoperatively. A hinged elbow brace is applied, and protected range of motion is advanced gradually until 6 weeks postoperatively. After 6 weeks, gentle strengthening is begun. More vigorous strengthening and weight training are allowed at 3 months postoperatively. Light throwing commences at 4 to 5 months, with gradual progression to more vigorous throwing and pitching. Postoperative rehabilitation is commonly undertaken 9 to 12 months after UCL reconstruction.

ANTICIPATED RESULTS

While there is an abundance of published information regarding the results of treatment of elbow OCD, most are retrospective case series of limited numbers of patients, often at different stages of disease, with short- to intermediate-term follow-up. Few prospective longitudinal studies have been performed, and very little comparative data exist to inform surgeons regarding optimal treatment. Despite these limitations, a number of conclusions may be drawn from the available body of literature.

Nonoperative treatment may be successful in patients with stable lesions.[29] In general, the highest healing potential is seen in younger patients with open physes and preserved elbow motion at earlier stages of disease.[35,56] Older patients with closed physes are less likely to demonstrate improvements with nonoperative treatment when compared to surgical intervention. Clinical and radiographic resolution may take time. In a series of 176 patients with stage I and II OCD, mean period required for healing was 14.9 and 12.3 months, respectively.[29] There is often a disconnect between the patient's, parents', and coaches' expectations of early, successful return to competitive sports and our worries about long-term arthritis in the elbow.

In cases of fragment instability, surgical treatment has been demonstrated to provide improvements in pain, motion, and radiographic appearance in most, but not all, patients. Baumgarten et al.[27] reported a series of 16 patients treated with debridement and loose body removal. Modest improvements in elbow motion were seen, and over 80% were able to return to the prior level of sports participation. Similarly, Rahusen et al.[57] reported improved motion and functional outcome scores in 15 adolescents following arthroscopic debridement.

Results after OATS appear to be more encouraging. Iwasaki et al.[44] reported seven good-to-excellent clinical results in their series of eight adolescent patients treated with mosaicplasty. Graft incorporation was seen radiographically in all patients, and no degenerative changes were noted at short-term follow-up. Yamamoto et al.[58] reported significant improvement in subjective and objective findings in 18 adolescent baseball players treated with OATS for OCD.

Perhaps more important than objective clinical results, patients and families often inquire about return to play following surgical treatment. Byrd and Jones[1] reported on 10 adolescents treated with arthroscopy and debridement for varying grades of elbow OCD. In their series, only four returned to their prior level of organized baseball at mean 3.9-year follow-up. Reports on return to athletic participation after OATS procedures have been more encouraging. Iwasaki reported six of eight patients returning to their prior level of sports participation after mosaicplasty.[44] Mihara et al.[59] reported that 25 of 27 patients were able to return to baseball after surgical reconstruction, particularly

when joint stability and the lateral margin of the capitellum could be reconstructed.

Ultimately, the long-term consequences of elbow OCD—as well as results of surgical treatment—remain poorly characterized. Bauer et al.[60] reported on 31 elbows followed for a mean of 23 years. Half were symptomatic, commonly reporting pain and limited range of motion. Radiographic degenerative joint changes were seen in the majority of patients, and two-thirds of patients demonstrated radial head enlargement. Based upon this and other reports, a realistic and guarded prognosis should be considered until more comprehensive long-term follow-up data are available.

COMPLICATIONS

While more commonly performed, complications may occur with elbow arthroscopy.[61] Although portal site drainage is common, this is typically self-limited and may be avoided if pump pressures are set low and portals established using the techniques described here. Neurovascular injury is uncommon but potentially devastating. In particular, the proximal anteromedial and anterolateral portals require precise placement to avoid iatrogenic injury to the ulnar and posterior interosseous nerves, respectively.

Donor site morbidity following OATS has been similarly examined as a potential source of postoperative complications. Painful hemarthrosis and even infection may complicate the initial postoperative course, though the donor sites often do fill in with bone and fibrocartilage.[62,63]

Perhaps the most concerning complication following surgery for elbow OCD is recurrence. Few published data are available regarding rates and risks of recurrent unstable OCD lesions following debridement, drilling, or OATS procedures. Continued serial examinations are recommended until skeletal maturity to monitor each patient's progress and evaluate for potential signs of recurrence.

CASE OUTCOME

The diagnosis of an unstable OCD lesion with an intra-articular loose body was made. Following arthroscopic loose body removal and drilling, pain resolved and motion improved. An interval throwing program was initiated at 6 months postoperatively, and the patient was able to return to baseball, though he chose to give up pitching. At the most recent follow-up, the elbow remained pain free without functional limitations or recurrence.

SUMMARY

Osteochondritis dissecans of the capitellum is a common cause of pain in the adolescent thrower and gymnast. Patients will present with pain, loss of motion, and mechanical symptoms of locking or giving way. Radiographic evaluation, including MRI, will confirm the diagnosis and assist with staging. While stable lesions may be treated nonoperatively, surgery is recommended for unstable lesions with intra-articular loose bodies. Elbow arthroscopy, loose body removal, drilling, and/or OATS procedures have been utilized to address symptoms and stimulate healing. While the short-term results have been satisfactory, further prospective, comparative investigation is needed to optimize outcomes.

COACH'S CORNER

OATS or Drilling/Microfracture?

Two different strategies have been utilized to address capitellar donor defects in elbow OCD: drilling/microfracture and OATS. Each has its own theoretical advantages and disadvantages, though to date there is little scientific evidence supporting the superiority of one versus the other.

Drilling and microfracture seek to improve vascularity to the OCD lesion and replace the hyaline cartilage defect with fibrocartilage via marrow stimulation. There has been extensive experience with this technique in the ankle, knee, hip, and shoulder, and this technique has been used in the elbow for decades. The technique is simple, safe, and obviates the additional morbidity of harvesting osteochondral grafts from another anatomic site. One of the main disadvantages is that fibrocartilage does not have the same biomechanical properties as hyaline cartilage, raising questions of its efficacy and durability.[60,67,68]

OATS provides the advantages of replacing diseased or damaged osteochondral lesions with both healthy hyaline cartilage and subchondral bone. It may provide a better reconstructive solution for large defects[69] and may give clinically superior results for lateral or uncontained lesions.[56] Early published reports are promising, and, to date, donor site morbidity appears to be minimal.[70]

It is clear, however, that OATS may not be easily performed in all patients. Based upon our experience with both techniques, there are several subgroups of patients that may not be amenable to OATS reconstructions. First, successful OATS procedures require adequate exposure and precise preparation and filling of the capitellar lesion. In obese patients or patients with loss of terminal passive elbow flexion, anconeus-splitting approaches will not provide adequate access to the affected cartilage regions. While ligament-sparing or ligament-sacrificing approaches to the lateral elbow may be employed, these still offer

imperfect exposure and should be pursued with caution in the young pitcher or gymnast. Second, OCD lesions of the trochlea or very anteroproximal capitellum may not be easily treated with OATS, due to difficulties with access and exposure. Finally, careful preoperative consideration should be given to the very young or small patients. Natural history studies tell us that their healing potential is greater. Furthermore, due to the small bony dimensions and short distance between the articular surface and adjacent physis and posterior humeral cortex, often there is insufficient room to allow for a 12- to 15-mm OATS plug. These patient factors should be kept in mind when choosing surgical treatment strategies.

ACKNOWLEDGMENTS

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CHAPTER

42

The Athlete's Wrist

CASE PRESENTATION

A 16-year-old varsity lacrosse player re-presents for persistent wrist pain on her dominant right side. Initially the pain arose with stick handling when in her attack position. Now discomfort was occurring when opening jars, doors, and carrying her books in school. Initial treatment included a strengthening therapy program starting 6 weeks ago. She now has equivalent pinch-and-grip strength compared to her contralateral side. Her exam reveals pain with supination beyond 30 degrees, ulnocarpal compression pain, and an asymmetric click with rotatory stress. She is symmetrically moderately ligamentously lax with scapholunate, lunotriquetral, and midcarpal stress testing. Radiographs reveal symmetric neutral ulnar variance.

CLINICAL QUESTIONS

- What conditions and injuries give rise to sports-related wrist pain?
- What are the differential diagnosis and work-up for chronic wrist pain?
- How often is surgical intervention necessary?
- How are triangular fibrocartilage complex (TFCC) tears classified?
- Which types of tears are most common in adolescents?
- What are the results of TFCC repair in children and adolescents?
- How are scapholunate ligament tears classified?
- Which patients are at risk for chondral injuries?
- Is arthroscopic debridement of partial ligament tears and/or chondromalacia successful?

THE FUNDAMENTALS

Etiology and Epidemiology

Soft tissue stability of the wrist is conferred by intra-articular intercarpal, radiocarpal, and ulnocarpal ligaments as well as distal radioulnar ligaments and the TFCC.[1] The proximal carpal row (scaphoid, lunate, triquetrum) is interconnected by scapholunate and lunotriquetral ligaments. The scapholunate ligament has three portions: dorsal, proximal, and palmar. The dorsal portion is the main stabilizer between the scaphoid and lunate, while the palmar portion of the lunotriquetral ligament is the main stabilizer between those two carpal bones. Carpal instability can be dynamic, with normal radiographs, or static, in which the carpal gap and malalignment can be seen on plain radiographs. Both static and dynamic instabilities can cause pain with activity.

The TFCC helps to stabilize the ulnar side of the wrist and the distal radioulnar joint (DRUJ). It consists of an articular disc, meniscal homologue, volar and dorsal radioulnar ligaments, ulnocarpal (ulnolunate and ulnotriquetral) ligaments, and deep surface of the extensor carpi ulnaris (ECU) sheath. It extends from the medial radius above the sigmoid notch to the base of the ulnar styloid (Figure 42-1). The vascularity of the TFCC is from the periphery, similar to a knee meniscus. As ulnar variance becomes more positive, axial load through the ulnocarpal joint, and stress on the TFCC, increases. The volar distal radioulnar ligaments and the TFCC prevent dorsal displacement and are most taut in pronation. Conversely, the dorsal distal radioulnar ligaments and the TFCC prevent volar displacement and are taut in supination.

Clinical Evaluation (Figure 42-2)

Golf is a game in which you yell "fore," shoot six, and write down five.
—Paul Harvey

The spectrum of sports-related adolescent wrist pain is broad[2–4] and includes, among others, overuse syndromes, stress fractures (see Chapter 39)[5,6] (Figure 42-3), wrist sprains, muscle imbalance, ganglia, hyperlaxity, dorsal impaction,[7] pain syndromes, inflammatory processes, and specific chondral and ligamentous injuries.[8–12]All patients should have plain radiographs as a part of clinical evaluation. Obviously, distal wrist and ulna, carpal (particularly scaphoid), and metacarpal fractures are a major part of wrist-area injuries in sports. Evaluation and care of fracture dislocations are covered in Chapters 34 and 35.

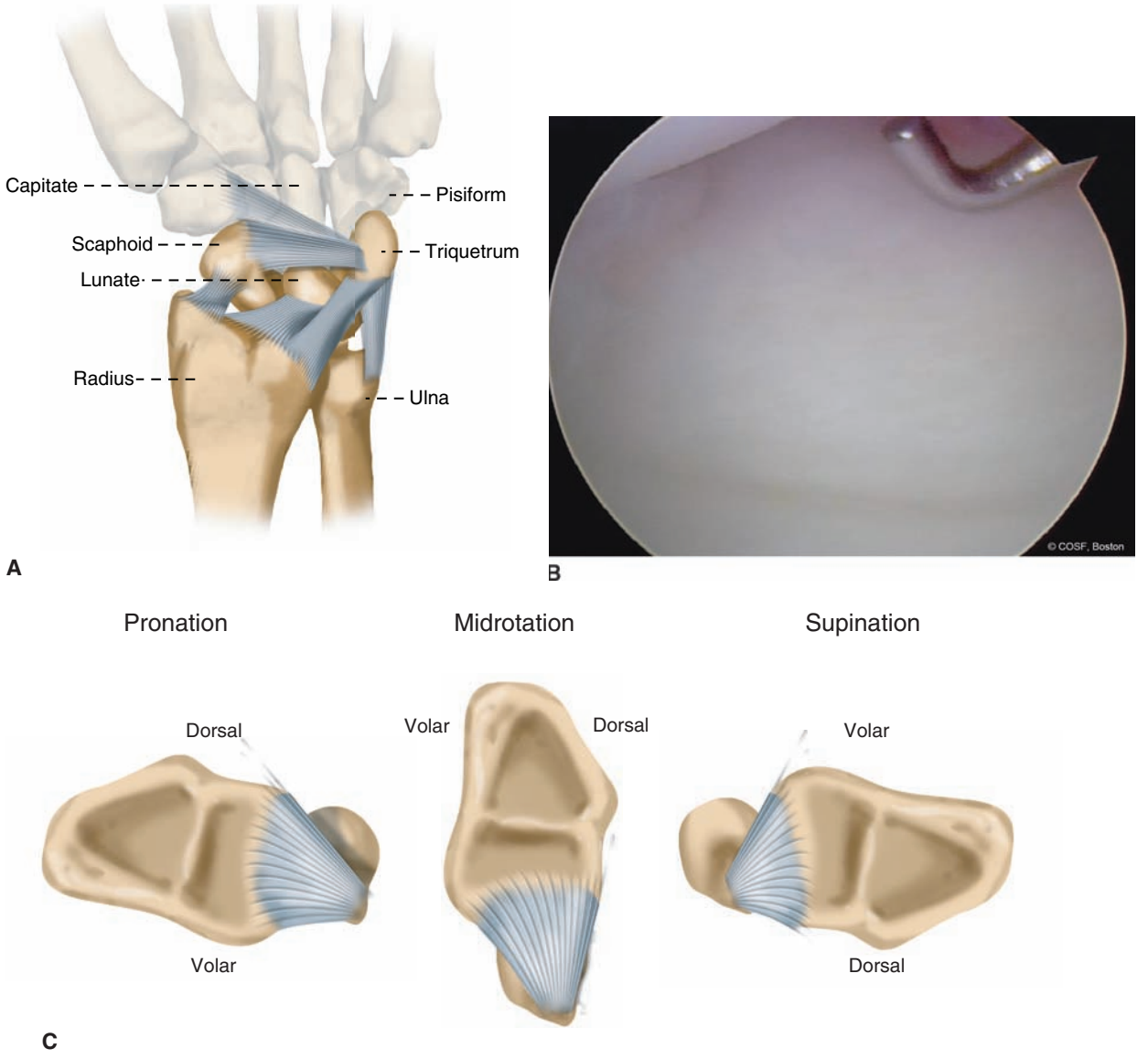


FIGURE 42-1 **A:** Illustration of normal wrist anatomy with scaphoid (S), lunate (L), and triquetrum (T) noted. The TFCC and volar ulnocarpal ligaments are shown. **B:** Arthroscopic view of the normal TFCC in a right wrist viewed from 3-4 portal. **C:** Normal function of DRUJ ligaments in pronation, supination, and neutral positions of the forearm.

Pain is often diffuse (see Coach's Corner). The opposite nonpainful wrist is used for comparison in all aspects of the physical exam. It is often best to start there, so the patient knows what you are going to do and establishes some trust. Specific locations (such as the ulnocarpal joint) can be diagnostic for anatomic injury (such as a TFCC tear). The presence of skin dystrophy and/or muscle atrophy is assessed before physical palpation or testing. Scaphoid, scapholunate, lunotriquetral, ulnocarpal, distal radioulnar, and volar radiocarpal joint areas are palpated in sequence. Palpation for ganglia in the usual locations (dorsal scapholunate, volar radiocarpal) is performed. Standard resistive strength (intrinsic and extrinsic), sensibility (light touch and two-point discrimination), and range-of-motion (passive and active) testing are performed on each patient to check for neuropathy, tenosynovitis,[13] tendinopathy, and muscle injuries.[14] Provocative testing for asymmetric ligamentous instability is necessary. Watson scapholunate shift, Lichtman midcarpal shift, lunotriquetral ballottement and shear, and ulnocarpal compression with forearm rotation are standard aspects of the exam. The presence of asymmetric clicking

FIGURE 42-2 Physical exam illustrations of midcarpal instability testing.

or clunking, particularly when it reproduces the patient's pain, guides diagnosis. Injection of local anesthesia in the maximum pain area can be helpful, but many adolescents are resistant to needles. Ultrasound imaging of a mass can distinguish ganglia.

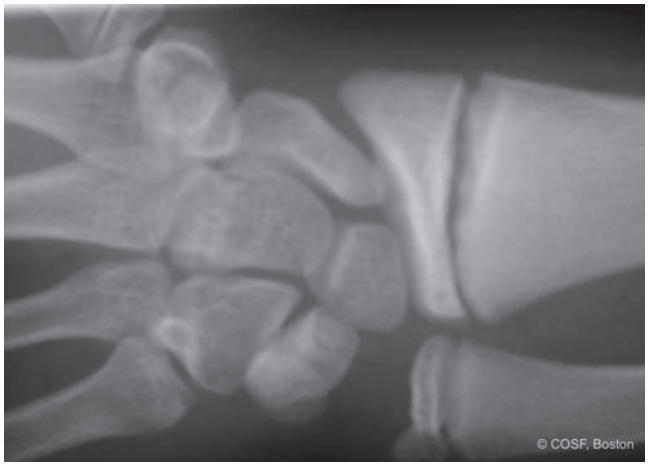


FIGURE 42-3 Radial stress injury in a gymnast.

Radiographs are obtained to assess for abnormalities such as physeal stress fractures (gymnast's wrist),[15] Kienbock's avascular necrosis of lunate, unhealed fractures (scaphoid nonunion, hook of hamate nonunion,[16] ulnar styloid nonunions and associated TFCC tears), carpal coalitions, and inflammatory arthritis, among others. Treatment is appropriately applied with each condition with a positive radiograph. With normal radiographs and a nonspecific exam, which is common, you are quickly at the crossroads of starting with the three R's (reassurance, rest, and rehabilitation) or proceeding directly to an magnetic resonance imaging (MRI)scan or wrist arthroscopy. Unless the exam is specific for an anatomic injury, we always start with rehabilitation. Approximately 80% of our highly specialized referral practice fits that pattern and can still be successfully treated with resistive strengthening. It is rare we use casting for these patients but often use intermittent splinting programs. We use strengthening not only as treatment but also as a part of our evaluation. Grip-and-pinch strength on both sides is monitored by a therapist during intrinsic and extrinsic strengthening (elastic bands and therapeutic putty) with the wrist stabilized in neutral position. We stress the value of a home program that incorporates multiple sessions a day with weekly supervised care. We reassure them that there is a difference between "hurt" and "harm" and that we want them to work through the "hurting" pain without fear of causing permanent damage. If all goes well, by 6 weeks the patient will demonstrate marked reduction in pain and near-normal strength. By 12 weeks, the problem is often resolved.

If the problem persists, you then have to decide on more thorough musculoskeletal evaluation and treatment or referral to a pain specialist or nontraditional caregiver. The use of MRI scans can be diagnostic but also confusing depending on the threshold of signal abnormality the radiologist uses to make a reading.[17–19] At our center, there are many more false negatives than false positives. The improving sequences narrow the gap of specificity and sensitivity but also make it imperative that we keep pace with the changing technology. The addition of arthrographic iodinated contrast material expands the diagnostic accuracy but, again, involves needles. In the remaining subset of patients with persistent problems, MRI scans often enable us, the patient, and the family to move definitively to surgery or away from orthopaedic interventions.

Surgical Indications

A limited number of adolescent patients presenting for evaluation of sports-related nonosseous wrist pain need surgery. As noted above, most can be treated with the three R's: reassurance, rest, and rehabilitation. However, there are athletes with focal soft tissue and cartilaginous disorders that benefit from surgery. These include (1) scapholunate and lunotriquetral ligament tears;[20] (2) chondral impaction injuries; (3) TFCC tears; (4) an unstable DRUJ;

(5) arthroscopy for diagnostic dilemmas;[21] and (6) rare, chronic tendinopathies. In addition, resection of the terminal branch of the posterior interosseous nerve at its insertion into the wrist can be a part of surgical management for chronic, recurrent conditions.

SURGICAL PROCEDURES

Do you know what my favorite part of the game is? The opportunity to play.
—Mike Singletary

Ganglion Excision (Figure 42-4)

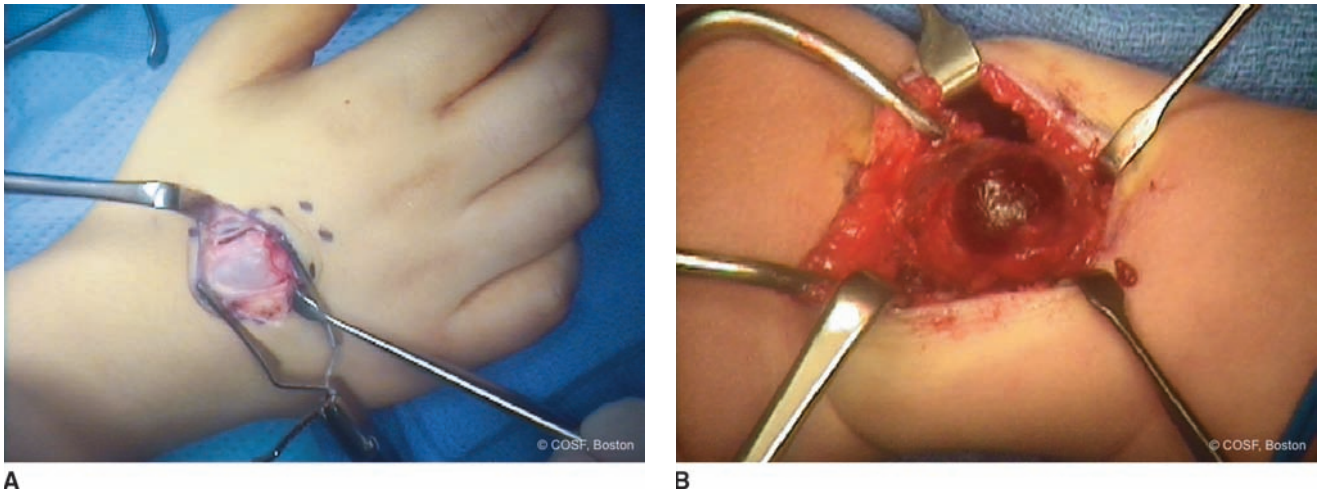
A dorsal ganglion, whether small or large, can cause symptoms with wrist arc of motion, especially dorsal impaction. However, not all ganglia are symptomatic. They can be associated with carpal instability, so excision alone may not resolve symptoms. They can be excised open or arthroscopically. An open procedure is performed through a transverse incision over the dorsal ganglion. The origin of the ganglion is typically the scapholunate ligament. The dorsal veins and extensor tendons are protected with dissection. Circumferential dissection requires care not to rupture the ganglion before isolation of the stalk. Failure to remove the stalk is an invitation to recurrence. A square or circumferential dorsal capsulectomy is performed, incorporating the ganglion stalk. Some have advocated an inside-out removal of the stalk by opening the ganglion and following the stalk from the inside down to the origin. This is an open adaptation of the arthroscopic technique. After capsulectomy and stalk removal, the area of origin is debrided with a mini-rongeur and cauterized without impairing ligament integrity. The tourniquet is deflated to inspect for any bleeding. After local anesthesia injection and layered closure with absorbable suture, we usually immobilize in a bivalved cast or splint for 2 weeks followed by unrestricted activity. Stiffness and loss of strength are usually not a problem with these children. If they are ligamentously lax, we have them do a supervised strengthening program to eliminate that element of their pain as well.

Osterman and Raphael reported the arthroscopic removal of dorsal ganglia, and many now follow this technique.[22] There may be cosmetic and rehabilitation benefits, especially in adults. Recurrence rates now appear to be similar, <5%.[23] The scapholunate ligament, along with the rest of the joint, can be better assessed. The 3-4 portal cannot be used, as it is adjacent to or overlying the ganglion. The 4-5 portal is too close. Thus, visualization of the ganglia is with the arthroscope in the 6-R portal. A needle is placed from the dorsal skin through the ganglion into the radiocarpal joint. The needle enters the joint obliquely. An inside-out debridement is performed with the shaver in this modified 3-4 portal. The defect in the dorsal capsule and the ganglion stalk from the dorsal capsule to the scapholunate ligament is debrided. A complete capsulectomy is performed, and, afterward, the extensor carpi radialis brevis tendon should be visualized through the dorsal aspect of the capsule. Postoperative care is similar to open procedures but requires less time for wound protection and healing.

Arthroscopic Debridement (See Sidebar) (Figures 42-5 and 42-6)

Arthroscopy is the gold standard for diagnosis of intra-articular pathology. This is not to advocate for bypassing prudent physical exam, radiologic evaluations, and non-operative management of most children and adolescents with acute and chronic wrist pain. However, arthroscopy will provide definitive information on the interosseous ligaments, chondral articular surfaces, and TFCC and allow for surgical management of these specific problems not otherwise adequately treated.[21,24]

Adolescent athletes with ligamentous laxity can recurrently sublux their midcarpal and radiocarpal joints. This



A B

FIGURE 42-4 **A:** Dorsal ganglion excision. **B:** Hemorrhagic ganglion from repetitive trauma.

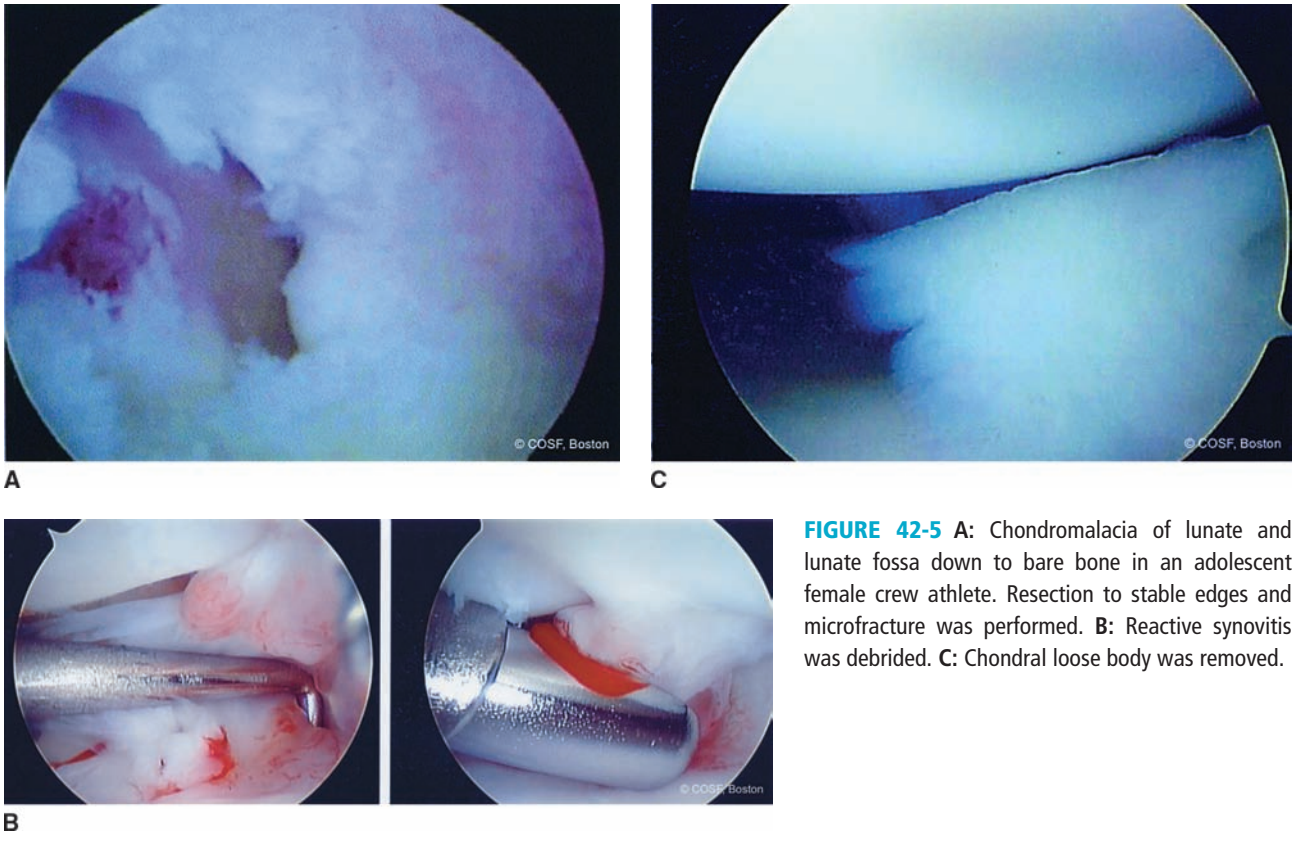


FIGURE 42-5 **A:** Chondromalacia of lunate and lunate fossa down to bare bone in an adolescent female crew athlete. Resection to stable edges and microfracture was performed. **B:** Reactive synovitis was debrided. **C:** Chondral loose body was removed.

can occur in crew, tennis, and gymnastics, among others. Or, they can have a single subluxation episode with impaction from a fall, such as in soccer. In their mildest forms, these recurrent episodes produce mechanical symptoms and an inflammatory response. In the patient unresponsive to rest and therapy, arthroscopy often reveals synovitis, reciprocal impaction lesions of the volar lunate fossa and dorsal lunate with varying degrees of cartilage loss. There may be loose bodies. There can be a partial scapholunate tear and/or associated TFCC tear. Atraumatic debridement of loose bodies, synovitis, and loose cartilaginous flaps with mini-shavers is performed in standard fashion. If there is bare bone exposed, mini-microfracture is performed with thin angled bone picks. Immobilization in a short-arm cast for 2 to 4 weeks is followed by splinting and rehabilitation. We emphasize extrinsic strengthening to compensate

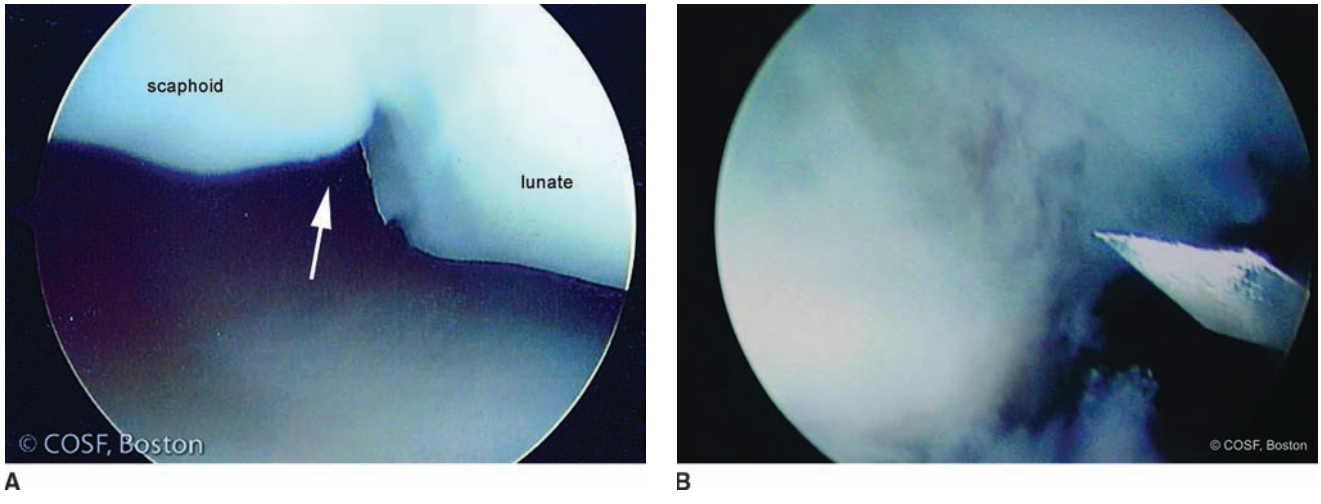


FIGURE 42-6 **A:** Partial scapholunate tear in athlete with chronic wrist pain. **B:** Drilling of osteochondral defect. There was associated chondromalacia and synovitis that was also debrided.

for intrinsic ligamentous laxity. We do not perform dorsal capsulodesis procedures at initial arthroscopic debridement. Capsulodesis is reserved for recurrent injuries and static instability patterns.

The stability of the scapholunate ligament is assessed from the 3-4 and midcarpal portals. The ligament is probed from the 4-5 portal with 3-4 visualization. From the midcarpal portal, the ligament should be tight without any step-off between the scaphoid and lunate. The lunotriquetral ligament is best seen from the 4-5 and midcarpal portals. It should be congruent from the 4-5 portal but can normally have a slight gap (1 mm or less) and incongruency from the midcarpal portal. Geissler developed an arthroscopic classification of interosseous ligamentous instability, graded I through IV. Type IV is a complete tear and requires ligamentous reconstruction. Types II and III have increasing dynamic instability and incongruency with a partial tear. Type IIs and the majority of type IIIs have been treated with successful arthroscopic debridement in adolescents[25] and adults.[26] The goal is debridement of the convex redundancy of the scapholunate and lunotriquetral ligament back to stable tissue without impairing the integrity of the ligament. With the scapholunate ligament, this can be performed with 3-4; 4-5; and midcarpal instrumentation and visualization. With lunotriquetral tears, this is performed with 3,4 (difficult visualization); 4-5; 6-R; and midcarpal surgery and visualization.[27] Associated chondral lesions and synovitis are also debrided. We have not percutaneously pinned the carpal bones with carpal reduction as some have advocated. Immobilization is performed for 4 to 6 weeks followed by 6 weeks of rehabilitation.

TFCC Repair

Athletes with chronic, ulnar-sided wrist pain, particularly with pronation and supination, should be evaluated for TFCC tears.[28] In children and adolescents, most of these are associated with previous radius fractures, malunions, ulnar styloid nonunions, and/or positive ulnar variance.[29] TFCC tears can also be seen in isolation. MRI can be diagnostic of the tear but not always; ulnar-sided TFCC injuries, in particular, may be difficult to characterize on MRI. Patients with unresolved pain and/or positive MRI scans should have arthroscopic exam and treatment. Any patient with an associated positive ulnar variance and ulnocarpal impingement should have a simultaneous ulnar shortening osteotomy. We do not advocate for wafer procedures in children and adolescents.

Palmer classified TFCC tears by mechanism[30] (traumatic [I] and degenerative [II] and subtyped them by location—A = central [Figure 42-7]; B = peripheral; C = volar; D = radial). Most adolescent athletes have type IB peripheral tears followed less commonly by ID radial tears.[31] Isolated tears are treated arthroscopically. Tears associated with bone and joint deformity can be treated either open or arthroscopically depending on the situation and in conjunction with osseous reconstruction. Ulnar shortening osteotomy should be performed whenever there is a

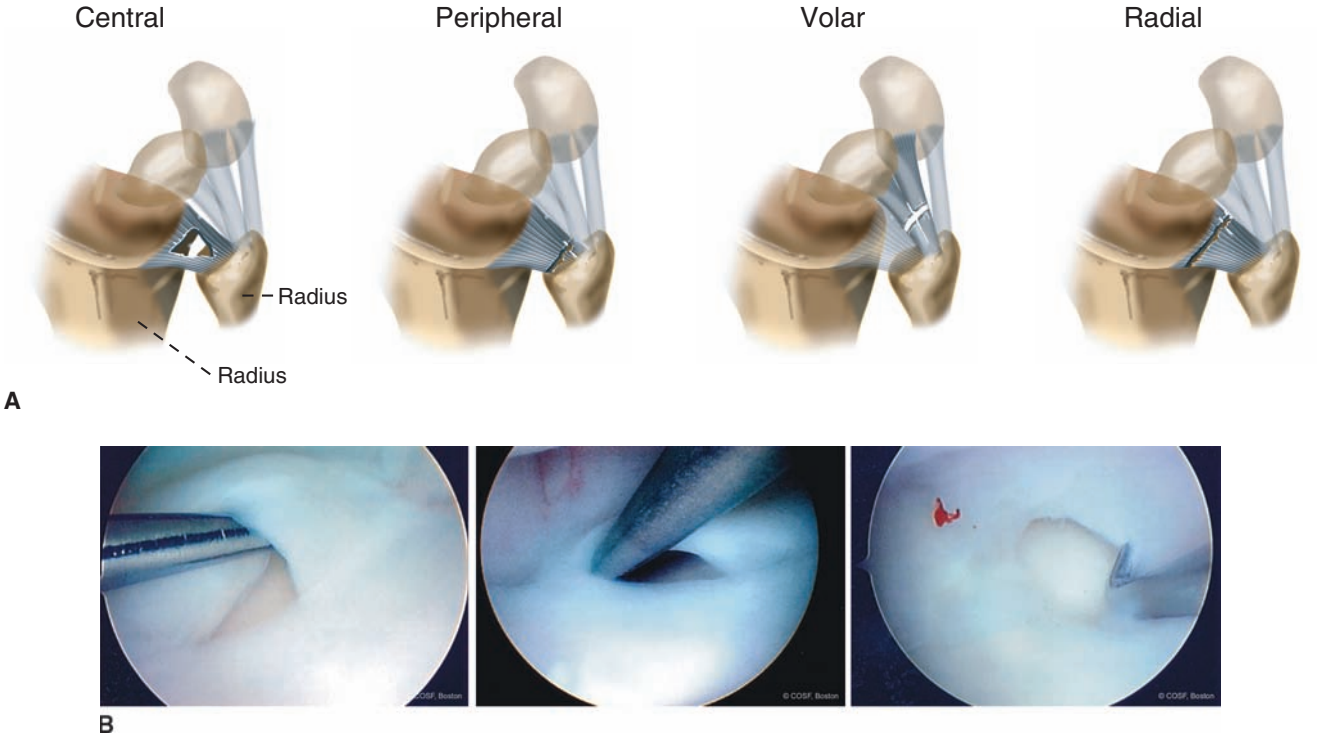


FIGURE 42-7 **A:** Traumatic tears are classified as IA = central (rare in children); IB = peripheral (most common type); IC = volar; and ID = radial (second most common in adolescents). **B:** Arthroscopic views of Central TFCC tears.

TFCC tear with positive ulnar variance.[32] Arthroscopy can be easier and atraumatic after rigid internal fixation of an ulnar shortening osteotomy for marked positive variance.

Arthroscopic IB Repair

Visualization is mainly through the 3-4 portal and 4-5 portal as needed. Debridement of the ulnocarpal synovitis from the 4-5 portal will reveal the peripheral tear. This is the most vascular aspect of the TFCC and allows for excellent results with direct repair. Probing of the lesion will define the extent of the tear. Outside-in suture repair is performed while protecting the dorsal ulnar sensory nerve. We usually use a single horizontal mattress 2-0 polypropylene suture (Prolene, Ethicon, Inc., Somerville, NJ). Others use two vertical mattress sutures. Two cannulated suture passers are placed through the capsule and across the tear (Figure 42-8).

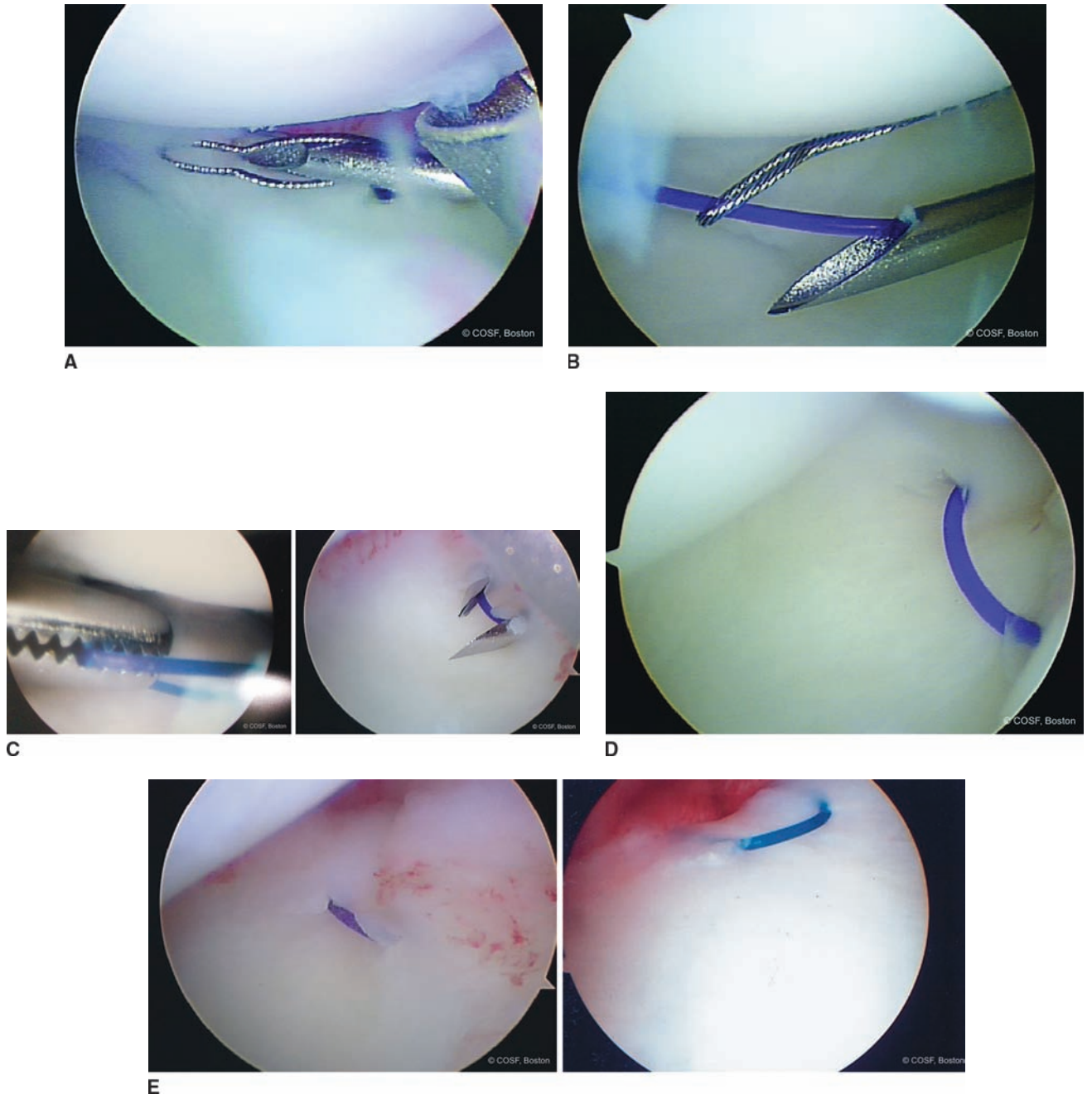


FIGURE 42-8 **A:** Peripheral TFCC repair with passage of cannulated needles. **B:** The wire loop is passed through one needle with the suture through the other. **C:** The suture is grasped in the wire loop and passed out the other cannulated needle. Care is taken not to lacerate the suture on the sharp edges of the needles. **D:** The cannulated needles are removed, and the suture is brought to the edge. **E:** The traction is lessened on the wrist, and the suture is tied tight. Images are of horizontal mattress suture repairs.

These can be manufactured specifically for TFCC repairs or 18-gauge Tuohy needles. The suture is passed through one cannula (Figure 42-8), then through a wire loop retriever passed down the other cannula (Figure 42-8), and brought back to the ulnar-sided entry. Dissection between both ends of the suture is performed to be certain the sensory nerve is not entrapped during suture tying. Tension is taken off the traction tower, and the repair is completed with suture knot tying. Visualization and probing confirm tight repair. Portals are closed with absorbable suture. Long-arm cast immobilization (3 to 4 weeks) to prevent rotatory disruption of the repair is followed by short-arm immobilization (2 to 3 weeks) for a total of 6 weeks of cast protection. Rehabilitation with intermittent splinting is continued until full motion and strength are achieved. Return to sports is after 6 weeks and complete rehabilitation.

◆ Arthroscopic ID Repair

Detachments from the radial side above the sigmoid notch are known as ID lesions. Partial lesions are debrided to a stable base. Complete lesions are repaired. This is more elaborate than a peripheral IB repair as (1) this is an avascular region of the TFCC and (2) stable repair requires osseous fixation. We use a transradial repair to best close the defect, stabilize the repair, and promote vascular ingrowth. For us, it has been more gratifying than transosseous suture anchors or open repair.

After inspection and probing of the lesion, the transradial repair is begun by drilling from inside the tear obliquely across the radius. Two 0.62″ smooth C-wires are passed from the 6-U portal through the radial detachment of the TFCC into and across the radius. Gentle, sequential oscillating power passage of the wires with a mild distal-to-proximal obliquity is performed. This should increase osseous vascularity to the repair site, and, if in doubt, further local bony debridement is performed to increase healing potential. These wires should exit the radius near the first dorsal compartment, in the region of the extensor tendons and radial sensory nerve. A small longitudinal incision is made over this area for direct visualization of pin penetration to protect the surrounding soft tissues, and eventually to tie the suture repair over the bone (Figure 42-9). In sequence, the wires are replaced with long Keith needles. The Keith needles must pass through the TFCC from the 6-U entry area, across the radius through the previously drilled hole, and exit without impaling nerve, vessel, or tendon. (Ideally this would be a single cannulated wire and suture passage system, but this is not yet commercially available in the proper size). This can be a bit of a dance. The area between the two needles is then opened while protecting the dorsal ulnar sensory nerve. This prevents entrapment of the capsule into the ulnocarpal joint with suture repair. The 2-0 polypropylene suture (Prolene, Ethicon, Inc., Somerville, NJ) is passed through both Keith needles. Each needle is brought out the radial-based incision in sequence, resulting in a horizontal mattress suture across the radial TFCC. Care is taken to be certain the repair suture is clean without any intra- or extra-articular entrapment. Tension is taken off the traction tower and the suture tied tight over the distal radial bone. Final inspection of the repair (Figure 42-9) is performed. Portals and radial-based skin incision are closed with absorbable suture. Long-arm cast immobilization (4 weeks) to prevent rotatory disruption of the repair is followed by short-arm immobilization (2 more weeks) for a total of 6 weeks of cast protection. Rehabilitation with intermittent splinting is continued until full motion and strength are achieved. Return to sports is after 6 weeks minimum and complete rehabilitation. We are more careful with this repair than IB repairs due to this area's poor vascularity, which can affect healing potential and repeat disruption risk.

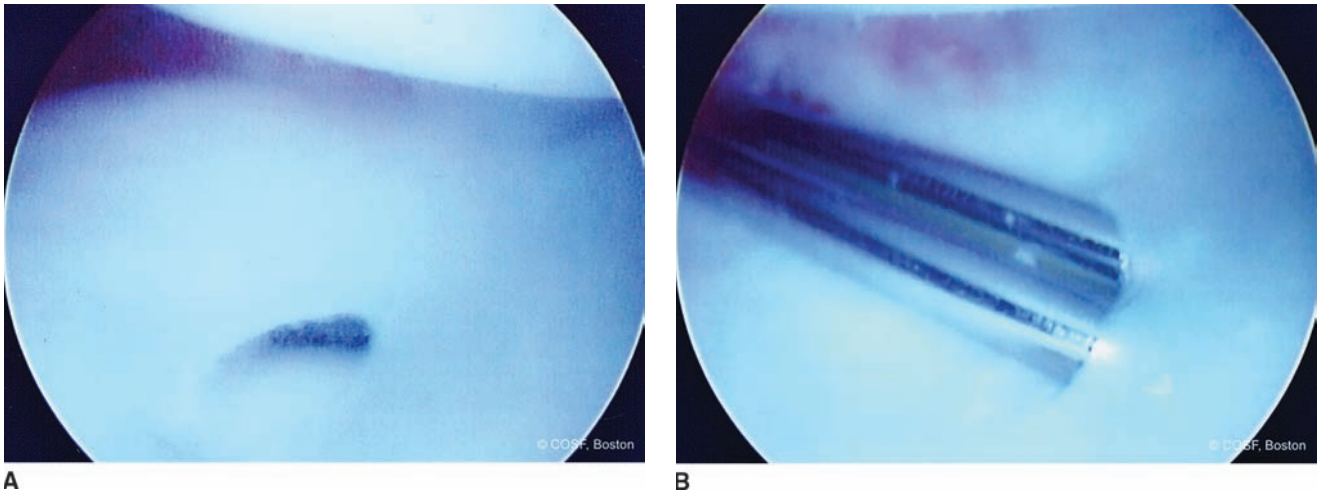
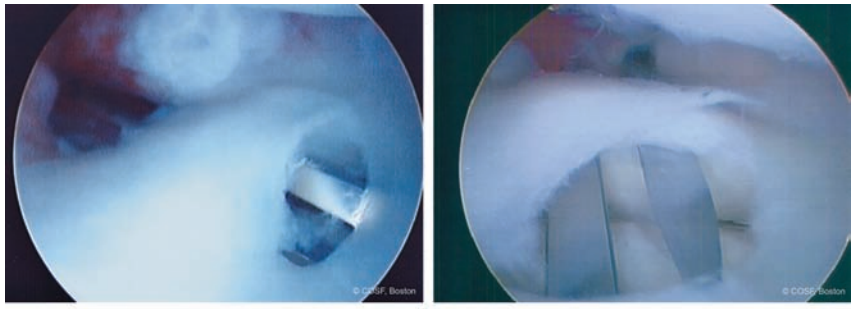


FIGURE 42-9 **A:** ID tear noted in a scholastic-level lacrosse player. **B:** Smooth C-wire drilling through the tear across the radius.

C



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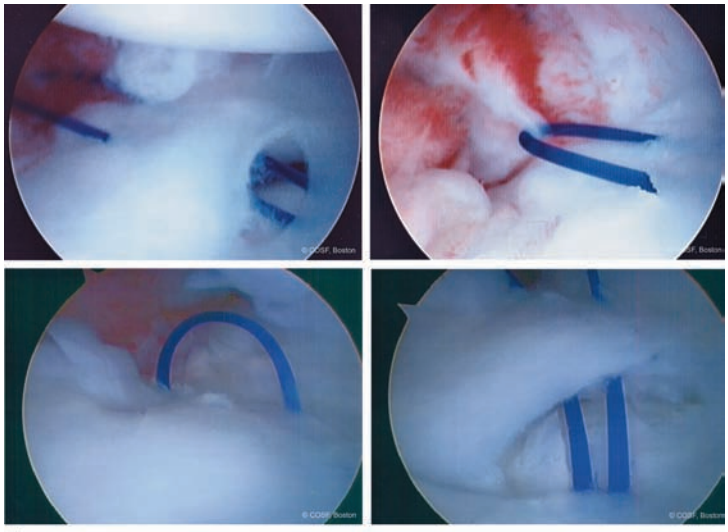

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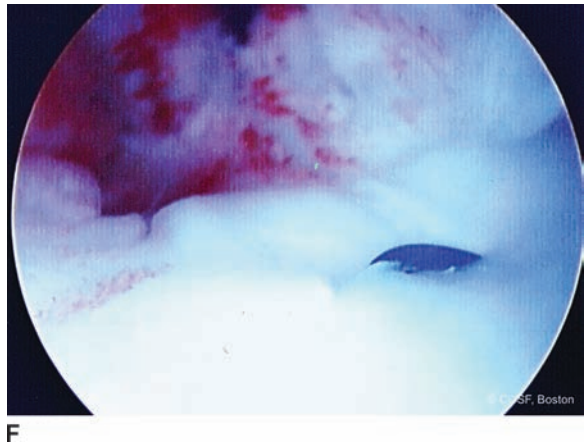


F

FIGURE 42-9 *(continued)* **C:** Radial incision to protect radial sensory nerve and extensor tendons for ID transradial osseous repair. **D:** Needle passage through central TFCC across the radius in preparation for suture passage. **E:** Suture passage. The suture must be free of the ulnar capsule for repair. **F:** Tension is taken off the wrist tower, and tightening of the suture on the radial side is performed.

◆ Interosseous Ligament Disruption and Reconstruction

There is a spectrum of interosseous ligament injuries and instability patterns. As noted above in Geissler's arthroscopic classification, these extend from minor tears to complete disruption. With scapholunate ligament injuries, dynamic instability extends from normal plain radiographs to widening of the scapholunate interval with ulnar deviation–clenched fist AP views. Static instability will have a >2-mm scapholunate interval, flexed scaphoid, and extended lunate consistent with a dorsal intercalated segment instability (DISI) pattern on plain radiographs. The risk of a DISI deformity is that over time a scapholunate advanced collapse wrist will develop with progressive arthritis in the radioscaphoid, midcarpal, and then radiolunate joints.

Scapholunate ligament reconstruction is indicated for static instability and dynamic instability not resolved by nonoperative or arthroscopic means.[33] There are multiple methods of reconstruction, all of which have had success and failure. Ligament reconstruction for dynamic

instability in adolescents is rare. In those rare situations, we have tended to utilize a dorsal capsulodesis procedure.[34–36] This is well described in multiple sources, and our technique does not vary. With limited long-term data, these patients have done well. The risk of arthritis in adulthood is unknown but presumably less.

◆ DRUJ Stabilization

Most of the adolescents with chronic instability of the DRUJ have TFCC tears. Repair of the TFCC will stabilize their DRUJ and relieve their symptoms. There is a small subset of children and adolescents who will have post-traumatic asymmetric instability of their DRUJ. Interestingly, some of these have come after nondisplaced radial metaphyseal fractures and represent true soft tissue instability. These need to be addressed with soft tissue reconstruction. Others include radial and/or ulnar fracture malunions. These require corrective osteotomies to realign the joint.

Similar to scapholunate ligament instability, there are multiple methods of DRUJ soft tissue reconstruction with varying degrees of success. Although we have used many of these methods, we are most satisfied with a dorsal partial extensor retinacular (a variation of the Herbert sling) reconstruction from the fifth and sixth compartments.[37] It is both simple and effective in this age group. On rare occasions, we have used the Salve-Kapandji technique with extraperiosteal excision to prevent reformation of the ulna in the young.[38]

Through a curvilinear incision over the fourth through sixth compartments, the extensor retinaculum is exposed while protecting the dorsal ulnar sensory nerve. The proximal 50% of the fifth and sixth retinaculum is elevated from radial to ulnar while isolating and protecting the extensor digiti quinti (EDQ) and ECU tendons. Direct inspection of the instability pattern and joint confirms the reconstructive plan. The dorsal redundancy in the capsule is included in the reconstruction with advancement. The proximal 50% of the fifth and sixth retinaculum are brought beneath the EDQ and ECU and repaired to the radius above the sigmoid notch in conjunction with capsular reefing. This repair is either done with radial-based periosteal sutures or osseous suture anchors. Proper tensioning of the reconstruction is in supination. Initially, in the operating room under anesthesia, there should be a mild limitation to passive pronation. This will stretch out over time postoperatively. Distally, the retinacular flap is repaired with nonabsorbable suture to dorsal and ulnar underlying the TFCC. This further stabilizes the joint. Once proper tensioning is reassured with stress testing of the DRUJ in neutral, supination, and pronation, the DRUJ may be percutaneously pinned in supination. Layered closure with absorbable suture is performed. A long-arm cast is used for 4 weeks, followed by pin removal in the office and a short-arm cast for two more weeks. Rehabilitation with intermittent splinting is performed for another 6 weeks. Return to sports is at three or more months depending on motion and strength testing.

POSTOPERATIVE

Soft tissue reconstructions require 4 to 6 weeks of healing. We maximally protect most children and adolescents due to more worries about disruption of repair than stiffness. In these complex soft tissue and chondral injuries, we utilize formal therapy to assist in regaining full motion and strength but also vigorously promote a daily home program. We restrict sports for at least 3 months, in essence one season, until there has been return of full motion and full strength.

ANTICIPATED RESULTS

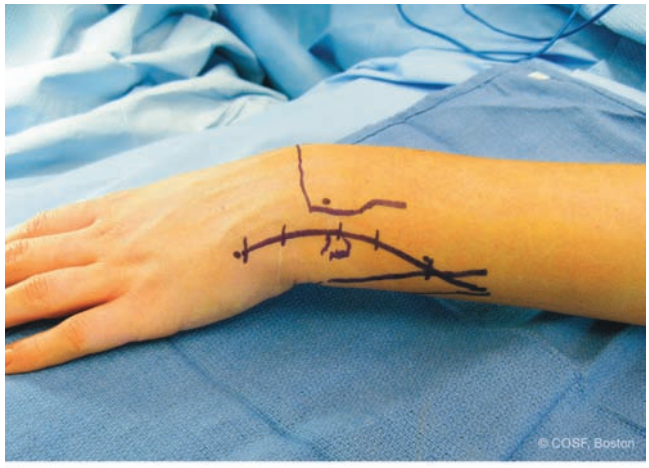
TFCC repairs have on average a >95% chance of healing without reinjury in adolescents. Similarly, partial scapholunate ligamentous and chondral injuries have excellent short-term outcomes for pain relief and return to full activities.[25] The major worry is irreversible chondral injury that will lead to arthrosis. Negotiating sports participation with patients, parents, and coaches is not always easy. Interestingly, some of the most skilled athletes with the brightest futures seem to be the most understanding regarding the importance of appropriate rehabilitation and preventive care.

COMPLICATIONS

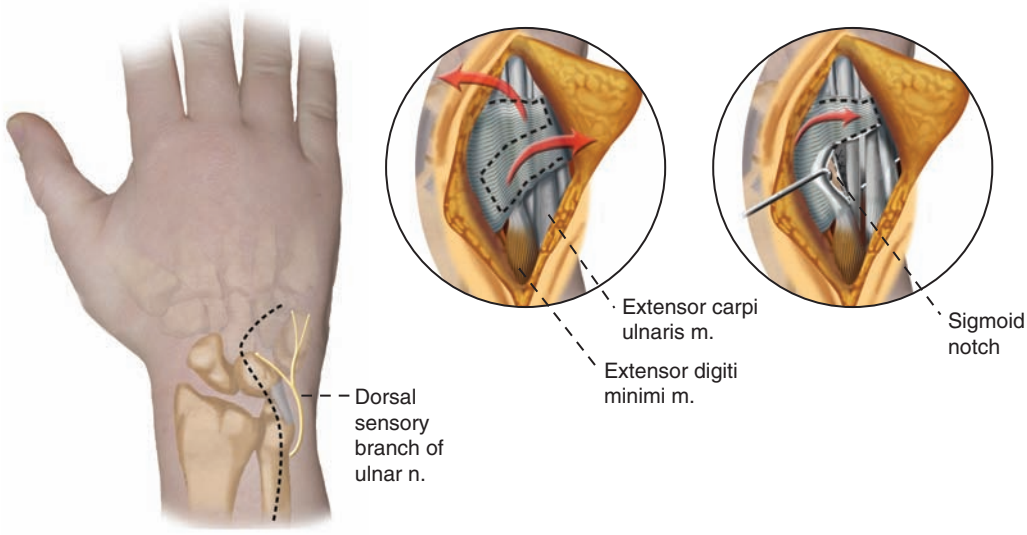
As addressed above, failure of the repair and recurrent injury are concerning. Full-thickness chondral lesions and ID TFCC tears are most at risk. Scapholunate gap formation has been often noted after reconstruction but is usually asymptomatic. Long-term risk of arthrosis with this is unknown. Recurrent DRUJ instability can occur with any type of repair. Repeat soft tissue reconstruction or conversion to Sauve-Kapandji radioulnar joint reconstruction is indicated in the symptomatic patients. Loss of motion can occur: pronation-supination with TFCC and DRUJ reconstruction and flexion-extension with ganglion excision and scapholunate ligament reconstruction. With instability, some tightness is expected for up to 6 months. In the long term, a little bit of loss may be of benefit, but major restrictions of motion are not desired. Finally, dorsal ulnar sensory nerve injury should be guarded against. Traction injuries usually resolve over 3 to 6 months. Entrapment, compressive, or laceration injuries require operative exploration and repair.

CASE OUTCOME

An MRI arthrogram revealed leakage of dye from the midcarpal to the DRUJ. The TFCC had a complete tear. Wrist arthroscopy revealed a peripheral type IB tear (Figure 42-10). This was repaired with an outside-in suture technique. Cast immobilization was for 3 weeks in a long-arm cast, followed by 3 weeks in a short-arm cast. The patient underwent motion and strengthening



A



B

FIGURE 42-10 **A:** Skin incision outlined for DRUJ reconstruction with extensor retinacular flap of fifth and sixth compartments. **B:** Outline of the retinacular flap.

rehabilitation for six more weeks with intermittent splint protection. Return to sports was at 3 months. Her pain resolved. Her modified Mayo wrist score rose from 74 preoperatively to 97 postoperatively.[31]

SUMMARY

As more and more children and adolescents have participated in competitive youth and extreme sports, soft tissue injuries about the wrist have become more common. Fortunately, most respond to the three R's: reassurance, rest, and rehabilitation. However, some may need surgery, and these can include ganglia; interosseous ligament tears with instability; chondral impaction injuries; and TFCC tears. With reconstruction, pain relief and restoration of function are anticipated.

SIDEBAR

The setup for wrist arthroscopy for children and most adolescents requires a small-diameter arthroscope, usually 2.7 mm. Most often the 30-degree visualizing angle is used. The wrist is distracted through finger traps at 10 to 15 lbs of traction. This can be done with a traction tower (ConMed Linvatec, Largo, FL) or shoulder holder. Counter traction is applied with a weight around the upper arm and the elbow in 90 degrees of flexion. In ligamentously lax individuals, some of this distraction force is lost through metacarpophalangeal (MCP) joint distraction. In some fracture cases in which both arthroscopy and fluoroscopy are used, the

(continued)

SIDEBAR (*continued*)

surgery is performed with the arm extended on a hand table. Rechecking of distraction throughout the case is important as tension can dissipate and visualization diminish. The standard 3-4 (between third [extensor pollicis longus, EPL] and fourth [extensor digitorum communis, EDC] dorsal compartments); 4-5 (between fourth and fifth [EDQ] compartments); 6-R (radial to ECU); 6-U (ulnar to ECU); and midcarpal (1 cm distal to 3-4; 4-5) portals are marked. Large dorsal veins are avoided. Tourniquet inflation is usually not performed until extensive debridement or repair is needed that will affect visualization.

The radiocarpal joint is inflated through needle injection of sterile saline. This is a saline arthrogram and palpation of the midcarpal and DRUJ during injection provides information about pathologic communication between the wrist compartments. The joint is maximally inflated. A pressurized pump is used at low flow. The 6-U portal can act as a needle outflow. One-centimeter skin incisions are used, starting with the main visualizing 3-4 portal distal to Lister tubercle. Trocar entry should be atraumatic to the chondral surfaces. Obviously, extensor tendons, dorsal veins, and sensory nerves are protected with portal entry and arthroscopic work. Trocar entry should be in the central proximal-to-distal aspect of the radiocarpal joint in line with the articular surface (normal volar inclination is 11 degrees but radiographs will reveal the specifics of each joint). The 4-5 and 6-R portals are the main working portals. Chondral loose bodies, dorsal lunate, and triquetral chondromalacia can impair entry. Move to another portal for visualization if entry is difficult rather than forcing it. Ligament probing is performed and the midcarpal visualization for a "drive through" sign is used if there is laxity of the scapholunate joint. Joint debridement is performed with various small-diameter shavers. The 6-U portal may be necessary for repair of a radial-based ID TFCC tear or peripheral outside-in suture repair of peripheral IB lesion. In these cases, the ulnar sensory nerve needs protection. Wrist arthroscopy can also be used in intra-articular fracture reduction.[39]

COACH'S CORNER

Golf appeals to the idiot in us and the child. Just how childlike golf players become is proven by their frequent inability to count past five.
—John Updike

There is subtlety to sorting out chronic wrist pain in the adolescent. We equate it to sorting out patellofemoral knee pain in the same age group. Both types of patients: (1) are in a growth acceleration phase of life; (2) have consequential muscle imbalance; (3) may be under significant performance pressure from coaches, parents, teachers, peers, and themselves; (4) may have secondary gain issues; (5) are teenagers, a subpopulation who are inherently difficult to "read"; and (6) usually have legitimate reasons to have an injury. By the time they present to the super-subspecialist, they probably have had several failed treatments. These can include cast and/or splint immobilization, therapy, anti-inflammatory medications, rest, ice and/or heat, corticosteroid injections, and even surgery.

Our initial assessment includes a thorough history with emphasis on listening, an exam to assess if there are focal anatomic abnormalities, and a screening radiograph for specific abnormalities. If there is specific concern, we proceed to laboratory screening blood work, and/or an MRI or artho-MRI scan. Many of the patients will already have had this when they present. If these are all negative, we usually proceed with a progressive resistive exercise (PRE) program, particularly in the ligamentously lax children with midcarpal instability by exam. Similar to the knee with patellofemoral pain, the strengthening needs to be done with a stable joint. Pretherapy grip-and-pinch strength are measured and monitored throughout the program. We stress the difference between "hurt" and "harm" to lessen anxiety about the risks of pain and permanent damage to the wrist. Initial wrist flexion-extension arc of motion PREs with weights will usually worsen the pain. Stable wrist in neutral strengthening is done with therapeutic putty of increasing resistance as strength objectively improves by grip-and-pinch measurements. We expect a 6- to 12- week time course with "good days and bad days." We stress a home program of many times a day ("squeezing the putty a million times a day may be enough"). The goal is normal pinch-and-grip strength as compared to the opposite side. Roughly 80% will achieve this by 6 to 12 weeks and have pain relief and restoration of function without limits. In the other 20%, we decide on MRI scan (hard not to get one), pain clinic, acupuncture, biofeedback, subspeciality referral, or diagnostic arthroscopy. Thus, the art of selection comes from seeing, listening to, and examining a lot of these children and adolescents.

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CHAPTER 43

Local and Regional Soft Tissue Coverage of the Hand

CASE PRESENTATION

A 4-year-old male presents emergently for evaluation of a fingertip amputation sustained after the right ring finger was caught in a closing door (Figure 43-1). The digital tip was avulsed and lost. Examination demonstrates a transverse fingertip amputation through the level of the distal phalanx with minimal contamination and exposed bone.

CLINICAL QUESTIONS

- What are the patterns of fingertip injuries/amputations in children? How does the pattern of injury dictate treatment?
- What is the reconstructive ladder?
- What are the treatment options for patients with fingertip avulsions without bone exposed?
- What are the treatment options for fingertip amputations with exposed bone?
- In cases of more severe hand trauma, what are the indications and treatment options for soft tissue coverage of the hand?

THE FUNDAMENTALS

Fingertip injuries are common in the pediatric population, particularly in toddlers and younger children. Although less common, severe combined injuries of the hand do occur and present their own set of clinical challenges. Awareness of the treatment principles and surgical options is essential for the pediatric hand and upper extremity surgeon. As each patient will present with unique anatomic and clinical considerations, the ability to use a number of different surgical tools will allow for individualized care and maximization of outcomes. Furthermore, as traumatic bony and soft tissue loss occurs suddenly and unexpectedly, the time of initial evaluation and clinical treatment is often emotionally charged and psychologically stressful for patients and families alike. Clear communication and thoughtful clinical approaches will ease anxieties, facilitate timely and definitive care, and establish realistic expectations for long-term results.

As discussed below, nonoperative and surgical treatment is based upon a number of patient and injury characteristics, including (1) size and depth of wound; (2) whether there is exposed bone, tendon, or neurovascular structure; (3) degree of wound contamination; (4) availability of local or remote tissue to assist with coverage; and (5) patient and family sophistication and compliance. Regardless of which treatment option is undertaken, thorough wound debridement is critical for prevention of infection and optimization of wound healing.[1]

Etiology and Epidemiology

Fingertip injuries, though most common in toddlers and younger children, affect patients of all ages. The vast majority of injuries are due to traumatic crush-avulsion mechanisms, such as when the affected digit is caught in a closing door or beneath heavy objects. Furthermore, in this age of increasing, high-energy sports participation, more fingertip and hand injuries are seen from sports-related activities. Therefore, the peak ages for incidence of finger injuries are toddlers (crush) and adolescents (sports). Classification is typically descriptive and anatomic.

Clinical Evaluation

We try to stress the little things because little things lead to big things.
—Steve Alford

FIGURE 43-1 Clinical photograph depicting a transverse fingertip amputation of the right ring finger.

Despite the sense of urgency that often accompanies the initial evaluation of patients with traumatic fingertip amputations or soft tissue loss, a thorough history and clinical examination should be performed. As with other traumatic conditions, hand dominance, functional demands, and any associated medical comorbidities must be documented. Careful assessment of wound contamination, vascular status, and the condition of proximal soft tissues (nerves, tendons, subcutaneous tissue, and skin) should be done. Furthermore, characterization is made for the pattern of tissue loss, which will help determine the most appropriate reconstructive technique (Figure 43-2). All amputated parts should be salvaged, saved, and examined for possible repair, replantation, or use as "spare parts." Radiographic evaluation of the affected anatomic parts is necessary to assess for the presence and pattern of skeletal injury and/or articular involvement. With more proximal amputations, x-rays of both the injured finger and amputated part are helpful in reconstructive planning. Antibiotics and tetanus boosters should be provided in the emergency setting. The injured hand/upper limb is irrigated with sterile saline and bulky soft bandages, and splint immobilization is applied. The amputated part is wrapped in saline-soaked gauze and placed in a sterile container.

Surgical Indications

The goal of treatment for fingertip injuries is the reconstitution of a durable, sensate, viable digital tip that possesses adequate bony coverage and, if possible, preserves digital length. As a host of treatment options are available, the particular reconstructive strategy must be tailored to each individual patient. Surgical indications are therefore equally variable. In general, surgical treatment is indicated in cases of extensive fingertip soft tissue loss exceeding 1 cm^2 in cross-sectional area and/or bone exposed. It should be noted that the vast majority of simple fingertip injuries may be treated effectively with nonoperative means, particularly in young children, who demonstrate great healing potential.

In cases of more extensive soft tissue loss, treatment is indicated for coverage of bony, tendinous, or neurovascular structures that cannot be achieved by simple primary closure alone.

SURGICAL PROCEDURES

Good sound habits are more important than rules—use concepts.
—Mike Krzyzewski

While a host of surgical procedures are within the armamentarium of the pediatric hand and upper extremity surgeon, a few fundamental principles are universally applicable. First, every effort should be made to avoid infection by thorough irrigation and debridement of contaminated wounds and timely soft tissue (and bony)

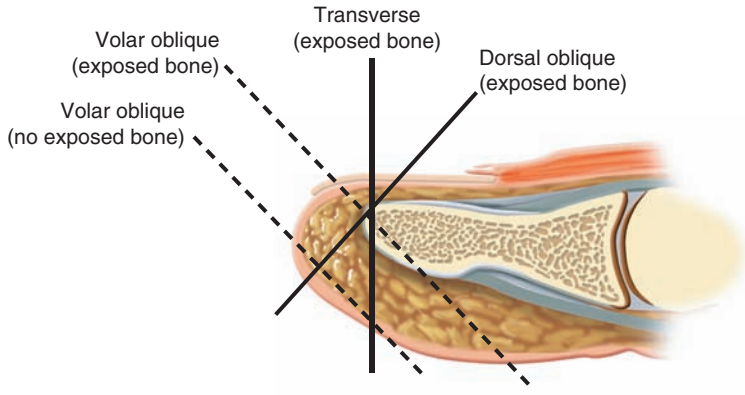

FIGURE 43-2 Schematic diagram depicting the patterns of digital tip loss: dorsal oblique, transverse, and volar oblique.

Table 43.1

The reconstructive ladder[2]

8. Distant/free flaps
7. Regional/pedicle flaps
6. Local flaps
5. Composite grafts
4. Full-thickness skin grafts
3. Bony shortening and primary closure
2. Healing by secondary intention
1. Primary wound closure

reconstruction. Second, in a child, emphasis is placed on preserving digital length, function, and growth potential whenever practical. Finally, simpler solutions are favored over more complex solutions, particularly in the anxious, distressed, often nonverbal child in whom multiple procedures and/or anesthetics are to be avoided.

The "reconstructive ladder" has been proposed to guide the surgeon on treatment options[2] (Table 43.1). Each successive "rung" of the reconstructive ladder represents a more complex surgical strategy to achieve soft tissue coverage and should only be considered if simpler, less complicated procedures are ruled out. Pediatric hand and upper extremity surgeons should be familiar with these surgical options, and a systematic approach to reconstructive decision making is recommended.

Primary Wound Closure, Healing by Secondary Intention, Bony Shortening and Primary Closure or Healing by Secondary Intention

Simple solutions are possible in the vast majority of pediatric fingertip injuries. When there is adequate skin and soft tissue available, primary wound closure is easy, effective, and almost universally successful. In cases with uncovered distal phalangeal bone, simple skeletal shortening by rongeuring the exposed tip of the distal phalanx will allow for primary wound closure or adequate healing by secondary intention.

In these cases, small defects (<1 cm^2 in cross-sectional area) may be treated with serial dressing changes, allowing the wound to heal by secondary intention.[3–6] When wound healing by secondary intention is pursued, the primary dressing may be left in place for 1 to 2 weeks in cases of clean uncontaminated wounds. At this time, once there is confirmation that there is no infection, parents and families may be instructed on daily half-strength hydrogen peroxide soaks and dressing changes. Our preference is to use petrolatum gauze (Xeroform, Covidien, Mansfield, MA) and Coban self-adherent wrap (3M, St. Paul, MN) to the affected digit. While the long-term results are highly satisfactory in terms of both sensibility and aesthetic appearance, this strategy takes time and may be challenging in the very young patient. Parents and other care providers must be dedicated and sophisticated in their understanding and adherence to this treatment plan.

Split-Thickness Skin Grafts, Full-Thickness Skin Grafts, and Composite Grafts

Skin grafting for fingertip injuries is rare in children. A prerequisite to skin grafting is an uncontaminated recipient soft tissue bed; adequate vascularity to support graft healing; and no exposed bone, tendon, or neurovascular bundles.

Split-thickness skin grafting (STSG) is rarely used in the hand except for large palmar areas of skin loss, such as with deep burns. The STSG is used in delayed closure of large traumatic forearm wounds, such as post fasciotomies for compartment syndromes, when there is an underlying bed of healthy muscle. The graft donor site is usually the upper posterior thigh to lessen the poor aesthetics of the resultant scar. An appropriate-size dermatome to match the recipient site is utilized. Usually this is 0.015″. Mineral oil is placed on the donor site, and tension is maintained on the dermatome throughout the harvest to obtain a uniform thickness graft. The STSG is meshed with standard equipment and then placed with mild tension over the recipient site. The STSG is sutured in place, so there is adherence of the graft over the entire recipient site. A petrolatum gauze (Xeroform, Covidien, Mansfield, MA) and moist cotton bolster are secured over the graft to promote healing. This is removed in the office at 5 to 14 days, depending on the clinical scenario.

Full-thickness skin grafting (FTSG) may similarly be utilized in cases of large (>1 to 2 cm) skin loss with adequate vascularized subcutaneous tissue. Skin grafts are not indicated in cases of exposed bone, tendon, or cartilage, and they may lack the bulk and durability desired for hand function; for this reason, it is unusual for skin grafts to be used in cases of fingertip avulsions or digital tissue loss. Potential donor sites for FTSG include the inguinal fold (lateral to the palpable femoral pulse to avoid harvest of future hair-bearing skin), antecubital flexion crease, wrist flexion crease (though this is not preferred given the potentially aesthetically and socially unpleasing transverse scar), and hypothenar eminence of the hand.[7] Ideally, glabrous skin of equal pigmentation is chosen to achieve a more durable and aesthetically pleasing result. After harvest and defatting, the skin graft may be sewn in using multiple interrupted 5-0 or 6-0 polyglactin suture (Chromic, Ethicon, Inc., Somerville, NJ), the tails of which are left long to secure a saline-soaked cotton and petrolatum gauze (Xeroform, Covidien, Mansfield, MA) bolster, which is placed over the graft to promote adherence and subsequent graft take. Dressings and the petrolatum gauze-cotton bolster may be removed after 2 weeks, and near-universal take is expected in young, healthy children with clean, vascularized soft tissue beds.

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FIGURE 43-3 Clinical photographs depicting the technique of composite toe grafting for digital tip amputations. **A, B:** Intraoperative photographs depicting the dorsal and volar aspects of the injured ring finger. **C:** Intraoperative photograph depicting the incisions used to harvest free composite toe pulp graft. The elliptical design facilitates primary wound closure of the harvest site while allowing appropriate recipient site coverage. **D:** Intraoperative appearance after graft placement.

E

F

G

H

FIGURE 43-3 *(continued)* **E:** The donor site is closed primarily. **F, G:** Appearance of the fingertip 2 months postoperatively. The pulp has been reconstituted with complete take of the composite graft. **H:** The appearance of the donor site postoperatively.

Another strategy that is particularly helpful for fingertip reconstruction in children is the use of *composite grafts*. If the amputated digital tip is available, it may be repaired primarily; in children, there is a higher likelihood of healing than in adults.[8,9] In cases where the digital tip is not available, contaminated, or too damaged to allow for "repositioning," composite toe grafting may be performed[10,11] (Figure 43-3). Under general anesthesia and digital tourniquet control, an elliptical-shaped incision is made over the plantar pulp of one of the lesser toes, the dimensions of which are determined by the size of the fingertip defect. Skin and approximately 4 mm of subcutaneous fat are excised as a composite graft. Provided that the major axis of the ellipse is two to three times greater than the minor axis, the donor defect may be easily closed primarily with multiple interrupted 4-0 or 5-0 polyglactin suture (Chromic, Ethicon, Inc., Somerville, NJ), followed by application of a simple bandage. The composite graft is then placed in the recipient bed and reapproximated using multiple interrupted 5-0 polyglactin suture (Chromic, Ethicon, Inc., Somerville, NJ), the tails of which are left long to secure a saline-soaked cotton and petrolatum gauze (Xeroform, Covidien, Mansfield, MA) bolster secured over the graft site. Sterile bandages are applied, followed by cast immobilization in the very young to ensure compliance with postoperative care.

FIGURE 43-4 Schematic diagram of the volar V-Y local advancement flap.

Local Advancement Flaps (V-Y, Moberg, Thenar)

Local flaps involve the use of adjacent vascularized skin and soft tissue to provide soft tissue coverage.[12] These flaps are used when the area involved is larger than healing by secondary intention will tolerate, and more substantial distal soft tissue coverage of the fingertip is required for durability and function long term. In most situations, the blood supply to this tissue is provided by the subdermal or subcutaneous microcirculation, so-called random pattern flaps. In other situations, the arterial inflow and venous outflow of the local flap are supplied by a single, identifiable vascular pedicle, the "axial" flap.

A number of random pattern local flaps are available for fingertip injuries. In general, these local flaps are preferred given their location, tissue match, and simplicity. This is particularly true in cases of preserved but exposed distal phalanx. Knowledge of the pattern of fingertip tissue loss in part guides decision making regarding the choice of flap to be used.

Transverse and dorsal oblique fingertip amputations may be successfully treated with *V-Y advancement flaps*.[13] While in theory up to 10 mm of "length" may be obtained, in reality these flaps are of greatest utility when greater than half the volar tissue measured from the digital tip to the distal interphalangeal (DIP) joint flexion crease is available for advancement. Under local or general anesthesia and digital tourniquet control, an apex-proximal V-shaped incision is created through the dermis only; the apex is placed at the level of the DIP flexion crease, and the distal extensions are made obliquely to the midaxial line (Figure 43-4). Following skin incision, blunt dissection is performed in the subcutaneous tissues via longitudinal spreading of tenotomy or Iris scissors, breaking up the fibrous septae of the digital pulp while preserving the subcutaneous tissue connections—and thus vascularity—to the overlying skin. After flap mobilization, the leading distal edge of the volar skin is advanced and sewn primarily into the dorsal skin and nail bed using interrupted 5-0 polyglactin suture (Chromic, Ethicon, Inc., Somerville, NJ). It is critical that the distal suture line not be made with undue tension, so as to avoid volar curvature of the nail bed and subsequent "hook nail" deformity. The two oblique limbs are similarly closed with interrupted 5-0 polyglactin suture (Chromic, Ethicon, Inc., Somerville, NJ), further alleviating any tension on the distal suture line. Given the distal tissue advancement, the most proximal aspect of the wound will be closed primarily, forming the stem of the resultant Y-shaped wound. The tourniquet is released to ensure digital tip and flap viability, and a sterile bandage is applied. The digit is splint or cast immobilized, particularly in the very young, active, noncompliant patient.

Fingertip reconstruction may be similarly achieved using radial and ulnar V-Y advancement flaps, first described and popularized by Kutler.[14] This technique is most effective in cases of transverse or volar oblique fingertip avulsions.

The *Moberg volar advancement flap* is also a useful tool for soft tissue avulsions of the thumb tip[15,16] (Figure 43-5). This technique of distal tip coverage is applicable to the thumb but not other digits, owing to the dorsal blood supply to the thumb tip, which is undisturbed during volar flap elevation and mobilization. Its advantages include preservation of thumb length and reconstruction with durable, thick, vascular and sensate tissue. Again, under general anesthesia and tourniquet control, midaxial incisions are created from the soft tissue defect at the thumb tip and extended proximally. Sharp dissection is performed down to the level of the flexor tendon sheath, and the volar skin, subcutaneous tissue, and both radial and ulnar neurovascular bundles are elevated from distal to proximal as a tongue of soft tissue. Care is taken to preserve the flexor tendon sheath during this dissection. After adequate soft tissue elevation, the volar flap is advanced distally and reapproximated using simple interrupted polyglactin sutures. Up to 1 cm of distal coverage may be achieved. The tourniquet is released and vascularity to the thumb and flap ascertained. Dressings are applied, as well as cast or splint immobilization as necessary.

The *thenar flap* is similarly useful for volar digital tip coverage[17–20] (Figure 43-6). Ideal candidates for thenar flap coverage include young patients with volar oblique pulp loss of the index, long, or ring fingers with preserved skeletal elements. Under general anesthesia in the operating room, the affected fingertip is debrided to healthy, bleeding tissue, and the dimensions of the soft tissue defect are measured. A similar-sized area is next outlined along the volar aspect, high on the thenar eminence, just proximal to the metacarpophalangeal (MCP) joint flexion

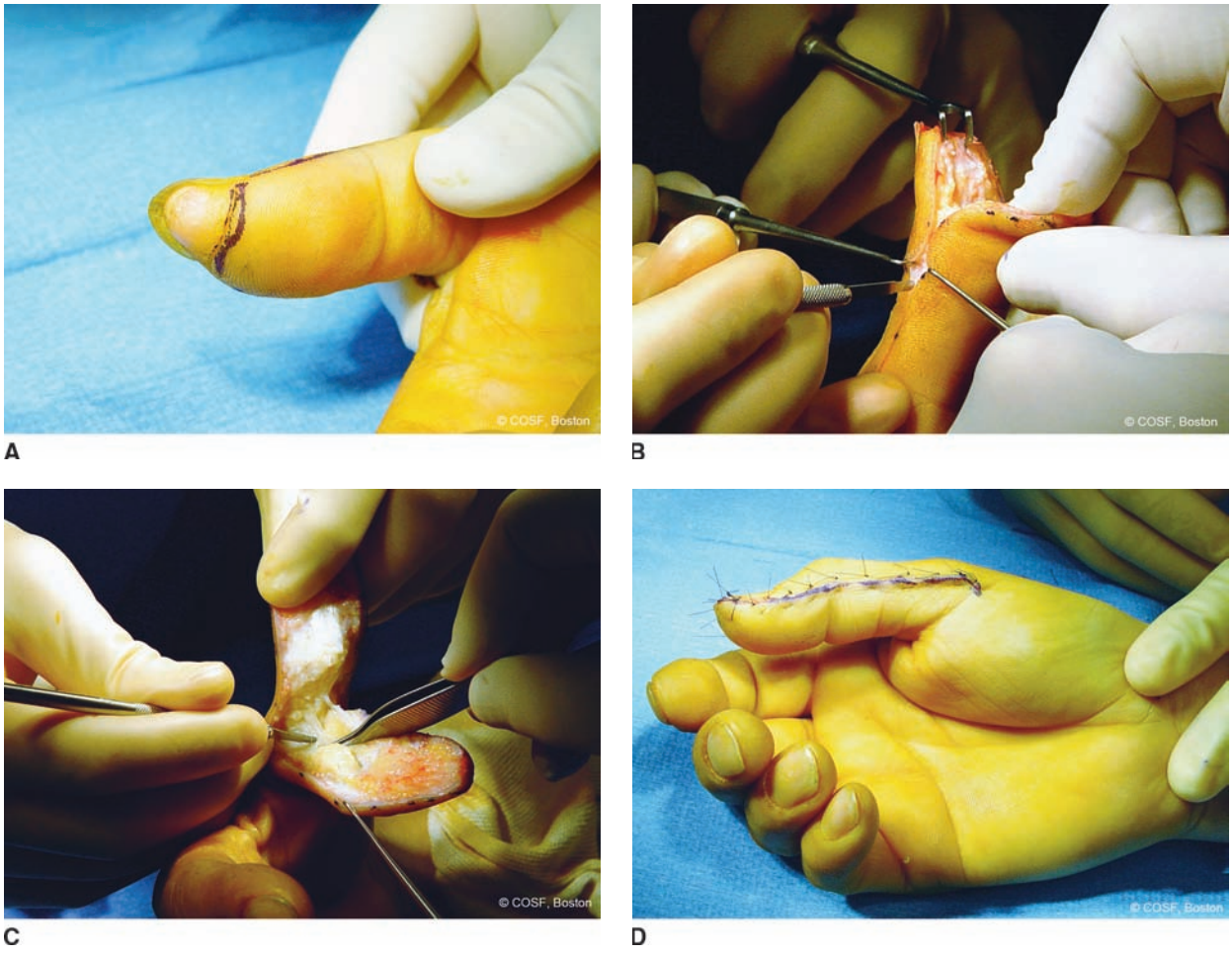

FIGURE 43-5 The Moberg volar advancement flap for the thumb. **A:** Preoperative photograph of a thumb previously treated with skin graft alone for soft tissue avulsion. The patient complained of pain and hypersensitivity at the thumb tip. There is a paucity of soft tissue bulk over the distal phalangeal tip. **B:** Midaxial incisions are created, and the volar skin flap is raised from distal to proximal, just superficial to the flexor tendon sheath. **C:** The flap is generously elevated, taking the neurovascular bundles with the volar tissue. **D:** After advancement and skin closure, there is reconstitution of a durable, bulky soft tissue pad over the distal phalanx, achieved without undue flexion of the interphalangeal joint.

crease. To facilitate this, the affected finger may be flexed until the exposed volar aspect creates a "stencil" along the thenar skin. It is recommended that each dimension of the thenar flap exceed the digital soft tissue defect by 10%. The thenar skin flap is then incised along three borders, allowing a single, preserved border to serve as the base of the flap. The other option is to raise an H-flap in the palm, which allows for primary closure of the thenar donor site. The proximal aspect of the thenar flap is elevated with its underlying subcutaneous fat, preserving the underlying tendon sheath and neurovascular bundles of the thumb. Once the flap is elevated, the resulting skin defect on the thenar eminence is covered with full-thickness skin graft or reapproximated by advancing the distal aspect of the H-flap to primarily close the donor site with 4-0 or 5-0 polyglactin sutures along the three borders previously incised. The thenar flap is then sewn into the flexed digit using interrupted absorbable sutures. Bulky soft dressings are applied after the tourniquet is released and flap viability confirmed. A dorsal splint and/or "boxing glove" cast is then applied, keeping the digit flexed to avoid undue tension on the thenar flap. Approximately 10 to 14 days later, the patient is brought back to the operating room for division of the flap base. It is important to recognize that the appearance of the digital tip is often bulbous and macerated at the time of flap division; diligent hand therapy with scar molding and edema control will assist with recontouring of the newly created digital pulp.

◆ Pedicled Flaps (First Dorsal Metacarpal Island Flap, Reverse Radial Forearm, Posterior Interosseous, and Groin Flaps)

Pedicled flaps may also be utilized for soft tissue coverage and reconstruction of the hand. For smaller zones of injury, the *first dorsal metacarpal island flap* may be

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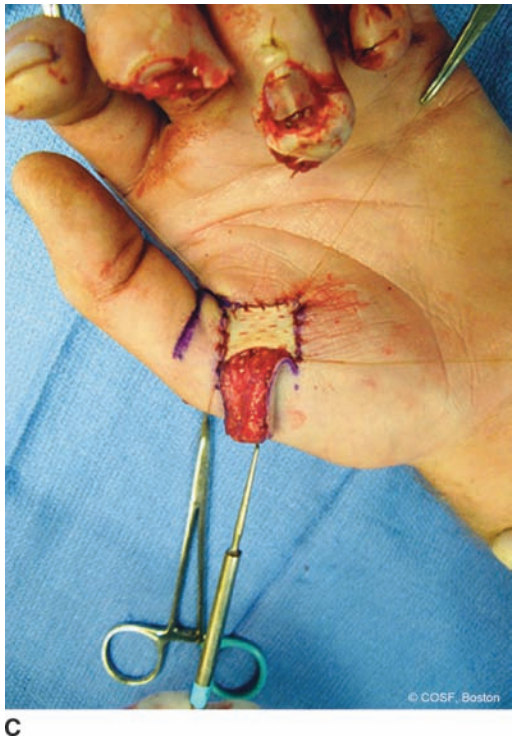

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FIGURE 43-6 The thenar flap. **A:** Preoperative appearance of a volar oblique fingertip avulsion of the long finger in an adolescent male. **B:** An appropriate-size, radially based flap of thenar skin and subcutaneous tissue is raised just proximal to the MCP flexion crease. The position and size of the flap may be determined by flexing the affected digit into the thenar eminence and noting the optimal position of the donor tissue. **C:** After flap elevation, the defect is covered with FTSG. **D, E:** The flap is reapproximated to the long finger defect.

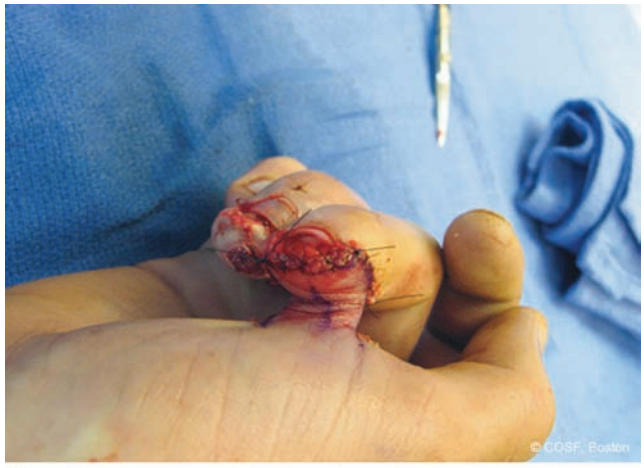

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FIGURE 43-6 *(continued)* **F:** Appearance of the digital tip after flap take-down, approximately 10 to 14 days after the index procedure. Note is made of the irregular contour and macerated appearance of the transferred tissue. **G:** At 3 months postoperatively, there has been restoration of normal long fingertip contour and bulk, with complete take of the skin graft at the donor site.

used.[21,22] Based upon arterial inflow and venous return provided by the first dorsal metacarpal artery, the skin and subcutaneous tissue overlying the dorsal radial aspect of the index proximal phalanx may be elevated and mobilized on its vascular pedicle, with or without branches of the superficial sensory branch of the radial nerve. The flap may be then rotated into the first web space or thumb. The donor site is then covered using FTSG.

At times when more extensive soft tissue hand coverage is required, the *reverse radial forearm flap* may be considered[23–27] (Figure 43-7). This flap is particularly useful for dorsal and volar hand defects, as well as thumb and first web space deficiencies. Based upon retrograde arterial flow through a competent deep and superficial palmar arch, the reverse radial forearm flap may be rotated on its arteriovenous pedicle to provide coverage of the dorsal and volar surfaces of the hand as well as the first web space. The overlying skin and subcutaneous tissue are supplied by multiple small perforating arteries arising from the distal portion of the radial artery.[28,29] Venous outflow is provided by the venae comitantes, not the cephalic vein. Due to its reliance upon retrograde inflow through competent vascular arches and proximal ligation of the radial artery during flap rotation, it is imperative that preoperative Allen's testing and other assessments of vascularity are normal.

Surgery is performed under general anesthesia and tourniquet control. The axis and line of the radial artery and associated intermuscular septum are marked on the forearm, connecting the scaphoid tubercle to the midpoint of the antecubital flexion crease. Alternatively, handheld Doppler may be used to map out the course of the radial artery in the forearm. A template of the (dorsal) hand wound is created and marked on the volar radial aspect of the forearm, centered on the previously marked radial

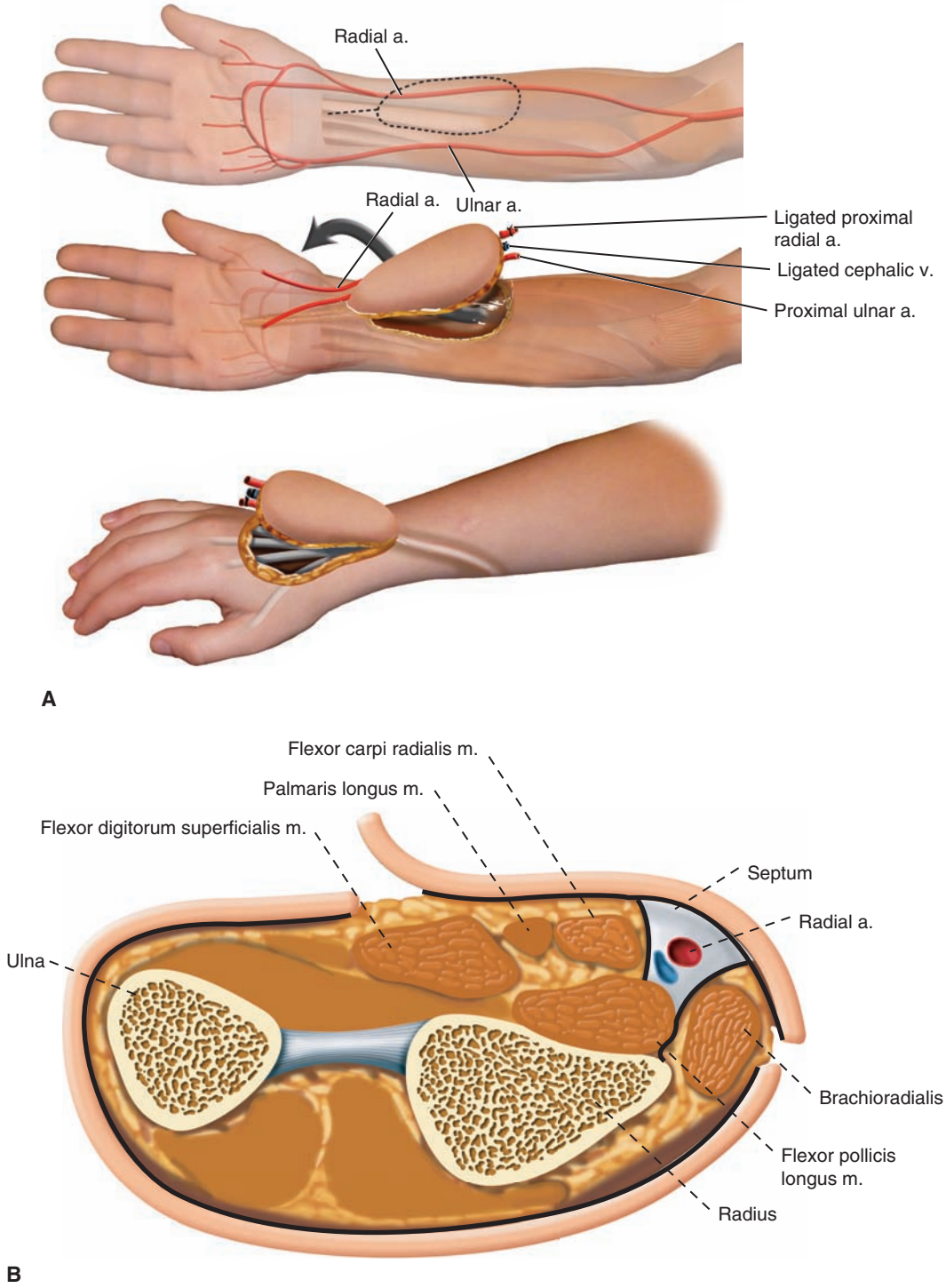

FIGURE 43-7 **A:** Schematic diagram depicting the anatomy and harvest of the reverse radial forearm flap. **B:** Cross-sectional diagram depicting the planes of dissection.

arterial line and equidistant from the palpable distal radial pulse or radial styloid as the distal radial pulse is to the soft tissue defect. (It is advisable to raise a slightly larger flap than needed slightly farther from the "pivot point" to allow for tissue shrinkage and retraction during elevation and avoid kinking of the vascular pedicle during rotation.)

Following this, the limb is gravity exsanguinated and tourniquet inflated. The surgical incision is made around the planned flap incision lines, with proximal and distal longitudinal extensions. The radial artery is identified proximal and distal to the planned flap. (If there is any concern regarding arch patency, the radial artery may

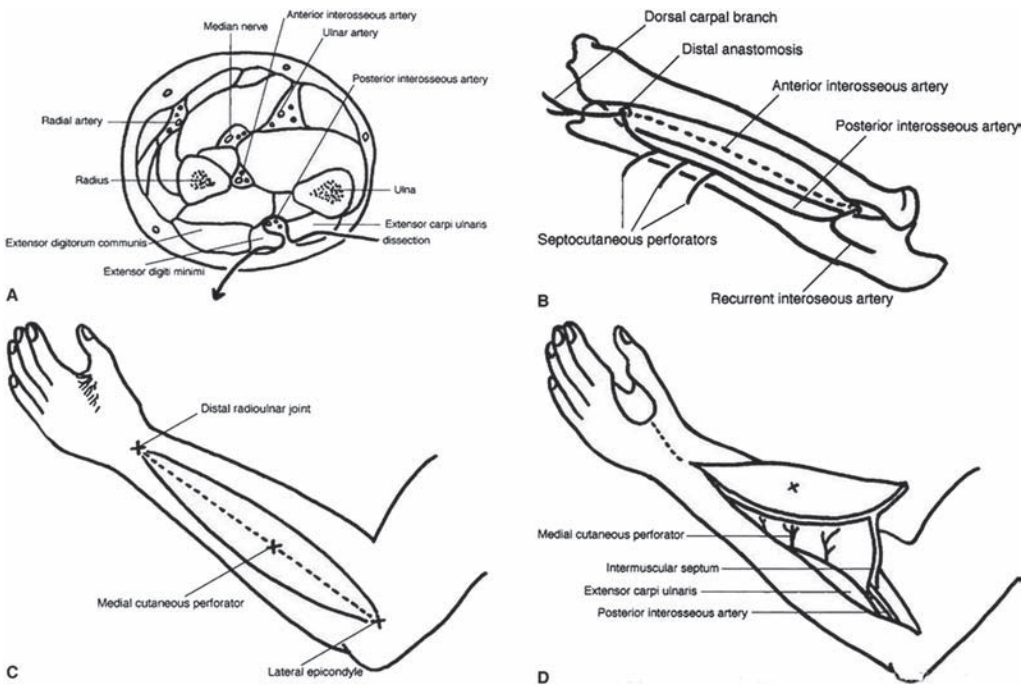

FIGURE 43-8 Schematic diagram of the posterior interosseous flap. (From Fujiwara M, Kawakatsu M, Yoshida Y, Sumiya A. Modified posterior interosseous flap in hand reconstruction. *Techniq Hand Upper Extrem Surg* 2003;7(3):102–109, with permission.)

be occluded with a vascular clamp, and the tourniquet deflated to allow for assessment of hand vascularity.) The skin around the planned flap is circumferentially incised and elevated from the radial and ulnar margins with the subcutaneous fat and deep fascia toward the vascular pedicle. Small interrupted sutures may be used to sew the skin and deep fascia together at the margins of the flaps to avoid excessive shear or delamination of the layers of the composite graft. As the radial artery is approached in the interval between the flexor carpi radialis and brachioradialis tendons, dissection is carried deep to incorporate the vessels and fasciocutaneous perforators in the harvested tissue flap. (Distally, the plane of dissection lies above the flexor pollicis longus muscle belly.) At this time, the radial artery is dissected free from the flap distal to the pivot point. The radial artery proximal to the flap is ligated, and the flap liberated on its distal, retrograde radial arterial pedicle. The flap may then be rotated into its place with care taken to avoid kinking or undue tension on its pedicle. The vascular pedicle and flap may be tunneled subcutaneously or passed directly to the recipient site through connecting incisions. The recipient site may be covered with split- or full-thickness skin graft.[30]

Another pedicled flap useful in hand reconstruction is the *posterior interosseous artery (PIA) flap*[31–35] (Figure 43-8; also see Figure 50-7B). The PIA flap provides relatively thin, pliable tissue for coverage without the need for sacrifice of a major peripheral artery or skin grafting of the donor harvest site. It is based upon the PIA, which emerges at the junction of the proximal one-third and distal two-thirds of the forearm, courses between the extensor digiti quinti (EDQ) and extensor carpi ulnaris (ECU) muscles just beneath the antebrachial fascia, and gives off four to eight septocutaneous perforators. The PIA typically arises from the ulnar artery in the proximal forearm and anastomoses with the anterior interosseous artery 2 cm proximal to the distal radioulnar joint (DRUJ).[36] Despite the described anatomy, variations in pedicle size, continuity, and distal anastomoses exist; the pedicle is not universally reliable and, for this reason, is not our first choice for soft tissue reconstruction.[33,37]

Intraoperatively, the axis of the PIA is marked by a line connecting the lateral epicondyle of the humerus to the midpoint of the DRUJ with the elbow flexed 90 degrees and forearm pronated. The medial cutaneous septocutaneous perforator is located approximately 1 cm distal to the midpoint of this line, and the planned flap is centered here. An elliptic skin incision is made, centered on this point, sized to fit the corresponding recipient defect. The fasciocutaneous flap is elevated first from ulnar to radial, lifting the fascia overlying the ECU. Radial to ulnar elevation is then performed, raising the fascia overlying the EDQ. Proximally and distally, the PIA, posterior interosseous nerve, and venae comitantes are identified. The proximal PIA is then ligated and flap elevated with the pedicle attached. The flap may then be mobilized around the pivot point 2 cm proximal to the DRUJ. Flap insetting is performed through direct connecting incisions or after subcutaneous tunneling, avoiding undue tension or kinking of the pedicle.

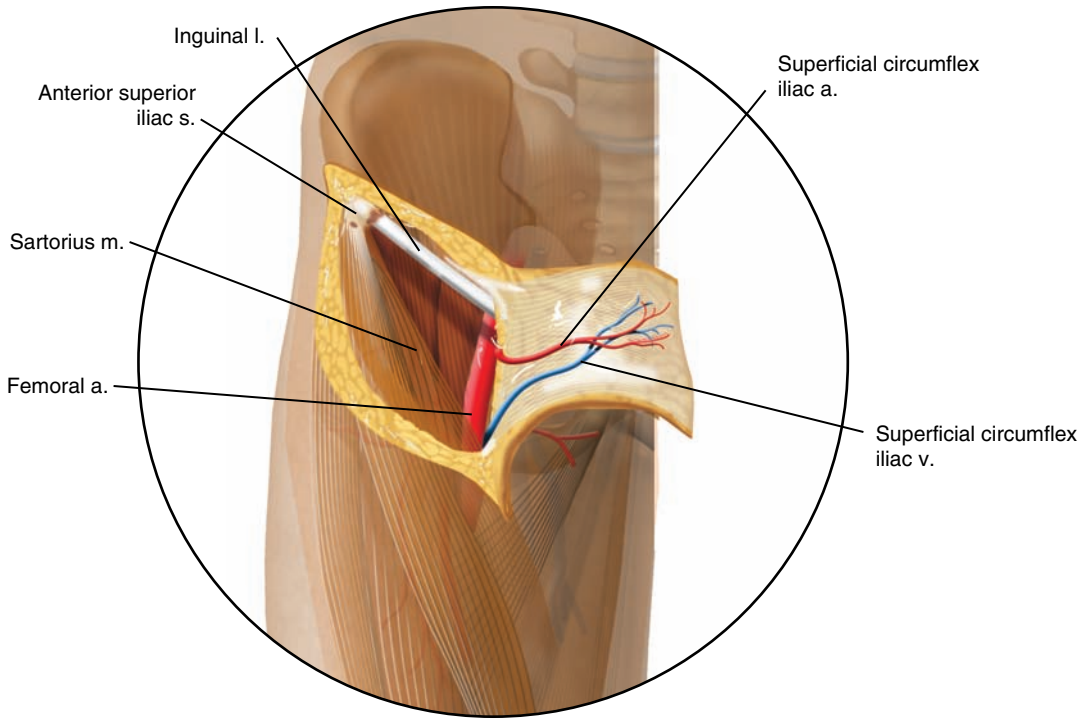

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FIGURE 43-9 **A:** Schematic diagram of the groin flap, depicting the superficial circumflex iliac arterial pedicle. **B:** Clinical photograph of a patient following groin flap reconstruction of the first web space.

Another useful tool in hand reconstruction is the *groin flap* (Figure 43-9). This is an axial pattern cutaneous flap based upon the superficial circumflex iliac artery (SCIA).[38,39] The SCIA arises from the femoral triangle and pierces the deep fascia as it crosses the sartorius muscle, running laterally and approximately 2 cm inferior to the inguinal ligament. As it passes lateral to the anterior superior iliac spine (ASIS), the artery branches, providing vascularity to the skin inferior to the iliac crest. This allows for lateral flap design and thus longer pedicle length. The groin flap is quite versatile and may be used for dorsal, volar, first web, and "wraparound" coverage of hand defects.

Intraoperatively, the axis of the SCIA is marked on the skin parallel and 2 cm inferior to the inguinal ligament, extending from the palpable femoral pulse laterally beyond the level of the ASIS.[39,40] The desired flap area is then marked, centered on this line and as lateral as possible. The skin is incised first at the inferior (caudal) margin down through the deep fascia, and the underlying sartorius and tensor fascia lata muscles are identified. Inferior-to-superior fascial elevation will allow for identification of the SCIA as it runs over the sartorius. Once identified and protected, the superior (cephalad) incision is created and dissection performed deep to the level of the external oblique aponeurosis. The superficial inferior epigastric artery will often be encountered and may safely be cauterized. The flap may then be raised lateral to medial, preserving the distal branches of the lateral femoral cutaneous nerve as they exit the sartorius-tensor interval. The

SCIA pedicle may be further circumferentially dissected from lateral to medial back to its origin off the femoral artery. The groin flap may then be reapproximated to cover the hand defect. The medial skin around the pedicle may be tubularized, if desired. The donor site is typically closed primarily, provided an elliptical flap was raised.

◆◆ Severe Traumatic Injury Coverage

In cases of severe traumatic injury, functional muscle transfers as well as soft tissue coverage are needed. For further details on these procedures, refer to Chapter 45 on free tissue transfers.

POSTOPERATIVE

Postoperative care is dependent upon the surgical technique employed. In cases of primary closure, skin grafts, or local advancement flaps (e.g., V-Y, Moberg), sterile bandages are applied and the affected hand immobilized in a cast or splint for 2 weeks postoperatively. After confirmation of wound healing, hand therapy is initiated for range of motion, edema control, and scar management.

After thenar flap placement, the patient is brought back to the operating room for flap take-down. (Flap division in the office setting under local anesthesia is possible but challenging in the young child or toddler.) Following flap take-down, hand therapy is begun for scar management, edema control and Coban self-adherent wraps (3M, St. Paul, MN), range-of-motion exercises, as well as recontouring of the digital tip.

In cases of pedicled flaps (e.g., reverse radial forearm, PIA), vascularity is monitored in the immediate postoperative period by examining the color and turgor of the skin paddle. Splint or cast immobilization is typically utilized. At 2 weeks postoperatively, immobilization may be discontinued and range-of-motion exercises initiated.

ANTICIPATED RESULTS

With appropriate patient and procedure selection, meticulous technique, and postoperative hand therapy, hand function may be restored expeditiously, with durable, sensate, and mobile soft tissue coverage. While little long-term published information is available, most short-term studies demonstrate high healing rates with minimal long-term morbidity or functional loss.

COMPLICATIONS

Each surgical strategy has its own set of potential postoperative complications. Flap necrosis is perhaps the most devastating, though rare. Careful and meticulous surgical technique, combined with frequent postoperative flap monitoring will allow for early identification and prompt treatment.

Failure of healing of STSG, FTSG, and composite tissue grafts may also occur. Achieving appropriate intraoperative hemostasis at the recipient site and use of appropriate postoperative dressings and immobilization, including saline-soaked bolsters over grafted tissue, may increase healing rates. Starting with an uncontaminated wound is vital to subsequent healing.

Hook nail deformities may occur in volar oblique fingertip injuries, particularly when primary closure imparts undue tension to the dorsal sterile matrix or when insufficient bony support of the nail bed exists. The nail bed and plate follow the contour of the underlying distal phalanx and soft tissues. If there is lack of bony support or the volar pulp is scarred so as to pull the nail bed volar and proximal, a hook nail deformity will result.

CASE OUTCOME

In this patient, the digital tip was not available for reapproximation, and, due to bony exposure, additional soft tissue coverage was desired. Bony shortening and primary closure was not deemed optimal given the desire to maintain digital length, preserve the distal phalangeal physis, and prevent a hook nail deformity. The patient was treated with composite toe graft with full return of function and a satisfactory aesthetic result (Figure 43-3).

SUMMARY

Fingertip injuries resulting in soft tissue loss are common presenting conditions to the pediatric hand and upper extremity surgeon. Careful clinical assessment and adherence to the principles of soft tissue reconstruction—including the reconstructive ladder—will allow the care provider to select the most appropriate surgical treatment strategy for each individual patient.

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CHAPTER

44

Free Vascularized Fibula Grafts

CASE PRESENTATION

A 13-year-old male presents for consultation regarding a complicated fracture nonunion of the left humerus. Pertinent past medical history is significant for Ewing sarcoma of the humeral diaphysis, which had been previously treated with chemotherapy, tumor resection with intercalary allograft reconstruction, and radiation. He subsequently developed a fracture nonunion between the proximal host-graft junction (Figure 44-1). The patient has had persistent pain and functional limitations due to this fracture nonunion. He is disease free from the standpoint of his prior malignancy. He now presents for hand and upper extremity consultation in conjunction with orthopaedic oncology care.

CLINICAL QUESTIONS

- What are the theoretical advantages of vascularized bone grafts?
- What are the surgical indications for free vascularized fibula grafting (FVFG)?
- How is the free vascularized fibula graft harvested?
- What are the techniques of transferring the fibula with its physis and epiphysis to preserve growth potential?
- What are the common complications of FVFG and strategies for their avoidance?

THE FUNDAMENTALS

Bone grafts are commonly used in all specialties of orthopaedic surgery. An understanding of the principles and applications of bone grafting is critical to the care of traumatic, developmental, and reconstructive musculoskeletal conditions, particularly in the pediatric patient. While most orthopaedic surgeons are familiar with the utilization of nonvascularized bone grafts and bone graft substitutes, the applications of vascularized bone grafts—and free vascular fibula grafts in particular—are often less well understood. The purpose of this chapter is to review the principles and techniques of FVFG, with particular attention to its applications in pediatric hand and upper limb surgery.

The Rationale for Vascularized Bone Grafts

Bone grafts and bone graft substitutes have a number of inherent properties that allow them to initiate, stimulate, and facilitate bony healing[1,2] (Table 44.1). *Osteoconduction* refers to the process by which the graft provides a scaffold for the ingrowth of capillaries, perivascular tissue, and osteoprogenitor cells. *Osteoinduction* refers to the recruitment of osteoprogenitor cells from the surrounding tissue. *Osteogenesis* refers to the formation of new bone from either the host or graft tissue. In addition to these three properties, it is important to consider the mechanical strength and vascularity of the bone graft material.

Autogenous and allogeneic cortical and cancellous bone grafts are all, to varying degrees, osteoconductive, osteoinductive, and osteogenic. For these reasons, nonvascularized bone grafts are effective in facilitating bony healing. When appropriately utilized, nonvascularized bone grafts may be incorporated into the adjacent host bone through the process of "creeping substitution." The bone graft material, through the invasion of capillaries, perivascular tissue, and inflammatory cells, is gradually revascularized and ultimately resorbed, allowing for the formation of new living bone, which is incorporated and remodeled into the host skeleton. However, this process takes time, during which the structural integrity and mechanical strength of the bone graft and host bone may be compromised.[2]

Vascularized bone grafts, by definition, retain their vascularity and thus are immediately viable. As a result, vascularized bone grafts obviate the need for incorporation by creeping substitution and may instead be incorporated into the adjacent host bone via primary (or secondary) bone healing. This process preserves the mechanical properties and structural integrity of the graft used, which confers greater strength and more immediate stability to the recipient site than nonvascularized grafts.

FIGURE 44-1 Preoperative radiograph of a 13-year-old male with a history of Ewing's sarcoma of the left humerus, previously treated with tumor resection and intercalary allograft reconstruction. He went on to develop a symptomatic fracture nonunion at the proximal host-graft junction.

Free Vascularized Fibula Grafts

Wouldn't it be interesting to have an occasional zebra in a horse race?
—The Vent

The fibula has long been recognized as an attractive choice for vascularized bone grafting procedures.[3,4] The fibula bears only 15% of the axial load across the ankle, allowing for its use as an autogenous bone graft with minimal biomechanical consequences on the weight-bearing status of the lower limb.[5] As the distal fibula also plays an important role in conferring rotational stability and restraint against lateral translation of the talus, the distal fibula is preserved during graft harvest to avoid subsequent ankle deformity or instability.[6–9]

Furthermore, the vascular supply to the fibula has been well established.[4,9] The endosteal blood supply to the fibula is provided by a nutrient artery, which typically enters the posterior fibular cortex at the junction of the proximal one-third and distal two-thirds. This nutrient artery is a branch of the peroneal artery, which runs along the posterior aspect of the fibular diaphysis. The fibula receives additional vascularity via a number of segmental musculoperiosteal vessels, which also emanate from the peroneal artery. Based upon this understanding of the vascularity of the fibula, techniques of vascularized fibula graft harvest have been developed that preserve both the nutrient artery and the rich periosteal blood supply.

Free vascularized fibular grafting has a number of additional theoretical advantages over conventional, nonvascularized bone grafting techniques. Given the length of fibular diaphysis that may be harvested, free fibular grafts are well suited for the reconstruction of segmental defects of the long bones, providing both mechanical strength and biological stimulus for healing. Furthermore, based upon the fasciocutaneous arterial branches of the peroneal artery, skin, fascia, and muscle may be harvested concomitantly with the fibula to allow for more complex soft tissue reconstruction. Finally, given the ability to transfer the proximal fibular epiphysis with the diaphysis during FVFG, there is potential for preserving continued skeletal growth of the fibular graft.[10]

Despite its many theoretical advantages and applications, however, FVFG is technically challenging and confers its own set of inherent risks and potential complications. Sound microsurgical technique is essential in performing the required arterial and venous anastomoses and ensuring long-term graft viability. Furthermore, donor site morbidity has been well documented, and up to 10% of patients may subsequently develop ankle pain, instability, and/or progressive valgus deformity if fibula harvest is not performed with proper technique.[7,8] Given these considerations, FVFG should be employed in specific clinical situations.

Table 44.1

Properties of bone grafts

Type of Graft	Osteoconduction	Osteoinduction	Osteogenesis	Mechanical Strength	Vascularity
Bone marrow	+/–	+	++	–	–
Cancellous autograft	++	+	++	+	–
Cortical autograft	+	+/–	+	++	–
Vascularized	++	+	++	++	++

From Buckwalter JA, Einhorn TA, Simon SR, eds. *Orthopaedic Basic Science.* Chicago, IL: American Academy of Orthopaedic Surgeons; 2000.

Table 44.2

Indications for FVFG

Segmental bone defects >6–8 cm	Traumatic bone loss Tumor resection Osteomyelitis Infected nonunion
Biological failure of bony healing	Persistent nonunion Osteonecrosis Congenital pseudarthrosis

Currently, the indications for FVFG fall into two categories[11] (Table 44.2). The first indication is for segmental bony defects of >6 to 8 cm, such as seen in tumor resection, post-traumatic, or postinfectious bone loss. The second indication is for smaller bony defects in which there has been a biological failure of bony healing, such as seen in recalcitrant fracture nonunions, congenital pseudarthroses, and osteonecrosis. In addition, there has been recent work examining the use of free vascularized fibular periosteum—with or without small "matchstick" strips of cortical bone—to bring biological bony healing potential to areas of bony defects or failed healing. While we have no personal experience with this technique, the potential applications are great and principles are similar to what is presented here.

Applications in Pediatric Hand and Upper Extremity Surgery

Congenital Ulnar Pseudarthrosis

Congenital ulnar pseudarthrosis is a rare abnormality of skeletal growth characterized by the development of pathological fractures of the ulna and long-standing pseudarthroses. Often associated with neurofibromatosis or fibrous dysplasia, congenital ulnar pseudarthrosis may lead to pain, deformity, and growth disturbance (see Chapter 48). Traditional methods of fracture care, including open reduction and internal fixation with nonvascularized bone grafting, are often unsuccessful. For these reasons, we have utilized FVFG to achieve bony healing in these challenging cases.[12,13] In addition to achieving bony healing across the site of the previous pseudarthrosis, careful restoration of ulnar length and alignment will result in preserved elbow and wrist motion and distal radioulnar joint (DRUJ) stability. Furthermore, when used in an intercalary fashion, vascularized fibula grafts can result in revascularization of the dystrophic, hypoplastic distal ulnar segment.

In addition, in the very young with marked growth remaining, concomitant proximal fibular epiphyseal transfer can preserve skeletal growth of the ulna. If successful, this will maintain a balanced wrist and forearm throughout skeletal maturation[10,12] (Figure 44-2).

Allograft Nonunion

Limb salvage surgery is an appealing option in skeletally immature patients with malignant bone tumors. In these situations, an intercalary or osteoarticular allograft is often utilized during bony reconstruction. Unfortunately, allograft fracture occurs in up to 20% of cases, and traditional methods of fracture care are often unsuccessful in these cases due to the high mechanical stresses and altered biological milieu.[14] In these situations, FVFG has been proposed to promote fracture healing while preserving allograft structural integrity. Vascularized grafts have been used both: (1) during primary tumor resection and allograft reconstruction and (2) during allograft fracture nonunion reconstruction. In our institution, FVFG is predominately applied to secondary reconstruction of allograft fracture nonunion.[15] About 90% of osteogenic sarcoma and Ewing sarcoma patients with upper limb allograft fracture nonunion will achieve successful bony healing following free fibular grafting. These patients will maintain limb preservation, with pain relief, extremity stability, and satisfactory functional outcomes.

Despite relatively high complication rates, we support the use of FVFG in these complex clinical situations. Careful attention to rigid internal fixation, meticulous microvascular surgical technique, and anatomic limb alignment is essential to optimize clinical outcomes.

Osteonecrosis of the Femoral Head

Osteonecrosis of the femoral head continues to be a cause of pain and disability to thousands of adolescents and young adults each year.[16] This is particularly true in the pediatric patient population, where osteonecrosis of the femoral head may be a result of hip trauma, septic arthritis of the hip, slipped capital femoral epiphysis, Legg-Calve-Perthes disease, or chronic steroid use (such as seen following solid organ transplantation). While many treatments have been proposed, no universal solution has been found.

The use of FVFG has been proposed to provide mechanical support to and revascularization of the femoral head[16–18] (Figure 44-3). Dean et al., in one of the largest published series of pediatric patients, reported the early results of free fibular grafting in 50 patients, with mean age of 14.8 years. The majority of patients developed osteonecrosis as a result of prior hip trauma, slipped femoral epiphysis, or steroid use. Average Harris Hip Scores improved from 55 preoperatively to 90 postoperatively, and at most recent follow-up, only 16% of patients had clinical symptoms or radiographic progression severe enough to warrant conversion to hip arthrodesis or arthroplasty. Based upon these results, the authors conclude that free fibular grafting in pediatric patients with femoral head

A

B

C

FIGURE 44-2 **A:** Forearm radiographs depicting a congenital ulnar pseudarthrosis in the setting of neurofibromatosis. **B:** Initial postoperative radiographs following distal ulnar resection and FVFG with concomitant proximal epiphyseal transfer. **C:** Follow-up radiographs demonstrating bony healing, preserved bony alignment, and longitudinal growth of the fibular graft.

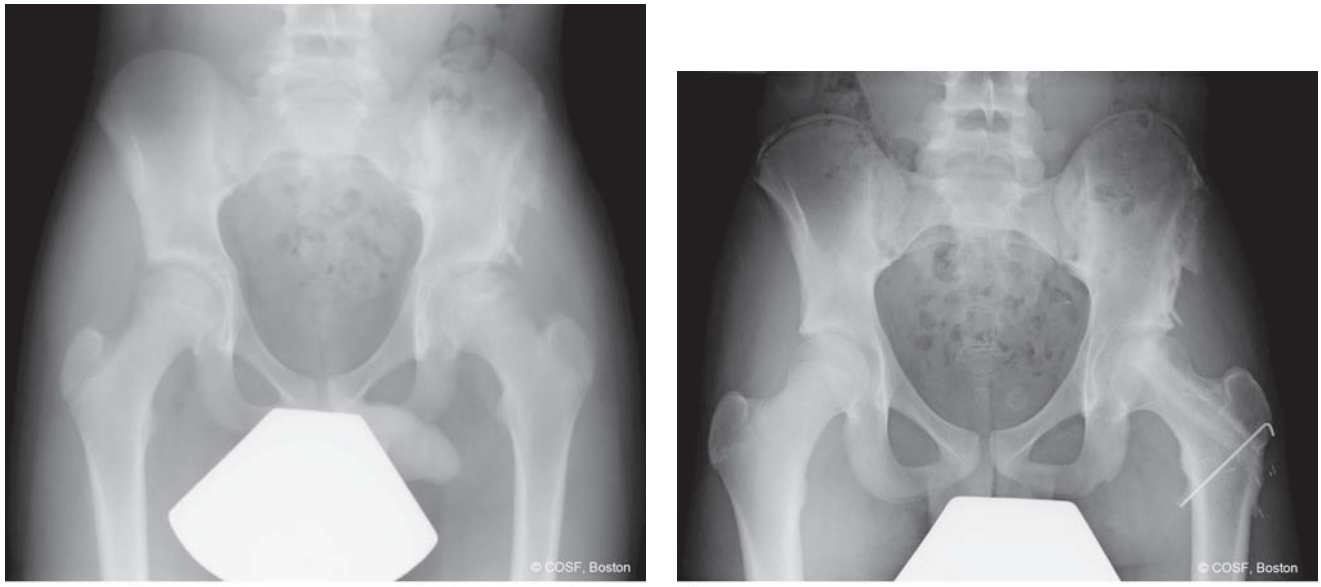


FIGURE 44-3 **A:** Preoperative pelvis radiograph demonstrating avascular necrosis of the left femoral head in a 15-year-old male following prior pelvis osteomyelitis and septic arthritis of the hip. **B:** Two-year postoperative radiograph following free vascularized fibula graft to the left proximal femur. Note is made of preserved femoral head vascularity and morphology. A single smooth wire used to transfix the fibular graft is seen.

osteonecrosis may relieve pain, improve function, and delay the need for future hip arthroplasty.

Clinical Evaluation

Clinical evaluation will vary greatly depending upon each individual patient's specific presenting condition. In cases where FVFG is being entertained, a number of clinical and radiographic factors must be considered.

Careful history must be taken regarding presenting symptoms and prior diagnoses. Review of prior medical records, operative notes, and pathologic reports is essential. In any cases of complex comorbidities, consultation with other subspecialists (e.g., oncologists, geneticists, pediatric medical staff) is recommended.

Examination of the recipient site of the upper (or lower) limb must note prior incisions. In addition to an appropriate musculoskeletal examination, careful note is made of the vascular status of the recipient site. In cases where there has been prior surgery at the recipient site, preoperative angiography is needed to map the vascular anatomy and identify potential vascular inflow to the proposed vascularized fibula graft. Furthermore, plain radiographs are obtained of the affected recipient site to assist with surgical planning.

Similarly, examination of the donor limb should make note of vascular and skeletal status. In the normal limb without prior trauma and with normal palpable dorsalis pedis and posterior tibialis pulses, routine angiography is not recommended. However, if there are any identified abnormalities with the preoperative vascular or skeletal examination of the potential donor limb, angiography will allow for confirmation of both the vascular pedicle to the fibula and appropriate collateral vasculature to the foot. If a proximal fibular epiphyseal transfer is contemplated, an angiogram is mandatory to define the epiphyseal blood supply and the impact a dual vascular harvest will have on the blood supply to the foot.

Surgical Indications

Generally, FVFG is indicated in one of two situations (Table 44.2). First, segmental long bone defects of >6 to 8 cm in length may be deemed potential candidates. These segmental defects may be encountered after severe trauma, following tumor resection, after debridement of osteomyelitis or infected fracture nonunions. Second, free vascular fibula grafts may be considered for long bones in which there has been a biological failure of healing. Examples include fracture nonunions, congenital pseudarthroses, or osteonecrosis of the femoral head.

SURGICAL PROCEDURES

Ingenuity, plus courage, plus work, equals miracles.
—Bob Richards

◆ Free Vascularized Fibula Harvest

Surgery is performed under general anesthesia, with patient positioning dependent upon the recipient site. In cases of FVFG to the upper limb, supine positioning with

harvesting of the contralateral fibula is usually performed. In FVFG to the hip for osteonecrosis of the femoral head, the patient may be positioned either supine or in the lateral decubitus position with harvesting of either the contralateral (supine) or ipsilateral (lateral decubitus) fibula (Figure 44-4).

In general, free vascularized fibula harvest may be performed using a number of defined steps (Table 44.3). A "two-team approach" is employed whenever possible—with one surgical team preparing the recipient site while the other harvests the fibula—to minimize anesthesia time and maximize surgical efficiency.

The fibula is harvested utilizing a direct lateral skin incision, preserving the distal 10% of fibular length to preserve ankle stability and avoid late valgus deformity (Figure 44-4C). Dissection is performed to the deep fascia, and the intermuscular interval between the soleus and the peroneals is identified. If no skin paddle is to be transferred with the bone, the superficial fasciocutaneous arterial perforators may be cauterized as they exit the intermuscular interval to the skin.

The fibular diaphysis is then circumferentially exposed in an extraperiosteal fashion, leaving its periosteum and some overlying muscle attached. This may be performed with either Bovie electrocautery or a Freer elevator and leaves the fibula with a "marbled" appearance (Figure 44-4D). This crucial step preserves the periosteal blood supply to the fibula.

Following circumferential dissection, the anterior and posterior intermuscular septae are incised, with great care taken to protect the adjacent posterior tibial artery and nerve and the motor nerve to the flexor hallucis longus (FHL). The peroneal artery and accompanying vein are identified in the depth of the wound as they run along the posterior aspect of the fibula. For the inexperienced surgeon, it is easy to confuse the posterior tibial pedicle with the peroneal vessels. Confirmation should be made that the posterior tibial artery and nerve are retracted and protected during the remainder of the harvest procedure.

A microsagittal saw is then utilized for transverse osteotomies proximally and distally in the fibular diaphysis, with the intercalary length matching the desired length of fibular graft. The fibular graft may then be lifted from the wound, isolated on its peroneal pedicle (Figure 44-4E). Maximum length of the vascular pedicle is achieved by careful dissection back to the arterial bifurcation. The peroneal nerve is protected throughout this dissection. The pedicle is kept intact until the recipient site has been prepared. Tourniquet on the lower limb may be released, confirming adequate vascularity of the harvested fibula. The fibula is left perfused until the recipient site has been readied for fibula transfer. Only then are the peroneal artery and vein ligated.

While the fibula is being harvested, the recipient site preparation for skeletal fixation and microvascular reconstruction is simultaneously ongoing. Screws or a combination of screws and plates are employed. As much fixation and stability as possible are achieved without impairing periosteal and/or pedicle vascularity. The microvascular anastomoses are usually end to end with the veins and end to side with the arteries.

◆◆ Epiphyseal Transfer

I love doubleheaders. That way I get to keep my uniform on longer.
—Tommy Lasorda

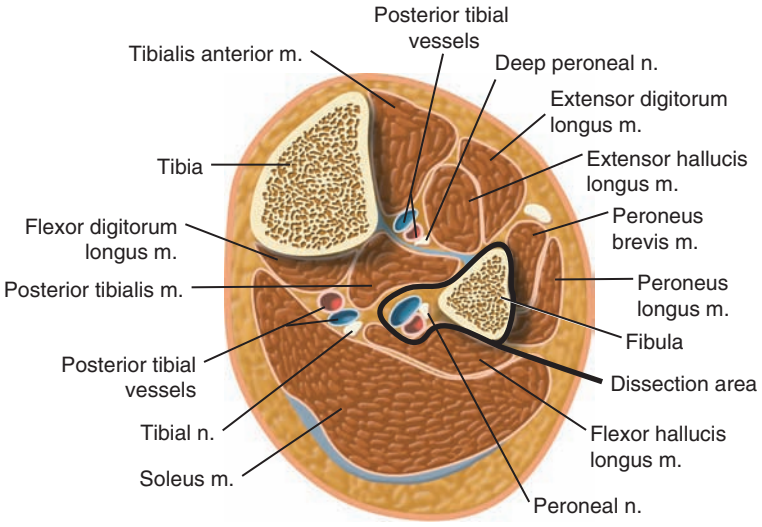
Special considerations are made in the skeletally immature patient in whom the fibular graft is utilized for the reconstruction of long bone defects (e.g., congenital pseudarthrosis of the ulna with a dysvascular distal segment).

Table 44.3

Procedural steps in free vascularized fibula harvest

Surgical steps
1. Incision and superficial dissection in peroneal-soleus interval
2. Extraperiosteal diaphyseal dissection
3. Identification and preservation/sacrifice of fasciocutaneous perforators
4. Anterior deep dissection
5. Posterior deep dissection
6. Proximal and distal diaphyseal osteotomy
7. Isolation of graft on vascular pedicle (division of intermuscular septum)
8. Division of vascular pedicle

From Gerwin M, Weiland AJ. Vascularized bone grafts to the upper extremity. Indications and technique. *Hand Clin*. 1992;8:509–523.



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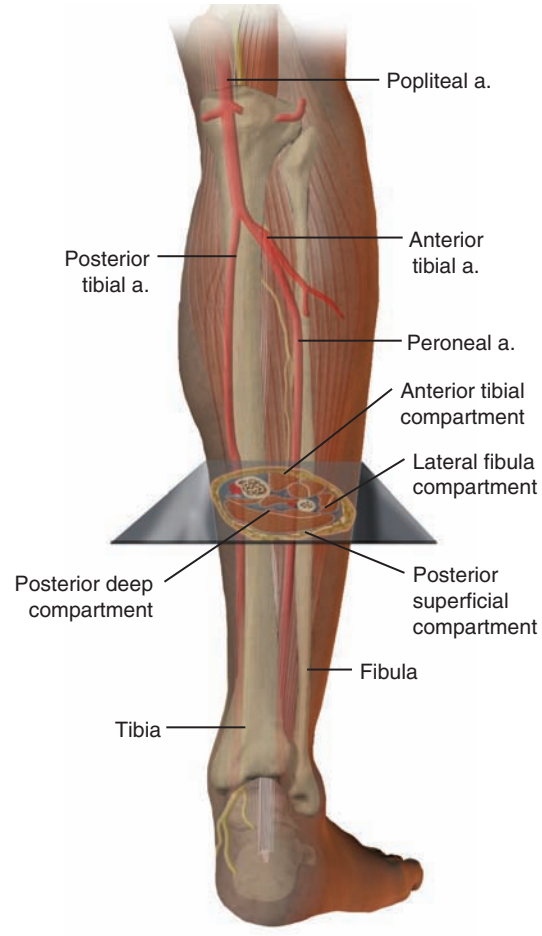

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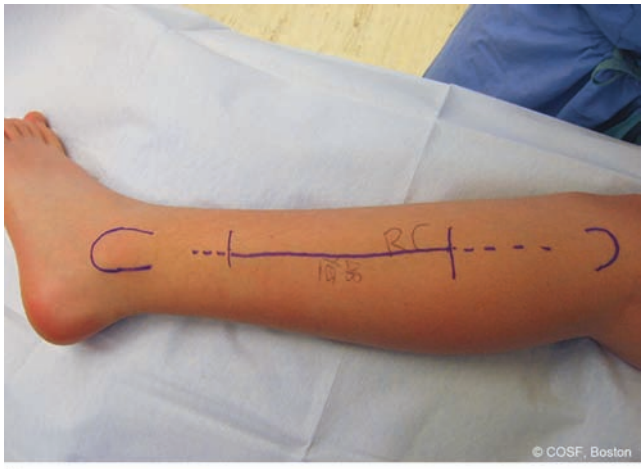

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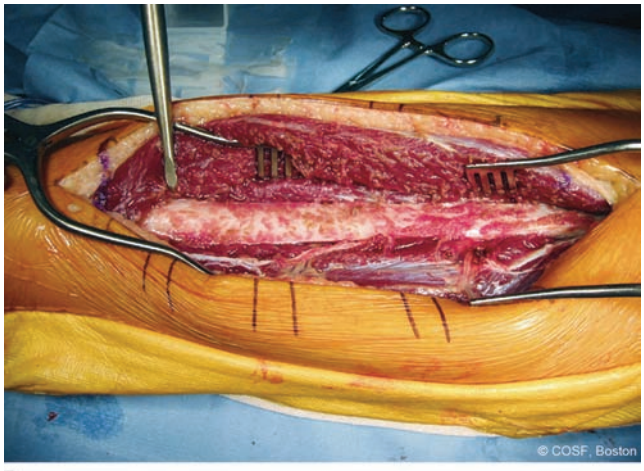

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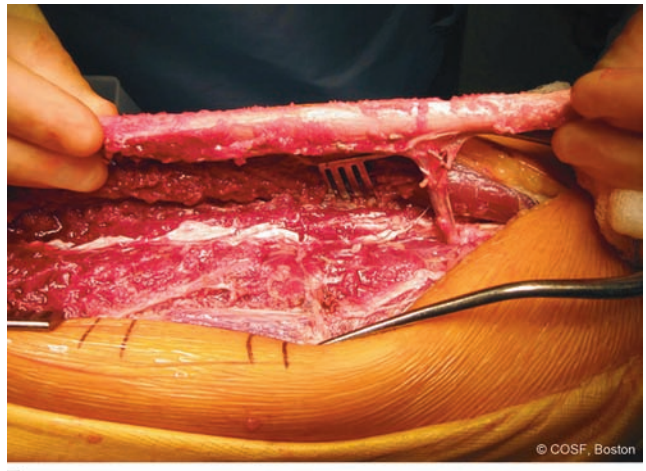

E

FIGURE 44-4 Technique of free vascularized fibula graft harvest. **A:** Schematic diagram depicting cross-sectional anatomy and path of surgical dissection. **B:** Diagram depicting the peroneal vascular pedicle to the fibula. **C:** Clinical photograph depicting skin incision on the lateral aspect of the lower leg. **D:** After superficial dissection, extraperiosteal dissection of the fibular diaphysis is performed. Preservation of the periosteum and muscle on the fibula gives it a characteristic "marbled" appearance. **E:** Following osteotomy, the vascularized fibula graft may be elevated from the bed of dissection with its vascular pedicle intact.

In these cases, the bony defect is reconstructed with a free vascularized fibular graft with concomitant proximal fibular epiphyseal transfer.

During dissection and preparation of the fibular graft, the anterior tibial and peroneal vascular pedicles are identified (Figure 44-5). The proximal tibiofibular joint is opened, and releases are performed of the lateral collateral ligament insertion, biceps femoris insertion, and peroneal muscle origin from the proximal fibula, with care taken to protect the integrity of the proximal fibular physis. The peroneal nerve is isolated and protected. Subsequently, the proximal fibular head and diaphysis together are transferred as a vascularized graft on their respective anterior tibial and peroneal vascular pedicles.[10] Internal fixation and microvascular anastomoses are performed as described above. In addition, adjacent soft tissue structures are repaired. In cases of congenital ulnar pseudarthrosis, for example, the triangular fibrocartilage complex (TFCC) and DRUJ are reconstructed via soft tissue repair to the transferred proximal fibular epiphysis.

Following epiphyseal transfer, vein graft reconstitution of the anterior tibial artery is performed to provide for two-vessel inflow and adequate lower extremity vascularity. In younger patients with significant growth remaining, a distal tibiofibular arthrodesis is performed. Corticocancellous bone graft and internal fixation with syndesmotic screw fixation are used, with care taken to preserve the distal tibial and fibular physes.[7]

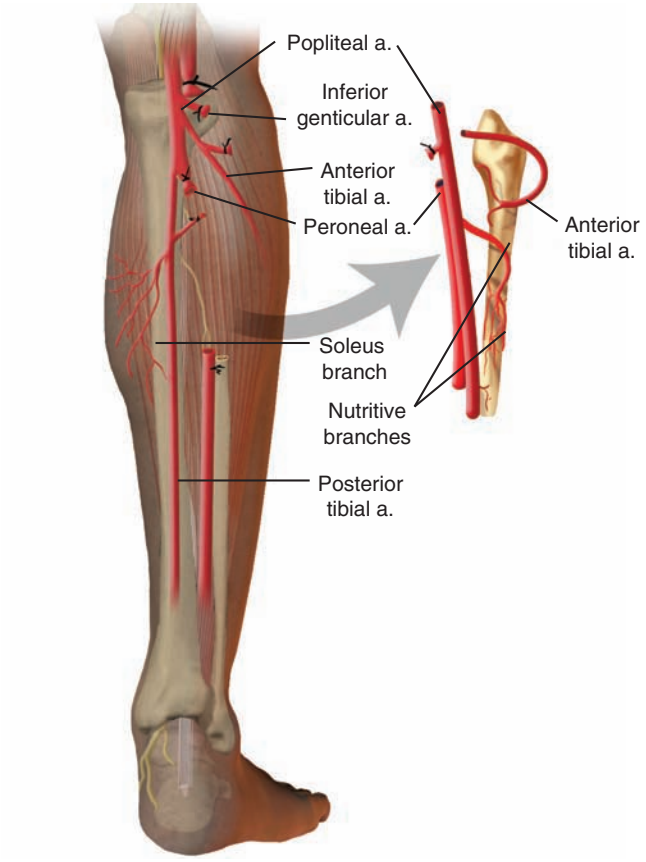

FIGURE 44-5 Schematic diagram of the proximal epiphyseal transfer. (From, Tsai TM, Ludwig L, Tonkin M. Vascularized fibular epiphyseal transfer. A clinical study. *Clin Orthop Relat Res.* 1986:228–234.)

POSTOPERATIVE

Following FVFG, patients are treated with intravenous dextran 40 at a dosage of 5 to 10 mL/kg/d for 3 to 5 days, followed by oral aspirin for an additional 2 weeks, for thrombosis prophylaxis. Volume expansion is sufficient in young, otherwise healthy children, and we do not currently use heparin or warfarin anticoagulation. The upper extremity is cast immobilized for 6 to 12 weeks postoperatively until bony healing, followed by a removable orthosis or bivalved cast with supervised range-of-motion exercises. If a tibiofibular synostosis is performed, the donor lower extremity is placed in a cast with the ankle in neutral dorsiflexion to prevent equinus and/or FHL flexion contractures until bony healing.

ANTICIPATED RESULTS

With attention to the principles described here and the use of meticulous microsurgical techniques, successful vascularized grafting may be performed in over 90% of cases. Ultimate healing rates of skeletal defects remain in part dependent upon the underlying condition (e.g., congenital pseudarthrosis, allograft fracture nonunion, osteonecrosis of the femoral head) and status of the adjacent bony and soft tissue structures.

COMPLICATIONS

Given the complexity and technical demands of these reconstructions, there are risks of complications to both the recipient and donor sites. Recipient site complications include bleeding and hematoma formation (particularly given the postoperative dextran and aspirin regimen), infection, and failure of graft incorporation. Although rare, loss of arterial inflow or venous outflow to the fibular graft remains a concern. At present, we do not typically utilize commercially available anastomoses monitors, nor do we routinely obtain postoperative bone scans to assess perfusion. Meticulous microsurgical technique, careful soft tissue handling, and judicious use of perioperative antibiotics will serve to minimize the likelihood of these complications. During our preoperative planning, if we are concerned about vascular integrity, we perform the FVFG with a skin pedicle to monitor its viability.

Donor site morbidity following fibular harvest remains a concern. Late valgus deformity of the ankle has been well described following fibular transfer, and this risk is particularly concerning in the growing child. For these reasons, we routinely fuse the distal tibia and

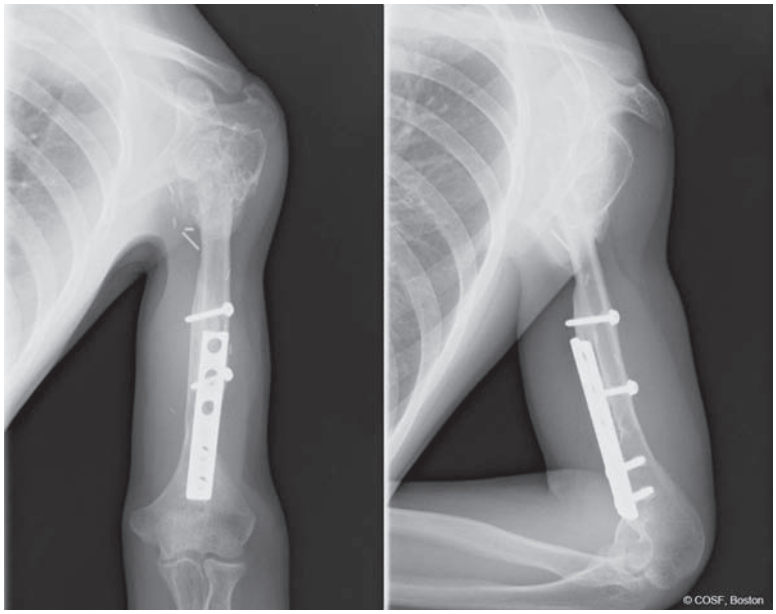

FIGURE 44-6 Postoperative radiographs taken 8 years following FVFG for humeral allograft fracture nonunion. Note is made of bony healing and graft incorporation across the prior nonunion site.

fibula proximal to the physis to preserve ankle stability and avoid late deformity.[7,19] Furthermore, the distal 10% (or 6 cm in a skeletally mature patient) of the distal fibula should be preserved during graft harvest. Finally, judicious use of postoperative splinting or casting will help to prevent equinus deformity and FHL contractures after fibular harvest.

CASE OUTCOME

After extensive discussion with the patient and family, and appropriate consultation among the orthopaedic oncology and hand surgery teams, decision was made to proceed with FVFG across the host-graft nonunion site. A 15-cm free vascularized fibula graft was harvested and placed in an onlay fashion spanning the nonunion site. Fixation was achieved with 3.5-mm cortical screws with washers. Arterial inflow was established via end-to-end anastomosis from the circumflex humeral artery into the peroneal artery. Venous outflow was obtained via end-to-side anastomosis from the peroneal vein to the axillary vein. Successful bony healing and limb preservation were achieved (Figure 44-6).

SUMMARY

Free vascularized fibular grafting provides an attractive reconstructive option for the orthopaedic surgeon. Given its ability to supply immediate structural support and vascularity—as well as its inherent osteoconductive, osteoinductive, and osteogenic properties—free fibular grafting should be considered in the management of large segmental bony defects as well as situations in which there has been a biological failure of bony healing. The use of rigid internal fixation, careful soft tissue and bony reconstruction, and meticulous microvascular surgical technique are essential in achieving the best possible outcomes.

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CHAPTER

45

Free Functional Muscle Transfers

CASE PRESENTATION

An 18-month-old female presented with an extensile mass of the extensor compartment of her dominant forearm. Her lesion is known by magnetic resonance imaging (MRI) to abut but not involve the posterior interosseous nerve (PIN). There was no bony involvement, and the mass did not extend through the interosseous ligament into the volar compartment. Biopsy confirmed the suspected diagnosis of malignancy, revealing a grade II synovial sarcoma with X:18 translocation. There was no regional node involvement or metastasis by radiographic staging (stage IIA). The patient underwent a primary resection of the extensor carpi radialis brevis and longus, supinator, and a portion of the brachioradialis (Figure 45-1). The PIN was resected beyond the bifurcation of the radial nerve motor and sensory nerves.

CLINICAL QUESTIONS

- What are the indications for functional free muscle transfer?
- Which muscles are used most often and why?
- What are the preoperative requirements to maximize success?
- Which nerves are used for reinnervation of the transferred muscle?
- What are the indications for myocutaneous flap coverage of the upper limb?
- Which muscles are used most frequently?
- What are the complications of free muscle transfer?

THE FUNDAMENTALS

The one man team is a complete and total myth.
—Don Shula

The absence of muscle function in a hand or upper limb can be devastating. This can be due to trauma, nerve injuries, compartment syndromes, cancers, and congenital deficiencies. Free muscle transfer is performed when (1) there are no other viable reconstructive options available, such as a regional tendon transfer, and (2) both the recipient site and donor muscle have a reasonable chance of successful functional outcome. Many muscles have been used for functional free muscle transfer with variable success. The best donor muscle for free transfer to the upper limb is the gracilis. The latissimus dorsi, pectoralis major, serratus anterior, and rectus abdominis have been used with less success. Restoration of elbow flexion, finger flexion, and finger extension are the most common functional goals of free muscle surgery, and much less commonly free transfers to the deltoid and triceps. This is complex surgery. Whenever possible, simpler solutions, if available, should be pursued.[1,2]

Free muscle transfer is also performed for coverage of upper limb major soft tissue deficiencies whenever other less complex treatments (skin grafts, regional or pedicle flaps) are not viable. This is most common after major trauma, oncologic resection, and chronic infection. The gracilis, latissimus dorsi, transverse rectus abdominis (TRAM), and serratus anterior muscles are the usual free musculocutaneous flaps used for coverage in the upper limb. Free tissue transfer surgery is best performed with an outstanding team. Simultaneous harvesting of the donor muscle and preparation of the recipient site lessens anesthesia time, surgeon fatigue, and the most likely patient complications. The optimal team consists of highly skilled nurses and/or midlevel providers, therapists, surgical subspecialists, and cooperative patients and families.

Etiology and Epidemiology

Severe avulsion and rupture injuries of the brachial plexus can result in a poor functional outcome by natural history. Nerve reconstruction by grafting (when there is at least one intact cervical spine nerve root), transfers in the first 1 to 9 months of life, or both are the usual treatment to alter natural history in these infants. When children present late or when nerve surgery fails,[3] tendon transfers,[4,5] tenodeses,[6] and musculoskeletal stabilization procedures are the preferred regional solutions to improve the involved limb function. However, when the injury is so devastating and the donor options are too limited, free muscle transfer

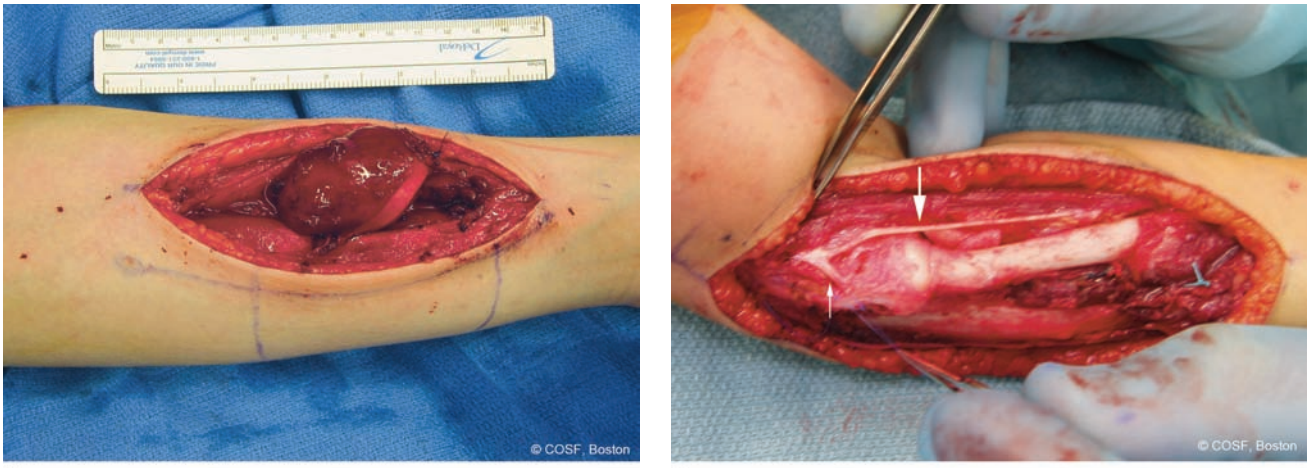


FIGURE 45-1 **A:** Intraoperative photograph of tumor resection with margin of healthy extensor mass and supinator muscle. **B:** The completed resection with radial nerve outlined. Sensory branch (*bold arrow*) and PIN (*narrow arrow*, retracted by forceps) outlined. PIN was used for reinnervation of flap.

may be indicated.[7] This is usually to restore elbow flexion and/or to improve hand function[8–10] with a functional free gracilis transfer.[11] Doi and his team developed the staged double muscle transfer for severe plexus avulsion injuries with (1) free gracilis for elbow flexion and finger extension neurotized by the spinal accessory nerve (SAN) and (2) second free gracilis for finger flexion neurotized by the intercostal nerves (ICNs). This is part of an extensive surgical plan also including sensibility and musculoskeletal stabilization procedures.

Volkmann's ischemic contracture can result in a devastating loss of flexor hand and wrist function. The preferred surgical solution is contracture release and regional transfers if possible (see Chapters 27 and 37). Free gracilis muscle transfer to the digital flexors with neurotization by the anterior interosseous nerve (AIN) is reserved for severe injuries with no other viable options.[12] Similarly, there are upper limb malignancy situations, most commonly with rhabdomyosarcoma, in which tumor resection can be followed by free muscle transfer to restore hand or wrist function.[13,14]

Mangled upper extremities[15,16] and severe, chronic osteomyelitis[17] in children are also rare clinical scenarios that can respond favorably to free tissue transfer. These procedures are usually for soft tissue coverage but can include composite and functional transfers. Multiple transfers may be necessary. If feasible, this approach is often preferred to a less functional amputation (Figure 45-2).

Clinical Evaluation

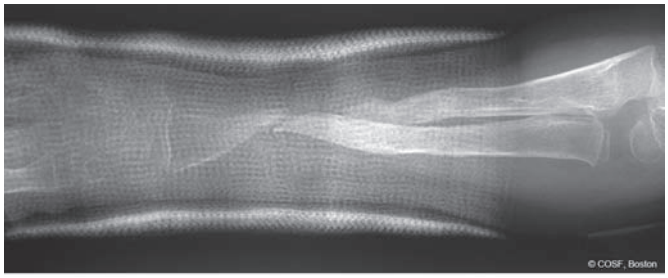
The goal of a free muscle transfer is adequate antigravity strength to provide a functional arc of motion and improved use of the hand and upper limb. There must be (1) adequate passive range of motion of involved joints; (2) a recipient artery, vein, and nerve for a viable, functional transfer; (3) sufficient soft tissue coverage for unimpaired tendon and muscle excursion; (4) reasonable hand sensibility and intrinsic strength; (5) balanced antagonistic muscle strength; (6) a highly motivated patient with long-term vision and the ability to wait for functional results; and (7) no better or easier solutions.[18] In our practice, this requires a lot of discussion, therapy, and often preliminary surgery to set the stage for a successful outcome. This is not for the faint of heart; weak of will; or impatient child, family, or surgeon. The message needs to be repeated often, the expected outcome made clear, and the patient's and family's ability to do the work and be reasonable tested along the way before diving into these procedures. These free muscle transfers are the ultimate "elective" operation. In the end, functional transfer and limb salvage surgery is not magic. If all goes well, the child will be better but not normal in function.

If there is any doubt about the vascularity of the recipient site, an angiogram is obtained. In trauma and oncology situations, this is almost always done. If there is uncertainty about the viability of a nerve donor, exploration and even nerve biopsy is done before donor-site harvesting.

Surgical Indications

It's not enough that we do our best; sometimes we need to do what's required.
—Winston Churchill

As discussed in the previous sections of this chapter, it is imperative that all the less complex solutions be considered first and compared against free tissue transfer. Patient selection is critical. Only when all the prerequisites for functional transfer have been met should surgery be



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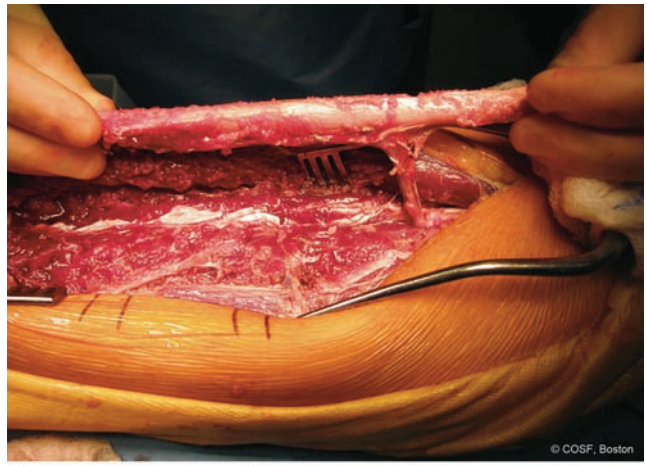


B

C

D

E

FIGURE 45-2 **A:** Patient referred for second opinion regarding amputation after numerous surgeries for nonunion forearm fracture from polymicrobial infection. **B:** Free fibula harvest for single bone forearm skeletal reconstruction after excision of nonviable bone. **C:** Postoperative radiograph of healed fibula reconstruction. **D:** Healed forearm with skin paddle from fibula. **E:** Free gracilis flap for flexor compartment reconstruction of hand and wrist.

seriously considered. Specifically, free muscle transfers are indicated in the right patient for (1) restoration of elbow flexion (brachial plexopathy); (2) digital flexor function (Volkmann's ischemic contracture); (3) prehension (brachial plexopathy, after oncologic resection); and (4) digital extension (Volkmann's ischemic contracture, after oncologic resection).[1,19,20] These elective procedures can be successfully performed (95% to 98% flap survival) in the child (even age 2 years or younger).[21–23]

Similarly, free flaps for soft tissue coverage are indicated as a part of limb salvage surgery for major trauma, chronic infection, and oncology care. Again, less complex options must be considered first.[24]

SURGICAL PROCEDURES

The key is not the "will to win"…everybody has that. It is the will to prepare to win that is important.
—Bobby Knight

The prerequisites for free tissue transfers are a high level of familiarity with the anatomy and performance of these procedures as well as expert microsurgical and hand reconstructive skills. There are no green circle or blue square level procedures here, only black diamond and double black diamond level skill for all members of the team. The thinking and planning part of these procedures strains the

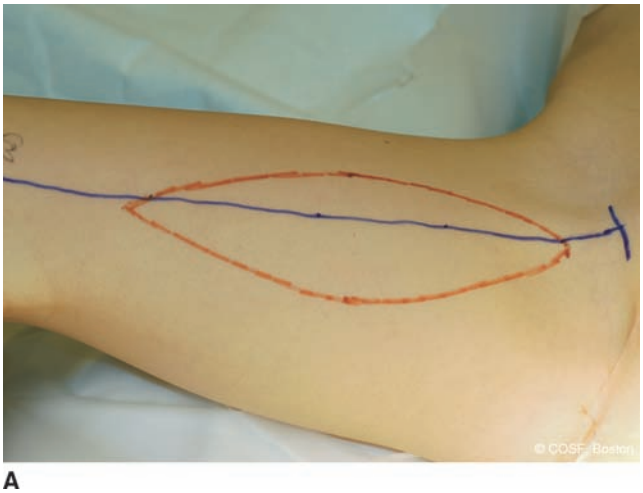
brain. The doing part is very hard ("Why do you think microsurgery is a four-letter word?") and requires a large treasure chest of expert technical skills. The communicating and doctoring part is critical to your patient's well-being and outcome. You need to build yourself and every member of your team up to an elite level if this is to be a part of your career. If not, find some outstanding professional colleagues to whom you can send these complex patients for the best care possible. And then help with the before and after care.

For functional free muscle transfers, a suitable donor nerve is essential to a positive outcome. One of the problems with a brachial plexus injury that has been treated with microsurgery is that there may not be adequate donor nerves for late reconstruction with a free muscle. If all reasonable ipsilateral donors were used in the initial microsurgical neural reconstruction, the only alternatives become the contralateral C7, contralateral pectoral, or ipsilateral phrenic. None of these are universally predictable and have been abandoned by most centers. Besides poor nerve surgery outcome with some avulsion injuries in adults, the dearth of donor nerves is one of the reasons that Doi advocated for early free gracilis transfer for elbow flexion and digital extension; the SAN could be used for neurotization without expending it in the initial nerve reconstruction. Similarly, the ICNs can be preserved for later reconstruction of digital flexion, elbow extension, and hand sensibility.[25] The best donor nerves are the SAN, ICNs, and the AIN and PIN for elbow and finger function. The gracilis is the best muscle for upper limb functional transfers. It is expendable; has predictable nerve and blood supply; and contours well for elbow flexion, digital flexion, and digital extension. It can be harvested with a skin paddle or covered with a split-thickness skin graft. Its functional excursion usually results in an improved limb.

◆ Free Gracilis to Flexor Forearm

The more I practice, the luckier I get.
—Jerry Barber, about golf

The ipsilateral gracilis and involved arm are prepped and draped. One team harvests the donor gracilis, while the other meticulously prepares the recipient site. The gracilis team is on the opposite side, so they have easy access to the medial thigh. The donor hip is abducted, externally rotated, and flexed; the knee is flexed. A straight line is drawn from the adductor longus tendon to the tibial tubercle. The gracilis is posterior to this line. The gracilis is either harvested with or without a skin paddle. If a skin paddle is used, an ellipse is created in the proximal one-third, centered over the muscle and posterior to the skin line noted above (Figure 45-3A). Its dimensions should match the required coverage in the upper limb. We often take a paddle for postoperative monitoring as long as it is not too bulky. The paddle needs to be sutured to the underlying muscle to prevent injury to the skin perforators throughout the operation. If no skin paddle is used, the longitudinal proximal incision is made posterior to the gracilis to allow exposure of the neurovascular pedicle from beneath the adductor longus muscle. The vascular pedicles to the adductor longus and magnus are ligated from the profunda to untether the pedicle to the gracilis (Figure 45-3B). The surgeon can choose to incise the entire medial thigh if there is difficulty with exposure and mobilization; or, more commonly, a proximal longitudinal incision over the bulk of the muscle and pedicles and a distal transverse or longitudinal incision over the tibial tubercle and tendon insertion are used. Endoscopic-assisted harvesting is also done by some surgeons.[26] The tendon is detached distally, and the tendon and entire muscle belly are brought out through the proximal wound



A

B

FIGURE 45-3 **A:** Outline of free gracilis muscle harvest with skin paddle for both coverage and postoperative monitoring. **B:** Gracilis flap elevation and isolation of neurovascular pedicle to muscle.

with neurovascular pedicle and muscle origin still intact. Electrical stimulation of the muscle confirms contractility. The muscle is brought out to the length, and sutures are placed every 5 cm to mark anatomic length. The color of the muscle and its electrical stimulation response are used to judge vascularity and avoid prolonged ischemia. The muscle is left in moist sponges until the recipient site is ready for transfer.

The recipient-site preparation includes extensile exposure from the medial distal humerus to the wrist. This is usually through a previous incision for contracture release, nerve decompression, and muscle debridement. Proximally, the brachial artery, median nerve, and superficial and deep veins are isolated and tagged with appropriate-colored elastic loops. The goal is find the right match for arterial, venous, and neural repair. When possible, we go end to end with the veins but end to side with major arteries or end to end with a matching-size artery, such as the interosseous. There must be excellent pulsatile flow (across the room, hit you in your eye sort of flow) from the transected recipient vessel. Do not place your elective transfer at risk by succumbing to using an impaired artery. Keep at it until you get the right one. Do not compromise. The vascular dissection is carried out for maximal excursion and no kinking. Be gentle with your vessels to lessen risk of spasm from iatrogenic trauma. The nerve used is usually the AIN, though at times it can be the flexor digitorum superficialis. Again, preparation of the nerve at the recipient site is quite extensive, so the repair work can begin as quickly as possible after ligation of the gracilis pedicle and the onset of ischemic time for the flap. The medial epicondyle and flexor-pronator origin are prepared for insertion of the origin of the free gracilis. Distally, the flexor digitorum profundus (FDP) tendons are mobilized and transected. Full excursion of the digits to the distal palmar crease should be possible with proximal pulling. The flexor pollicis longus (FPL) is isolated in the same fashion. If possible the gracilis will be split into separate neuromuscular units for independent control. If not, conjoint repair will occur. Then the pedicles are ligated, and the nerve is sharply divided with maximum length. The gracilis is brought to the recipient field, and the ischemia clock is started. A second team can close the leg wound, while the microscopic team completes the transfer.

The muscle is positioned so the pedicles are an easy match. Then the proximal portion is temporarily sutured to the medial epicondyle and flexor-pronator mass. The vein is repaired first if all is going smoothly and the ischemia time is reasonable. Next, the artery is done and finally the nerve. There should be no tension or kinking on any of the neurovascular pedicles. If there is any persistent distal muscle ischemia, it is debrided. The muscle is then brought out to maximum excursion and tension by re-creating the exact 5 cm suture intervals. This will give the best functioning transfer. The wrist and digits are placed in full extension, and the point of repair of the gracilis to the FDP and FPL tendons is marked. The proximal muscle repair is then completed to the medial epicondyle and surrounding soft tissues. The FDP tendons are then repaired to the gracilis tendon or weaved through the muscle depending on the anatomy of each case. The FDP gracilis is done with a group repair, so the digital cascade is maintained. The skin is closed over drain(s) without undue tension. This is either with gracilis skin paddle to the forearm skin or with split-thickness skin graft over the muscle. The arm is protected in a nonconstrictive long-arm splint for 4 weeks. Close monitoring of the vascularity is done in the hospital for 5 to 7 days.

◆ Free Gracilis to Elbow Flexion

Brachial Plexus Injury or Major Trauma

The two-team approach and free muscle harvesting are identical for transfer to the elbow as they are for the forearm as outlined above. The preparation of the anterior arm is extensile from acromion to upper medial forearm. Proximally, the gracilis muscle origin is usually attached to the acromion and clavicle rather than the coracoid due to the length differential of the gracilis to the upper arm. The attachment of the gracilis is done by periosteal, transosseous, or osseous anchor sutures to the acromion and clavicle. Distally, the gracilis is inserted into the biceps tendon.

Neurotization is either by ICNs (T2–T4 motor branch) or SAN (inferior portion cranial nerve XI in a brachial plexus injury).[27–31] Three-stage reconstruction is performed with nerve graft contralateral arm, then free gracilis for elbow flexion, then biceps tenodesis for finger flexion[32]; or direct neurotization from the motor branch of the musculocutaneous in major trauma with biceps loss or no other alternatives.[15,33,34] The ICNs are dissected free with a curvilinear incision or longitudinal incision centered on T2–T4. If the SAN is used, it is dissected free in the supraclavicular region under the trapezius, and the inferior branches used are passed beneath the clavicle for direct repair (see Chapters 21 and 37). The goal with both the ICNs and SAN neurotization is to do a direct neural repair without a graft. Vascular repair is usually end to end to a matching side branch of the brachial artery or end to side to the brachial artery itself.

The gracilis muscle is always marked with sutures every 5 cm when it is out to maximum tension. These markings are used to determine the optimal length of muscle in setting the distal insertion point. The distal gracilis and the biceps tendon are marked to create this maximum tension with repair. The proximal attachment of the muscle is attached to the acromion and lateral clavicle. Then the vascular repairs are carried out, usually the veins first followed by the arterial repair. Finally, the nerve repair is done. The proximal attachment is then completed with care taken to avoid compression or kinking of the neurovascular pedicles. The distal insertion is performed in elbow flexion at optimal length by the previous markings. The skin is closed over a drain without tension. The distal

FIGURE 45-4 Shoulder spica cast protection for free gracilis to biceps in child with failed recovery of biceps by nerve reconstruction with grafts at an outside institution. The *arrow* identifies the cast window, allowing for postoperative monitoring of flap viability.

muscle and tendon are closed directly. Proximally, either the skin paddle closure (the usual for us) or split-thickness skin graft is used to prevent vascular compression with too tight a closure. A shoulder spica (Figure 45-4) or posterior long-arm splint/cast with access to the skin paddle is placed with a supportive sling. Immobilization is for 4 weeks.

◆ Latissimus Dorsi Free Muscle Flap

Trauma, Oncology, or Chronic Infection Flap Coverage

I figure practice puts your brains in your muscles.
—Sam Snead, about golf

The general indication for flap coverage rather than split- or full-thickness skin graft closure is exposed tendon, bone, cartilage, nerves, or blood vessels (no paratenon or periosteum); large wounds in terms of both depth and size; and uncovered areas that will do poorly without more substantial soft tissue coverage.[13,14,17,35–37] The preference is to use local or pedicled flaps when appropriate, but (1) the size and location of the wound; (2) concerns about local flap viability from the same traumatized limb; and (3) concerns regarding the negative effects of immobilization during the pedicle flap healing (such as groin flap to hand in some trauma situations) may necessitate a free flap for the best outcome.

It is imperative that the local wound is completely debrided back to healthy tissue. Whether it is due to infection, tumor, or trauma, extensive debridement of nonviable tissue is critical to a successful outcome with a free flap. Whenever vital structures require debridement (bone, tendon, muscle, or nerve), composite grafts and/or additional musculoskeletal reconstruction are required. The timing of these complex reconstructions around flap placement and healing is important, and this needs to be worked out in advance. Again, this is often a team decision including all our subspecialty surgeons.

There are many flaps used for coverage of complex problems in the upper limb and hand. These include cutaneous, fasciocutaneous, and musculocutaneous free flaps. The latissimus dorsi, TRAM, and serratus anterior are the most common myocutaneous free flaps used in the upper limb. Fasciocutaneous flaps include posterior interosseous, lateral arm, and radial forearm, among many others. Cutaneous flaps include scapular and parascapular donors as well as a host of others. The myocutaneous flaps usually include a skin paddle for additional skin and postoperative monitoring system of the viability of the flap. Over time, the latissimus dorsi flap has been the most common flap for coverage by our team because it is so versatile. For us, the decision for flap choice, design, and surgical care is always done with our outstanding plastic surgery team.

The latissimus dorsi muscle arises from the posterior iliac crest, thoracolumbar fascia, and lower thoracic ribs. It inserts into the humerus adjacent to or in conjunction with the teres major tendon along the posterior axillary fold. The blood supply to the latissimus is from the thoracodorsal artery. The thoracodorsal artery is a continuation of the axillary and suprascapular arteries. The branching pattern includes in sequence the circumflex scapular, branch to the teres major, and branch to the serratus anterior. Mobilization of the vascular pedicle gives length (10 to 12 cm) and, therefore, versatility while insetting the flap. The nerve supply is also the thoracodorsal off the posterior cord.

Harvesting of the flap is done in a lateral position with care taken to protect the underlying brachial plexus. Exposure is extensile in a curvilinear incision from the axillae toward the iliac crest posteriorly. The skin paddle is outlined with an ellipse for desired coverage. Combined shoulder abduction and forward flexion >90 degrees provide axillary exposure. Care must be taken not to cause neurovascular stretch or compression injuries of the ipsilateral plexus or arm blood supply with this positioning. Dissection is carried down the anterior border of the latissimus muscle through the posterior axillary fold. The anterior border of the muscle is rolled up posteriorly and toward the ceiling with retractors and stay sutures to expose the thoracodorsal neurovascular pedicle. Tension on the flap greatly aids in dissection. The pedicle enters the muscle at about nipple level. Mobilization of the pedicle involves ligation of the serratus anterior (unless a dual serratus-latissimus flap is planned), teres major, and circumflex scapular branches. Dissection is carried back to the subscapular artery origin of the thoracodorsal pedicle. The muscle is released from its origin distally and then elevated from distal to proximal off the underlying serratus anterior muscle. The vascular pedicles are ligated, and the nerve is sharply cut with maximum length once the recipient site is ready for flap inset.

The recipient-site preparation can be part of two-team simultaneous exposure or in stages in the same operative setting depending on patient positioning and the anatomic site of the defect to be covered. Similar to the gracilis muscle flap, arterial anastomosis is usually end to end with an expendable branch or end to side to a major branch. Venous repair is end to end with appropriate-size vessels. If possible the vein(s) are repaired first followed by the artery, then the nerve. This proceeds after temporary insetting of the myocutaneous flap. There is usually some surgical "tinkering" time before vascular repair to work the vessels in the right place without tension or kinking; maneuver the flap around external fixators or the like; place the skin paddle appropriately; and infold the muscle to cover the depth, width, and length of the complex wound without problems. After vascular repair, more complete closure of the deep, subcutaneous, and skin wounds is meticulously performed; the donor site is closed in layers over drains to prevent seroma formation.

◆◆ Doi Double Muscle Transfer

Brachial Plexus Avulsion Injury

In severe avulsion injuries, a double gracilis transfer technique has been advocated by Doi and used in many centers for adults with brachial plexus injuries.[9,10,27,30,38] Fortunately in infants, this is not frequently necessary.[8] The initial gracilis transfer is neurotized by the SAN as outlined above. Its origin is from the acromion and lateral clavicle. However, distally its insertion is into the dorsal forearm by placing it beneath the brachioradialis and extensor carpi radialis origins into the extensor digitorum communis. Adjustment of the proper tension (1) follows the same principles of gracilis markings every 5 cm outlined above; (2) is marked between free muscle and insertion site with shoulder abducted (~60 degrees) and slightly flexed (~15 degrees); with the elbow fully flexed, the wrist in neutral, and the fingers in full extension; and (3) may require distal adjustment of the digital extensor tendons at the wrist level. The goal is to achieve both elbow flexion and finger extension.

The second free muscle transfer is performed for finger flexion. This is done approximately 3 months later when therapy has restored passive elbow and finger motion from the first transfer. The ICNs are used for neurotization, and the technique is the same as outlined above and in the nerve transfer section of the book. The muscle origin is now from the second and third ribs with direct periosteal or osseous repair. Vascular repair is end to end with arterial side branches (thoracoacromial) and end to end venous outflow. The transfer is placed along the medial upper arm to prevent acting as an elbow flexor. Insertion is beneath the flexor-pronator mass into the FDP tendons. The tensioning is the same as outlined above except the fingers are now in maximum flexion. Distally, adjustment at the wrist may be necessary with FDP tendons to obtain optimal tension. Doi does this operation in conjunction with neurotization of the triceps and reinnervation of the hand by transfer to the medial cord with additional ICNs.

POSTOPERATIVE

The major concern with free flaps is loss of vascularity to the flap. This occurs either by loss of arterial inflow or venous outflow with the eventual back clotting and no reflow phenomenon. Controlling for as many factors as possible that could lead to vasospasm or clotting is critical to success. This includes systemic influences or disorders such as blood pressure, peripheral blood supply, hematocrit, anxiety, dietary intake, ambient temperature, arm positioning, and dressings, among others. Thrombolytic agents (aspirin, dextran, and heparin, among others) have all been used regularly as a part of postoperative protocols or emergently in cases of failing flaps. Monitoring systems have been simple (capillary refill, bleeding with needle stabs) to complex with everything in between (temperature probes, vascular acoustic or laser Doppler, implantable oxygen/pH, and O_2 saturation, to cite a few).[39] Major keys to success are an outstanding initial operative vascular repair and meticulous closure and dressings that will not compromise the flap. In our routine free flaps, we usually use aspirin as prophylaxis; monitor with Doppler ultrasound and/or temperature probes depending on pedicle location; and control the patient's environment, diet, pain, and anxiety with appropriate medications and regional blocks.

The failing flap requires emergent attention. To know when a flap is failing, in-hospital professionals have to be paying close attention day and night. If your personnel do not have the time to do careful, frequent observations, then mechanical monitoring with alarms is imperative. The longer the failing flap goes without rescue maneuvers, the less chance of success. Initial moves are simple but can have drastic results: remove compressive dressings, warm the room and limb, calm the patient, give intravenous fluid bolus if urinary output is down, remove compressive sutures, reposition the patient, and evacuate local hematoma. Leeches and intravenous thrombolytic agents have been used but more often in replant situations. If these maneuvers do not get a rapid response, return to the operating room emergently. As Jones and Lister[40] pointed out, if you are at this point, "the situation is almost always worse than it appears." Suture removal may relieve occlusion in a swollen flap and limb. Supplemental skin graft and/or flap repositioning may be indicated. Any hematoma or submuscular clots require gentle evacuation with warm saline and careful mechanical removal around the pedicle. Close inspection of both the venous and arterial repairs is necessary. Kinking and compression need relief. Vascular clotting

requires clearing out with clamp protection to prevent distal microemboli. Rerepair is performed if necessary with excision of the damaged segment. Vein grafting may be necessary. Salvage of the flap can occur in 50% to 60% of flaps with emergent surgery. Do not do these operations unless you are ready to return to the hospital or operating room in the days following the long, fatiguing initial repair. And, you, your patient, and his or her family know flap loss is a real possibility in a very small percentage of patients.

ANTICIPATED RESULTS

All sports are games of inches.
—Dick Ritger

When all is said and done, the patients should have improved but not normal function with a free muscle transfer. Active flexion of the elbow of 60 to 90 degrees with gracilis to biceps is desired and usually achievable. This is more likely in a traumatic situation than after a brachial plexus injury.

Active grip to near or at the palm is expected with a free transfer to the deep digital flexors. Grip strength has a wide range but on average is about 40% of the opposite side. Patients with intact intrinsic and antagonist extensor function clearly do better with extrinsic flexor transfers. Similarly, free transfer for digital extension usually results in active antigravity strength. Tenodesis assistance with wrist flexion is often seen in these patients. The plasticity of their brains adapts quite readily to functional transfers, and this is particularly true of young children.

Free flaps for coverage in limb salvage from major trauma, severe infection, and oncology reconstruction have a similar >95% survivability. Since upper limb prosthesis is still relatively poor in aesthetics, function, and patient compliance, the more that can be achieved with coverage and staged surgical reconstruction the better. The alternative is amputation for these patients. A sensate biologic limb with some functional use and no instability or infection is probably a better result.

COMPLICATIONS

You will choose to do elective operations in your career dependent on what complications you can tolerate.
—John E. Hall, MD

These operations are not without serious concerns for minor and major complications.[41] Grief is to be expected, and problems occur in up to 60% of pediatric patients undergoing free tissue transfer. Staged surgical tinkering to maximize outcome is usually necessary. These include tenolysis, joint releases and stabilizations, and additional tendon transfers or tenodesis procedures, among others.

The most serious complication is flap loss. This has been reported in 1% to 5% of all pediatric free flaps in the most skilled centers. Thrombophilic patients are clearly at risk, and screening for factor V Leiden and other hypercoagulable states is appropriate.[42] Close monitoring can help you identify and hopefully rescue the failing flap.

In some patients, the transfer never achieves antigravity functional strength. This is very disappointing for one and all. It can be a real outcome, and families need to be aware. The quality of the donor nerve is clearly a factor. Motor-to-motor nerve coaptation of healthy fascicle to healthy fascicle, without tension, and without a graft, has the best results.

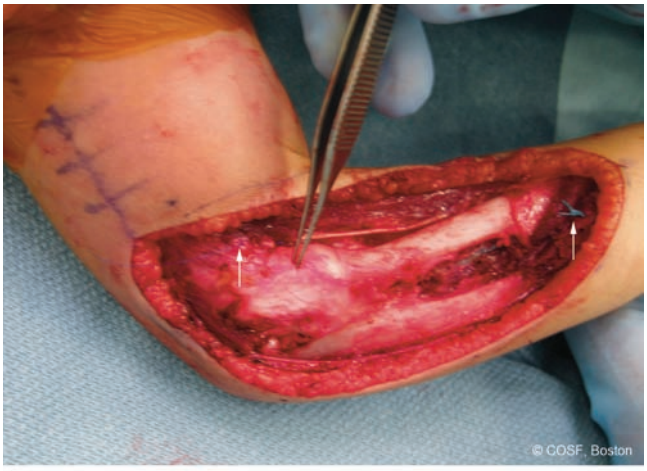
Some patients, particularly those with free gracilis to the forearm for Volkmann's contracture, can have decreased growth of the forearm and hand if the operation is done at a very young age. Since the average age of supracondylar humerus fracture is 5 years, this growth deficiency is of concern with a free functional muscle transfer in those patients.

CASE OUTCOME

When the primary resection of the tumor revealed tumor-free margins (Figure 45-5A, B), the reconstruction options were discussed. A decision was made for a free gracilis reconstruction of the dorsal forearm extensors based on histology from biopsy, MRI scans, and tumor board consultation. A free gracilis muscle transfer was performed with direct neurotization of the PIN, end-to-end anastomosis with the posterior interosseous artery and veins. Distally the wrist and finger extensors were reconstructed with separate portions of the free gracilis by tendon weave technique (Figure 45-5C). Eight years later, the patient has antigravity wrist and finger extension. More importantly, there is no local or distant recurrence.

SUMMARY

Functioning free muscle transfer is a viable option for restoring active joint motion and resistive strength in patients for whom local and regional reconstructive options of tendon transfers and tenodesis procedures are not available. Free muscle transfers are also used for soft tissue coverage in complex reconstructions for limb preservation in patients with severe infections, primary musculoskeletal malignancies, and devastating trauma to the upper limb.



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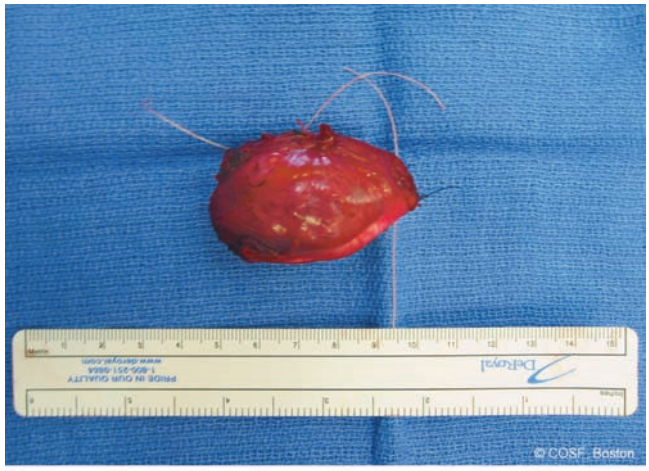

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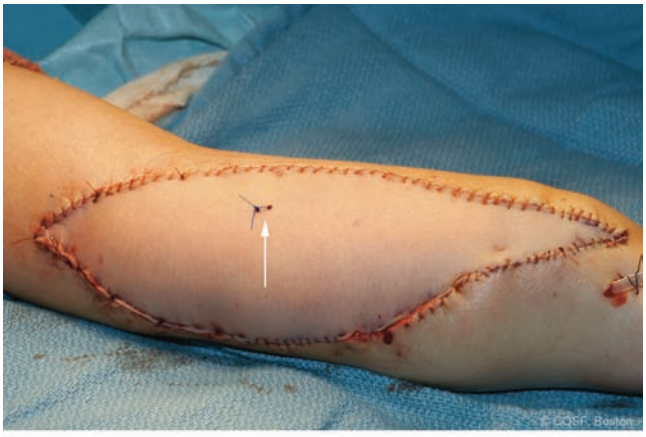

C

FIGURE 45-5 **A:** Complete resection of the tumor and extensor-supinator mass was performed to the level of the elbow joint ligaments, radius, and interosseous space. The proximal blue polypropylene suture (*arrow*) marks the PIN; the distal green polyester suture (*arrow*) is through the wrist and digital extensor tendons. **B:** Resected tumor specimen with proximal and distal suture markings. **C:** Free gracilis with skin paddle coverage. Central suture outlined by *arrow* indicates the vascular pedicle that can be monitored postoperatively by Doppler ultrasound.

SIDEBAR

Gracilis Anatomy

The gracilis muscle lies on the medial side of the thigh, extending from its origin on the pubis and ischium to its insertion on the medial tibia below the tubercle. Proximally it is posterior to the adductor and sartorius muscles and distally between the sartorius tendon anteriorly and the semitendinous posteriorly. The pedicle(s) to the gracilis arises from the deep femoral artery beneath the adductor longus. There can be variability in the number of vascular pedicles with two or three common; the most proximal pedicle is usually the dominant blood supply. It usually enters the muscle about 8 to 12 cm from the muscle's origin and is generally up to 6 cm in length depending on the size of the patient. The motor nerve is a branch of the obturator, also lies underneath the adductor longus, and enters the muscle just proximal to the vascular pedicle. The nerve often has multiple fascicles, and these can be separated into different functional, longitudinal sections of the muscle with observed electrical stimulation and dissection. The anterior portion can often be separated from the rest, and then each portion of the muscle and its fascicle can act independently, such as for finger and thumb function in a Volkmann's ischemic contracture. Harvesting the gracilis has no functional loss for lower extremity function.

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CHAPTER

46

Toe-to-Hand Transfers

CASE PRESENTATION

A 4-year-old child with amniotic band syndrome presents for evaluation of congenital hand deficiencies (Figure 46-1). The patient is otherwise healthy, and the contralateral hand is normal in appearance and function. Radiographs of the affected hand demonstrate a metacarpal hand with absent phalanges of the thumb and fingers. The patient and family now seek pediatric hand and upper extremity consultation for surgical options to improve hand function.

CLINICAL QUESTIONS

- What are the indications for toe-to-hand transfers in children?
- What are the patient- and condition-specific characteristics that favor toe-to-hand transfers?
- How are toe-to-hand transfers performed?
- What are the anticipated results and possible complications?

THE FUNDAMENTALS

To someone with nothing, a little is a lot.
—Sterling Bunnell

When caring for the child with congenital hand differences, the ultimate goal of the pediatric hand and upper extremity surgeon is to improve hand function by providing, if possible, sensate pinch and grasp. While the majority of conditions may be treated by reconstructing or augmenting existing anatomic structures, cases of severe deficiency provide greater challenges due to the absence of local anatomic structures. With the advent of microsurgical techniques, free toe transfers to the hand have provided the pediatric hand and upper limb surgeon a powerful tool to improve hand function and aesthetics.[1–5]

Free toe-to-hand transfers offer a number of theoretical advantages. By definition, the procedure brings additional functional units to the deficient hand. No sacrifice of an adjacent, functional digit is required; this is particularly important in the hand without the normal complement of digits. Technically, transfers are facilitated by the similar surgical and functional anatomy shared between toes and fingers. And finally, the aesthetic and psychological benefits of a more normal appearing hand can be profound.[6,7] Specific congenital deficiencies and post-traumatic scenarios are the usual indications for the rare pediatric toe-to-hand reconstruction.

Clinical Evaluation

Clinical evaluation begins with thorough history and physical examination. Prenatal history, associated medical conditions, patterns of hand use, and prior treatments should be carefully reviewed. Physical examination should focus both on the congenital deficiencies as well as the anatomic features of the structures present. Careful observation of spontaneous hand use will provide insight into the functional needs of the hand (e.g., the need for a thumb to pinch and grasp, the need for a stable ulnar post against which a native thumb may move in opposition). In systemic conditions such as amniotic band syndrome, physical examination of the feet is also important to confirm the presence of suitable donors. Radiographs of both the affected hand and potential donor foot are reviewed to assess the skeletal structures available to serve as a foundation for a transferred toe. If there is any suggestion of vascular abnormalities, or any history of prior surgical intervention, angiography is performed to map the vascular anatomy prior to surgery.

Surgical Indications

I think that the good and the great are only separated by the willingness to sacrifice.
—Kareem Abdul-Jabbar

The indications for toe-to-hand transfers in children remain controversial and continue to evolve. In general, toe-to-hand transfers may be considered in cases of congenital and post-traumatic deficiencies of the hand—and

A

B

C

FIGURE 46-1 **A, B:** Clinical photographs of a patient with congenital amputations of the right thumb and fingers in the setting of amniotic band syndrome. **C:** Plain radiographs demonstrate normal skeletal structures proximal to the level of amputation.

particularly the thumb—in which local procedures or other, less complex procedures are not possible due to the absence of adjacent functional elements of the hand (Table 46.1). Specifically, in congenital cases, free toe-to-hand transfers may be considered in thumb aplasia without normal adjacent digits to pollicize, amniotic band syndrome with congenital amputations, symbrachydactyly, and other transverse failures of formation. Aphalangia with bilateral hand involvement is also considered an indication. In all these situations, there is an absent thumb, absent fingers, or both. With traumatic situations, it is often a failed or unattempted replantation, particularly of a thumb.

The nature of the underlying condition is critical in patient selection and surgical indications. Survival and ultimate function of the toe-to-hand transfer are dependent in part upon the presence and quality of the proximal bony, tendinous, and neurovascular structures at the recipient site. Conditions in which the proximal anatomy is normal, such as in the congenital amputations seen with amniotic band syndrome or traumatic loss of the thumb, are more suitable candidates for free toe transfer.

Table 46.1

Strategies for thumb reconstruction for congenital deficiency or traumatic loss

First web space deepening
Nonvascularized toe phalangeal transfer
Bone lengthening via distraction osteogenesis
Index (or radial digit) pollicization
Free toe-to-thumb transfer

Eaton and Lister[8] have enumerated other characteristics that support—or argue against—the use of free toe-to-hand transfer (Table 46.2). Patient characteristics favoring toe-to-hand transfer include bilateral hand involvement, absent thumbs, younger age, presence of normal metacarpals, and normal proximal anatomy (e.g., amniotic band syndrome, traumatic amputation). Unfavorable factors include unilateral hand involvement excluding thumb, absent metacarpal heads, and older age in the setting of symbrachydactyly.

Finally, comprehensive discussion with the family must be made regarding the risks, benefits, realistic expectations, and alternatives to free toe transfer.[7,9] This is best achieved longitudinally over multiple visits during the child's first year of life or post-traumatic amputation, fostering a trusting relationship between surgeon and family and allowing for open discourse regarding treatment options.[10]

The optimal timing of toe-to-hand transfer remains equally controversial and highly patient and surgeon dependent. Advantages of earlier transfer in a congenital absence include faster and easier adaptation to the new functional element of the hand during a time in which the cortical representation of the thumb/hand is still forming. Disadvantages of early transfer include the technical challenges of performing microvascular surgery in the very young child. Patients with unilateral differences may achieve better functional results when transfers are done earlier in life, prior to the establishment of fixed patterns of use with the normal, contralateral hand.[8,11] In bilateral hand involvement, particularly in the setting of symbrachydactyly where the proximal neurovascular anatomy is likely to be abnormal, later surgery can be entertained. As fine motor function continues to develop up to 3 years of age, we favor free toe transfers between 18 and 24 months of age. The technical aspects of the surgery are reasonable for skilled microsurgeons at this age, and the advantages of early learning are achieved.

SURGICAL PROCEDURES

◆◆ Toe to Thumb for Congenital Differences

Surgery is best performed with a two-team approach, one to prepare the recipient site and one to harvest the donor[12] (Figure 46-2). Preparation of the recipient site is done under tourniquet control and loupe magnification; this should be performed first to confirm that adequate neurovascular pedicles are present to allow for toe transfer. While the details of recipient-site preparation will vary from condition to condition and patient to patient, a number of principles apply. Extensile surgical exposure is necessary, typically via zigzag dorsal and volar incisions. Appropriate proximal arteries, veins, nerves, flexor tendons, extensor tendons, and bony elements are identified. In rare cases, if adequate vascular structures are only identified well proximal to the recipient site, interpositional vein grafts may be needed to span the gap(s) and preserve digital length.[13]

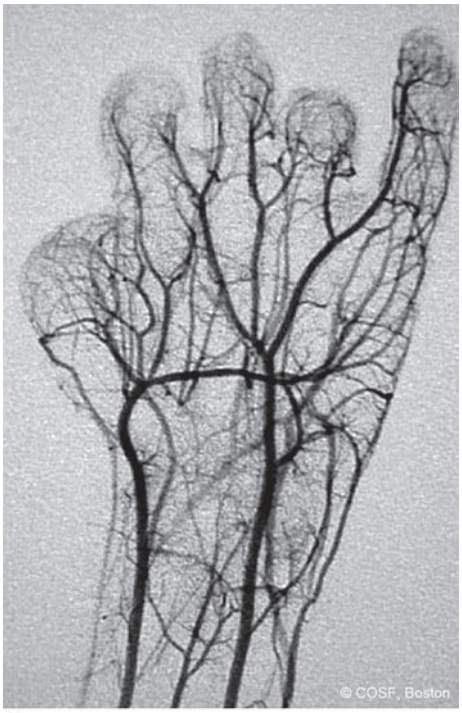
The toe is harvested via triangular dorsal and volar incisions created around the base of the toe, which are then extended proximally along the dorsum of the foot.

Table 46.2

Factors for and against free toe-to-hand transfer for congenital hand differences

	For	Against
Etiology	Constriction band	Symbrachydactyly
Laterality	Bilateral	Unilateral
Age	<2 y	>2 y
Function	Absent thumb	Metacarpal hand
Thumb metacarpal	Present	Absent
Thenar muscles	Present	Absent
Finger MCP joints	Present	Absent

From Eaton CJ, Lister GD. Toe transfer for congenital hand defects. *Microsurgery*. 1991;12:186–195.



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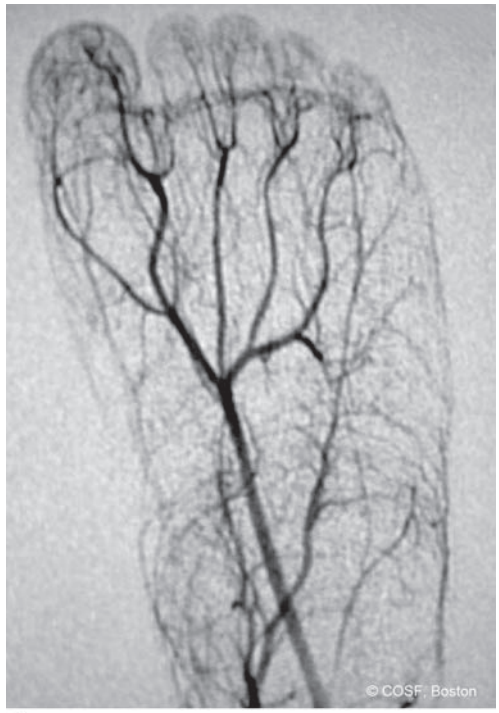

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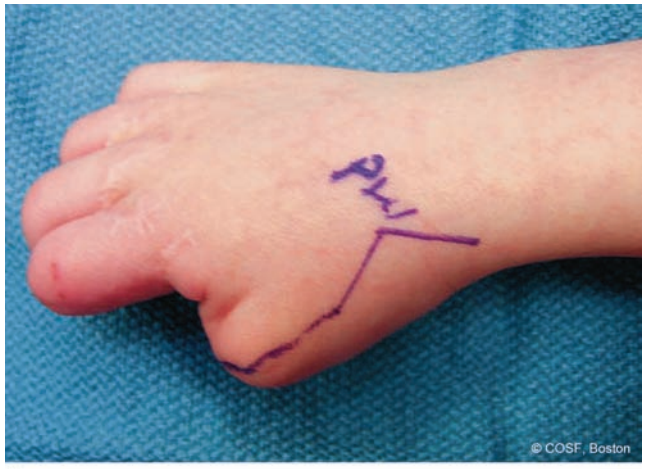

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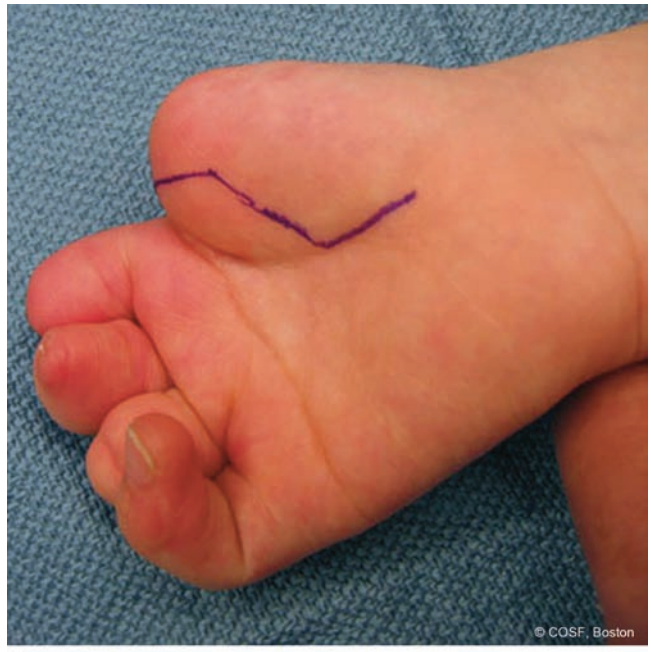
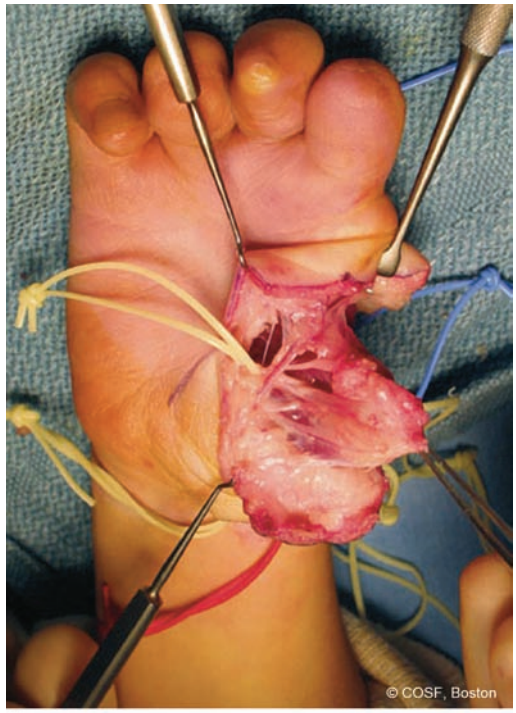


D

FIGURE 46-2 **A, B:** Preoperative angiograms demonstrating normal vascular anatomy proximal to the level of the hand deficiencies and normal anatomy of the foot. **C, D:** Clinical incisions for exposure of the recipient site for planned free second toe-to-thumb transfer.

E



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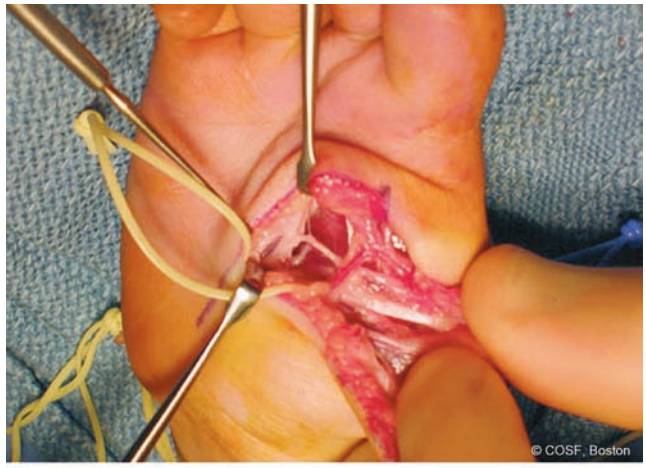

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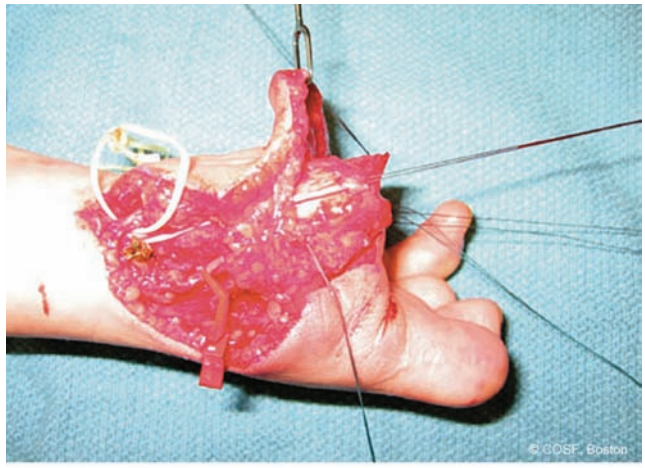

H

FIGURE 46-2 *(continued)* **E:** Clinical incision used for second toe harvest is marked with the *solid line*. *Dotted lines* overlie the dorsal veins. **F:** Intraoperative photograph demonstrating normal neurovascular bundles proximal to the level of thumb deficiency. **G:** The flexor tendon is similarly identified. **H:** Dorsal dissection allows for visualization of the dorsal veins and extensor tendon, tagged with a traction suture.

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I

J

K

L

FIGURE 46-2 *(continued)* **I:** After skeletal stabilization and tendon repairs, microsurgical arterial and venous anastomoses are performed. **J:** Appearance of the foot after primary closure of the donor site. **K:** Appearance of the toe transfer at the completion of the procedure. **L:** Postoperative radiograph of the hand demonstrating bony alignment and toe position.

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M

FIGURE 46-2 *(continued)* **M:** Postoperative weight-bearing radiograph of the foot following toe harvest.

Typically, the second toe is utilized (see Sidebar). After careful skin flap elevation, the dorsal veins are identified and traced back to their origin from the greater saphenous at the level of the proximal foot or ankle. The arterial pedicle to the toe is then identified (Figure 46-3). The dorsalis pedis may be traced distally to the first dorsal metatarsal artery in the first web space and then subsequently to the digital vessels supplying the toe. (The dorsalis pedis bifurcates into the dorsal and plantar metatarsal arteries just distal to the base of the first and second rays.) Often the first dorsal metatarsal artery will dive deep in the first intermetacarpal space or within the interosseous muscle, though will always remain dorsal to the transverse intermetatarsal ligament. It is critical to remember that the first dorsal metatarsal artery will only be present and sufficient in two-thirds of cases![14–16] If a dorsal pedicle is not identified, then plantar dissection must be performed to identify the first plantar metatarsal artery. Others have advocated a distal-to-proximal arterial pedicle dissection.[17]

Similarly, the medial and lateral digital nerves can be identified and dissected free. The digital nerves of the toe are often smaller and shorter than in the hand, requiring epineural dissection and interfascicular dissection to provide adequate length prior to transsection.[18] Flexor and extensor tendons are identified, dissected free, and transected well proximal to the harvest level. Release of the transverse intermetatarsal ligaments is often required to gain sufficient access to the flexor digitorum longus and flexor digitorum brevis tendons proximal to the tendon sheath. Finally, when the amount of skeletal length needed

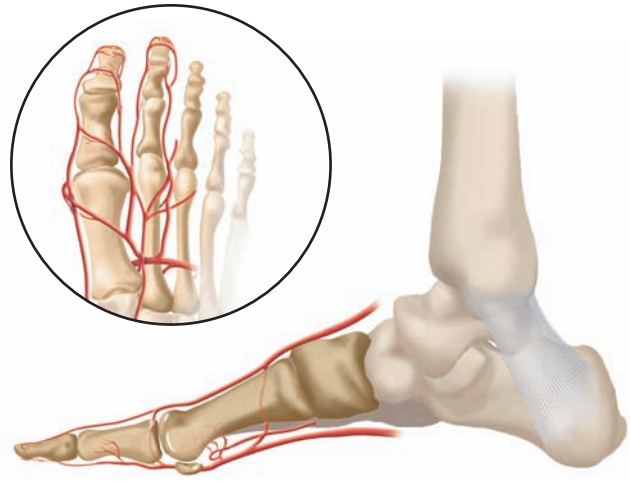

FIGURE 46-3 Clinical diagrams demonstrating the vascular anatomy of the great and second toes.

SIDEBAR

Great Toe versus Second Toe…Which Is the Optimal Donor?

Both the great toe and second toe have been utilized for toe-to-thumb transfers. Each has its advantages and disadvantages, advocates and opponents.

While the great toe may be utilized for thumb deficiency distal to the thumb metacarpal, great toe harvest results in greater functional loss to the foot. Furthermore, the great toe is approximately one-third wider than the thumb, with a larger nail plate and more abundant plantar pulp, resulting in persistent aesthetic mismatch.

The second toe generally is preferred, as it provides more than adequate length with the least donor-site morbidity. Even proponents of great toe transfers acknowledge that the second toe is superior in cases of thumb deficiency through the thumb metacarpal, as the second toe may be harvested with a portion of the second metatarsal with minimal donor-site morbidity. However, the second toe has its own limitations. It is narrower than the normal thumb, with a smaller nail plate and more bulbous, square-shaped digital pulp. The interphalangeal joints of the lesser toes have less flexion and exhibit a tendency to claw following transfer. Critics of the second toe argue that it may provide less stability and strength for vigorous pinch and grip than a great toe transfer.[19] Despite these acknowledged limitations, we favor the use of the second toe for free toe-to-hand transfers.

is determined from the recipient site, the bony level can be identified and the toe freed either through bone or joint. The tourniquet is then deflated and vascularity of the toe—now connected only by its neurovascular pedicles—is confirmed. When the transfer is ready to be performed, the artery and vein(s) are ligated and divided. Usually, primary closure of the harvest wounds may be achieved with little tension and a pleasing aesthetic result.

When the toe is free, a single longitudinal smooth pin (0.028″ or 0.035″) is passed in a retrograde fashion from the tip to the base. The toe is then positioned in appropriate alignment and length onto the recipient site, and the previously placed pin is used to provide skeletal fixation. The flexor and extensors are repaired; appropriate tension on the extensors is needed to avoid late flexion contractures. Although thenar muscles may be absent or hypoplastic, we do not favor concomitant opposition transfers at the time of toe transfer; instead, the toe is positioned in appropriate pronation to allow for adequate pinch and grasp. Secondary opponensplasty may be performed, if needed, in a staged fashion. Finally, under microscopic magnification, the arterial and venous anastomoses may be performed. This is typically done in an end-to-end fashion using interrupted 10-0 nylon sutures. The tourniquet is released, and confirmation is made of adequate vascular inflow and outflow. A bulky dressing is applied, followed by a long-arm cast. Great care is taken to avoid constrictive dressings, which may kink or occlude arterial inflow or venous outflow from the transferred toe.

◆◆ Toe-to-Hand Transfer for Traumatic Loss or Failed Thumb Replantation

Although the general principles and techniques of toe-to-hand transfer for traumatic loss are similar to those performed for congenital differences, a number of specific distinctions bear special mention.

Indications for toe-to-hand transfer include traumatic thumb amputations through the proximal phalanx, metacarpophalangeal (MCP) joint, or metacarpal, in which the distal part is not replantable or prior replantation attempts have failed.

Regarding timing of surgery, toe-to-hand transfers may be performed primarily as the index reconstructive procedure or secondarily after preliminary wound debridement and coverage. The results in terms of survival and complication rates appear to be similar.[19] Therefore, the decision regarding when to do a toe-to-hand transfer for traumatic loss depends on individualized surgeon and patient/family factors. The advantages of early/immediate transfer include more expedient recovery and avoidance of repeated procedures and multiple hospitalizations. Secondary reconstructions, however, allow for more deliberate preoperative discussion with patients/families regarding treatment options and long-term expectations. If secondary reconstructions are planned, coverage of the traumatic defect with healthy, vascular tissue will allow for easier subsequent toe transfer, due to the presence of more local tissue for coverage, the need for less transferred soft tissues, and the avoidance of scar formation in the new, mobile unit.[19]

Preparation of the recipient site on the hand is highly variable, depending upon the nature of the prior traumatic injury. In general, mobile skin flap elevation is needed, via either midaxial incisions or a "cruciate" incision over the recipient stump. Skin flaps should be trimmed and excess soft tissue removed prior to vascular anastomoses being performed to optimize toe inset and avoid the edema and bleeding that lead to suboptimal toe placement.[20]

POSTOPERATIVE

Following free vascularized tissue transfers, we routinely use intravenous dextran (dextran 40, 5 to 10 mL/kg/d) for thrombosis prophylaxis for 5 postoperative days, followed by oral aspirin for a total of 3 weeks postoperatively. Serial examinations to assess for color, turgor, and warmth of the toe transfer are performed in the immediate postoperative period. At present, we do not utilize implantable or invasive monitoring of the anastomoses. We do routinely use postoperative Doppler examinations directly over the anastomosis or, if not feasible, surface temperature monitors to assess viability.

ANTICIPATED RESULTS

The trouble with referees is that they just don't care which side wins.
—Tom Canterbury

With meticulous surgical technique, successful free toe-to-hand transfer is achieved in >95% of cases, if "success" is defined as viability of the transferred tissue[3,11,13,21–24] (Figure 46-4). Viability rates in children have been reported to be similar to those in adults, despite the technical challenges in smaller, younger patients.[20] In most cases, growth is preserved in the transferred part and achieves 60% to 100% of its potential.[14,18,23]

Functional results, however, remain less predictable and often require secondary surgery.[10,18,23] Typically, passive motion exceeds active motion of the transferred digit. Tenolysis, while tempting, often does not reliably improve this deficit.[22,25,26] There can be an extension deficit, leading to varying degrees of flexion contracture.[8] While sensibility is preserved, careful testing reveals it to be frequently >5 mm of two-point discrimination.[14,21] Typically, strength is about 50% of normal.

Despite this, patients with severe congenital or traumatic deficiencies do demonstrate improvements in overall hand function. The toe is incorporated into hand use, and pinch is restored when toe-to-thumb transfer is

FIGURE 46-4 Clinical photograph of a prior toe-to-thumb transfer at long-term follow-up.

performed.[23] These improvements have been reported in cases of symbrachydactyly, where the proximal anatomy is abnormal, as well as in cases of amniotic band syndrome and traumatic loss.[24] Furthermore, functional gains do appear to be long-lasting.[27,28]

COMPLICATIONS

Progress always involves risks. You can't steal second base and keep your foot on first.
—Frederick B. Wilcox

Ischemia and necrosis of the transferred toe is the most devastating postoperative complication. While rare, every effort should be made to adhere to sound microvascular surgical principles to minimize the risk of postoperative vascular complications. Maintenance of adequate perfusion pressures and judicious use of dextran or other antithrombolytic agents may help to further minimize the risk of vascular thrombosis.

Vasospasm is a more common complication in the intraoperative or immediate postoperative period. Spasm may be addressed utilizing a number of maneuvers, including adequate analgesia or sedation, maintenance of adequate perfusion pressures, warmth, and application of local vasodilatory agents (e.g., lidocaine, topical nitroglycerin). When identified intraoperatively, adventitial stripping may be helpful, though it should be done under microscopic visualization with meticulous technique. If no improvement is seen during the immediate postoperative period, a low threshold exists for surgical exploration and/or decompression.

Late complications include marginal skin/soft tissue necrosis, joint stiffness, extensor lag, and bony nonunion. Secondary procedures, while often considered, do not always improve function and should be entertained with caution.[26]

Finally, persistent donor-site morbidity remains a concern after free toe transfers. While prior biomechanical analyses have suggested increasing forces borne by the great ray after second toe transfer, these changes are thought to be minimal, and clinically there do not appear to be long-term functional problems following toe transfer.

CASE OUTCOME

After discussion with the family regarding treatment options, the decision was made to proceed with toe-to-thumb transfer (Figure 46-2). Successful second toe-to-thumb transfer was performed using the techniques highlighted here. With the presence of thumb length, stability, and power, the patient was able to achieve lateral key pinch and improved hand function.

SUMMARY

Free toe-to-hand transfer remains a powerful tool in the armamentarium of the pediatric hand and upper extremity surgeon, both for congenital deficiencies and traumatic loss. Careful patient selection and thorough preoperative discussion are essential to ensure maximization of function, avoidance of postoperative complications, and realistic expectations regarding expected outcomes.

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CHAPTER 47

Osteochondromas

CASE PRESENTATION

A 4-year-old female presents with an osteochondroma (OCE) of the distal ulna, a foreshortened ulna relative to the radius, increased radial inclination of the articular surface, ulnar translocation of the carpus, ulnar deviation of the hand, proximal radial head dislocation, and reduced forearm rotation that has produced functional limitations (Figure 47-1).

CLINICAL QUESTIONS

- What is the inheritance pattern of multiple hereditary exostoses (MHE)?
- What are the gene mutations responsible for OCE formation?
- What is the natural history of MHE?
- What are the indications for surgical excision of an OCE?
- Will excision of an OCE restore skeletal growth?
- What are the expected outcomes from excision of an OCE?
- When is an ulnar lengthening indicated?
- When is creation of a single bone forearm indicated?
- What are the complications associated with surgical reconstruction of an imbalanced forearm and wrist with osteochondromatosis?
- What is the risk of malignant degeneration with an OCE?

THE FUNDAMENTALS

Etiology and Epidemiology

Arising from juxtaphyseal regions, OCEs are the most common (20% to 50%) type of bone tumor. The differential diagnosis includes metachondromatosis, dysplasia epiphysialis hemimelia (Trevor disease),[1] multiple enchondromatosis (Ollier disease), and malignancies, among others. OCEs can either be solitary or multiple. Known also as multiple osteochondromatosis, multiple cartilaginous exostoses, and diaphyseal aclasis, among other synonyms, multiple hereditary exostosis (MHE) is typically (~80% of cases) an autosomal dominantly inherited disease associated with mutations in tumor suppression genes (EXT1 and EXT2) that are required for heparan sulfate synthesis. Specifically, these EXT1 and EXT2 mutations lead to defective glycotransferases and altered endochondral ossification by abnormal chondrocyte proliferation and maturation.[2] The OCE lesions begin as microchondromas within the periosteum adjacent to the normal physis, in the groove of Ranvier.[3] Of note, metachondromatosis and dysplasia epiphysialis hemimelia are not due to abnormalities of the EXT pathway.[4]

The incidence of OCE is on average 1 to 2:100,000 live births but varies greatly depending on the genetic pool in specific geographic regions. Patients and families with EXT1 have a more severe phenotype than EXT2 patients. The EXT1 patients have more lesions, more severe deformities, more short stature, more length discrepancy in involved bones, and more involvement in flat bones and undergo more operations than other EXT subtypes.[5–7] The EXT1 patients are also more at risk for malignant degeneration of an OCE lesion, as are patients with Maffucci syndrome (enchondromas and hemangiomas). The overall risk of malignant degeneration is about 2% for MHE patients.[8] Sequencing differentiation of the EXT1 and EXT2 mutations in individual pedigrees is ongoing in many diverse ethnic families with MHE and will provide more definitive, patient-specific information in the future.

Clinical Evaluation

Patients with solitary OCEs usually present when the lesion is large enough to be palpated. This is often during

FIGURE 47-1 Preoperative radiograph of upper arm and forearm of a 4-year-old child with distal ulnar OCE and a marked dislocation of the radial head.

an accelerated growth phase, such as during the preadolescent growth spurt. The presence of a firm mass raises a serious concern over malignancy by parents, providers, and patients. The parental and patient worry about a possible cancer is often the "elephant in the room," and addressing this grave concern of theirs promptly is a great relief to patients and families.

Patients with MHE usually present earlier because their genetically aware parents will repeatedly examine their children for lesions. The severe EXT1 pedigrees will have lesions at younger ages, some present in infancy and even in flat bones such as ribs. Digital malalignment and a prominent finger mass arising from the phalangeal articular cartilage can occur in infancy with an EXT1 patient. The ratio of ulnar length to patient height has been used to distinguish EXT1 and EXT2 patients.[9]

Restricted and/or painful joint motion; long bone deformity; growth discrepancy of involved bones; joint subluxation; and impingement symptoms of neurovascular structures, muscles, and/or tendons are common complaints of patients with an OCE and MHE.[10] The lesions will increase in size with growth, and, therefore, complaints and problems are common in children over the age of 10 years.[11] In essence, pain (~80% of patients) is their most common complaint since it is frequent and directly impacts the daily function of many patients.[12]

The most common upper limb problem with OCEs is forearm and wrist deformity that impairs function. Involvement of the distal ulna is common and can lead to relative shortening of the ulna compared to the radius. If the growth discrepancy is marked, there will be (1) increased radial articular inclination, (2) ulnar deviation of the hand, (3) ulnar and proximal translocation of the carpus, and (4) increased radial diaphyseal bowing and/or proximal radial head dislocation.[13] The shorter the ulna relative to the radius, the more loss of motion and function will occur.[14]

Hand involvement with MHE is common with juxtaphyseal lesions in metacarpals, proximal and middle phalanges. There are often more than 10 hand lesions per MHE patient that result in brachydactyly and less commonly angular deformity.[15] Distal phalanx and thumb involvement are rare. Unusual presentations in the hand include mallet finger, nail plate deformity and intra-articular OCEs.

Winging of the scapula, crepitus, and/or pain can be the presentation for anterior scapular OCEs.[16] Rarely these can be palpated by exam or seen on plain radiographs. A computed tomography (CT) or magnetic resonance imaging (MRI) scan will be diagnostic. Proximal humeral OCEs are common since approximately 80% of the growth of the humerus is at the proximal physis. These lesions will initially hide under the deltoid. Later, with growth, they can become more prominent. Local impingement can cause functional pain and limit both motion and strength.

One of the most worrisome clinical features is an intraspinal OCE that leads to spinal cord compression.[17] This occurs in <1% of MHE patients. The most common regions are upper cervical (C2), upper thoracic (T4–T8), and base of skull. Plain radiographs may reveal the lesion but often these intraspinal lesions are small. Neurologic exam with clonus, increased reflexes, and positive Babinski signs is diagnostic of myelopathy, and assessing for this should be a part of all annual and preoperative physical exams. Spinal cord imaging with tomograms, myelograms, or more commonly now MRI and thin-slice CT scans is diagnostic.[18,19] Surgical removal of the intraspinal OCE before progressive myelopathy or complete neurologic loss, such as under anesthesia for elective surgery for other reasons, is strongly recommended.[20]

There are several clinical classification systems for MHE patients. The forearm can be used to gauge the severity of total body MHE and the risk of malignant degeneration. Taniguchi defined three groups: group I, no involvement of the distal forearm; group II, involvement of the distal forearm without shortening of the radius or ulna; and group III, involvement of the distal forearm with shortening of the radius and/or ulna.[21] Group I was mildly affected, and group III had axial and severe appendicular skeleton involvement and was most at risk for malignant degeneration. Masada classified forearm deformity by group I, ulnar shortening and radial bowing due to a distal ulna OCE; group II, dislocation of the radial head due to an OCE of the proximal radius (IIA) or distal involvement

(IIB); and group III, relative radial shortening due to a distal radius OCE.[22] Radiographic parameters on the anteroposterior (AP) view to measure the degree of deformity include radial articular angle, carpal slip, ulnar variance, and forearm to third metacarpal angle. Ulnar variance in the skeletally immature requires measurement of the radial metaphysis to the ulnar metaphysis.[23]

Malignant degeneration of OCEs is a risk in approximately 2% of MHE patients[24] and is higher in EXT1 patients.[25] These patients, especially those with EXT1 gene mutations, clearly need to be made aware of the possible occurrence and followed expectantly. In some populations, serial bone scans have been used to monitor lesions.[26] Worsening pain or increased size of a lesion in adulthood is serious cause for concern. The size of the cartilaginous cap is a factor, with a cap thicker than 2 cm being high risk for chondrosarcoma. Cartilaginous cap size discrimination can be determined with a high degree of accuracy by both MRI and CT scans.[27] Positron emission tomography scans can aid in diagnosing malignant chondrosarcomas, local recurrence, and metastases by the metabolic activity of the lesion(s).[28] In the end though excisional biopsy is indicated for suspicious lesions.

Surgical Indications

The presence of a mass alone is not an indication for surgical excision of an OCE. Otherwise, patients with MHE would have aggressive and frequent surgeries for both primary and secondary resections. The presence of pain associated with an OCE is an indication for surgery, understanding that pain is relative. Resection of a painful OCE provides pain relief in more than 90% of patients.

Excision of an OCE to prevent growth deformity is more controversial.[29] In the forearm, excision of a solitary OCE on one of the two bones can restore and improve growth. If OCEs are present on both the distal radius and ulna, growth restoration does not occur with simple excision.

Surgery to correct deformity and/or length discrepancy is indicated when there is marked deformity, painful restriction of motion, and functional deficits. Surgery has to be compared with natural history, as adults with OCEs, growth discrepancy, and upper limb deformity can be pain free and functional.[30–32] There is clear evidence that symptomatic patients can obtain pain relief, improved motion of wrist and forearm, and aesthetic enhancement with forearm rebalancing surgery.[13,33–36] Forearm rebalancing is usually a combination of OCE excision, distal radial osteotomy or temporary growth retardation on the radial side of the distal physis, and ulnar lengthening (by single-stage or distraction osteoclasis). Reconstructive procedures performed at an early age often require reoperation with growth. The ability to successfully reduce and maintain reduction of a dislocated radial head is controversial. A dislocated radial head, especially in a very young patient, for us is an indication for single bone surgery.[37,38]

SURGICAL PROCEDURES

Excision of OCE

Common symptomatic sites in the upper limb are (1) distal ulna with impingement against the radius, limiting motion and causing pain (Figure 47-2); (2) proximal humerus causing impingement and pain (Figure 47-3); and (3) distal radius with compression and contact pain. Other less common sites and indications are (1) anterior scapula with winging, crepitus, and painful motion; (2) metacarpal or phalanx with pain and at times angular deformity (simultaneous corrective osteotomy may be indicated); and (3) an intra-articular OCE in infancy with limited motion and angular deformity (see Figure 6-8).

Exposure of the symptomatic OCE is made considering the neighboring neurovascular bundles and cutaneous nerves. Frequently, the local nerves and arteries are displaced from their native anatomic sites by large, symptomatic OCEs, for example, ulnar nerve and artery by a large, volar distal ulnar OCE (Figure 47-2) and radial, axillary nerve(s) or brachial plexus by proximal humeral OCEs (Figure 47-4). The incision needs to be sufficiently extensile to perform a careful excision of the entire cartilaginous cap and OCE while protecting not only the neurovascular bundles but the physis as well. If there is a concern about a malignant degeneration, surgery should be performed with or by an orthopaedic oncologist, so the incisions and

FIGURE 47-2 Large OCE of the distal ulna with foreshortening ulna and mild deformity of radius in response to OCE impingement.

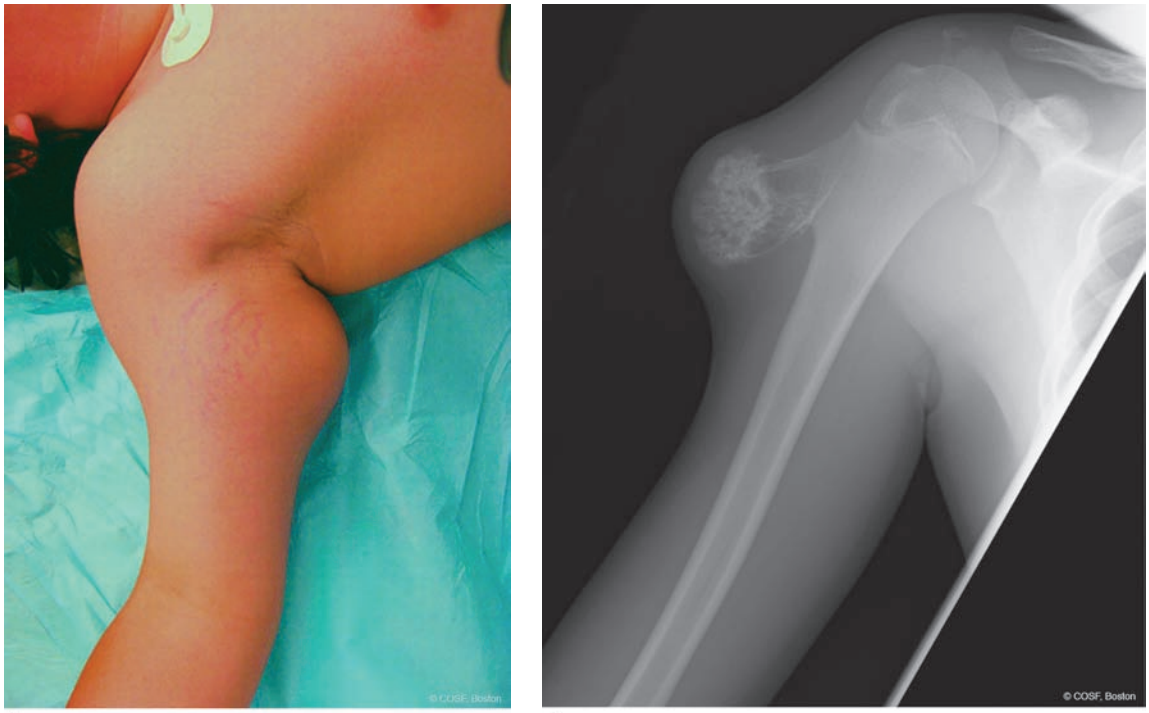

FIGURE 47-3 **A:** Clinical photograph of large OCE of the proximal humerus with painful impingement. **B:** Radiograph of similar proximal humeral OCE except on lateral rather than medial side.

dissection do not jeopardize limb salvage. Circumferential dissection around the base of the OCE is performed with elastic loops or gentle retractors mobilizing the neurovascular bundle. Once the entire base, body of the OCE, and cartilaginous cap are isolated (Figure 47-5), the periosteum is incised with electrocautery, and excision is performed with an appropriate-size curved osteotome. (Rongeuring of the sharp edges of the base is performed to prevent further impingement and persistently symptomatic bony prominences.) Fluoroscopy can be utilized to aid in avoiding excessive or insufficient resection. Insufficient resection can lead to continued symptoms or recurrence. Excessive resection can result in subsequent growth disturbance or pathologic fracture. After completion of the desired resection—at times, this may involve multiple OCEs in the same operative field—bone wax is applied to the base. Closure is in layers after gently placing the displaced nerves and vessels back into the wound without tension. Immobilization is with splint, bivalved cast, or sling depending on the anatomic site of the surgery. Length of protection is dependent on pain and risk of pathologic fracture. Overall, more than 90% of the preoperative symptoms are resolved with OCE excision, making it a successful treatment of symptomatic OCEs with a low morbidity.[39,40]

Nail Reconstruction

Some patients with MHE will develop with a subungual exostosis.[41,42] Once you have seen one of these, you have seen them all. The surgical focus is on the exostosis excision and restoration of a flat, aligned nail bed. Once that occurs, the nail plate will grow out with minimal to no deformity.

Removal of the nail plate is performed with a smooth, curved elevator (Freer) or small, curved snap while protecting the underlying nail bed. The thinned nail bed is carefully elevated with a small, sharp knife blade from lateral to central to expose the exostosis completely. The nail bed can be very thin over the exostosis, so very delicate elevation is required. The exostosis is removed with a rongeur to a flat base. Bone wax is placed over the open bony surface. A radiograph or fluoroscopy view is obtained to confirm complete excision. There have been instances when we thought our excision was complete only to realize it was inadequate by radiographic assessment. After complete excision, the nail bed is replaced so that it is as flat and smooth as possible. There are times when the exostosis has created a central hole in the nail bed. We do not graft those defects initially. Surprisingly, the nail plate almost always grows out with minimal to no deformity. We cauterize a hole in the center of the nail plate and replace it under the eponychium, or we use petrolatum gauze (Xeroform, Covidien, Mansfield, MA) for this purpose if the nail plate is too deformed. A protective dressing is used for 2 weeks and then serial soaks with a saline–hydrogen peroxide mix and dressing changes with Xeroform; gauze and self-adherent wrap (Coban, 3M, St. Paul, MN) are used until the wound is fully healed. It takes 3 to 6 months for the final outcome of the nail plate to be determined.

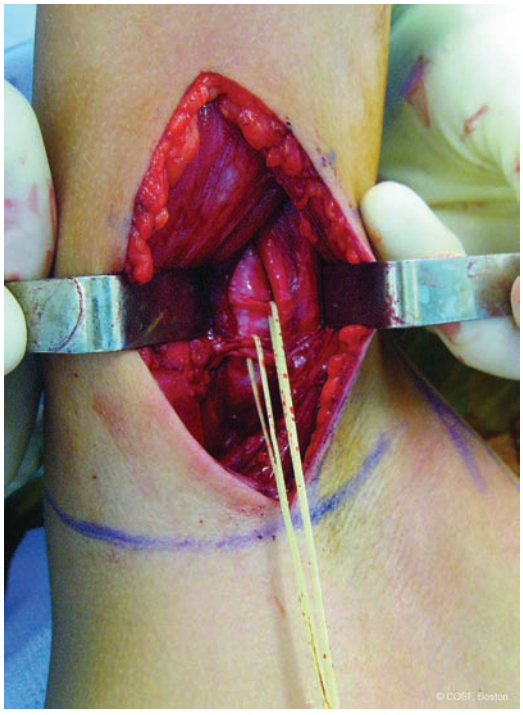

FIGURE 47-4 Intraoperative photograph of OCE of the proximal humerus with branches of the radial nerve isolated with elastic loops for protection during excision.

Excision of OCE and Sauve-Kapandji Procedure

Wrist stabilization and forearm realignment after OCE excision can be achieved in many ways. Ulnar lengthening with a Sauve-Kapandji procedure (fusion of the distal ulna to the radius with the creation of a more proximal ulnar pseudarthrosis to allow for pronation-supination) is one technique that has been successful in a small series of patients with moderate length follow-up.[43] It is a tool worth knowing and keeping in your armamentarium.

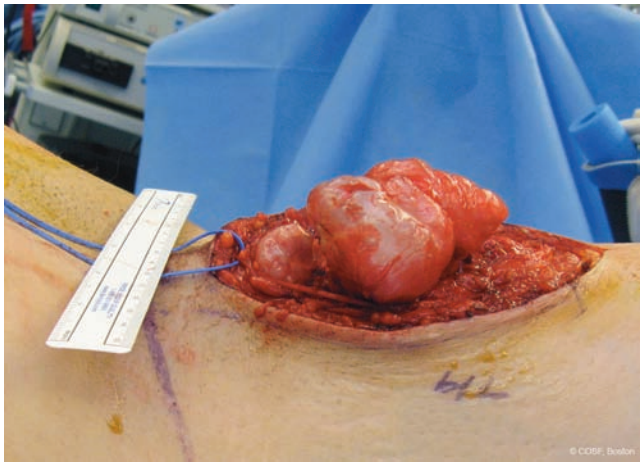

FIGURE 47-5 Intraoperative photograph of proximal humerus lesion in preparation for excision.

The distal diaphyseal and metaphyseal portions of the ulna are exposed through a straight longitudinal incision with deep dissection between the extensor carpi ulnaris (ECU) and flexor carpi ulnaris (FCU). Fluoroscopy aids in identifying the physis and more proximal area of resection. In the skeletally immature patient, it is important to be more proximal than in the skeletally mature, about 2 cm proximal to the physis. Resection of the bone needs to include the periosteum, or recurrent healing of the resection will result in a single bone forearm. A 2-cm section of bone and periosteum is excised. The ulna is stretched out to neutral variance by metaphyseal measurement.[23] The ulna is fused to the radius through a bone block to maintain the interosseous space and correct alignment of the radius and ulna that will allow for full forearm rotation without impingement. K-wire or cannulated screw fixation is used. Two wires or screws are necessary for rotational control. In the skeletally mature, this operation is performed just proximal to the distal radioulnar joint (DRUJ) with compressive screw fixation. At this level, bone graft is rarely needed because bone-on-bone compression can be achieved without distorting the alignment of the radius to the ulna.

This procedure can be performed in conjunction with OCE(s) excision and radial osteotomy or temporary growth arrest as appropriate. Long-arm cast immobilization is utilized until healing is sufficient enough to change to a short-arm cast without worry of rotatory stress negatively affecting healing or fixation. Smooth wires are removed in the office, or screws are left in place with full healing. Rehabilitation is important to restore full forearm rotation. Radiographs through the first year are important to be certain the ulnar pseudarthrosis stays open and there is no impingement of ulna on radius with rotation movements.

Radial Osteotomy

There are patients with MHE/OCE who are referred near skeletal maturity with a chief complaint of increased ulnar deviation deformity of their wrist. Radiographs reveal ulnar shortening and increased radial articular inclination, as expected. However, their distal radius and ulna will not accommodate each other for a stable, reduced DRUJ if the ulna is lengthened. A radial closing wedge osteotomy will improve their aesthetics and wrist motion without the complexity of an ulnar lengthening, DRUJ reconstruction, or Sauve-Kapandji procedure (Figure 47-6).

Using fluoroscopy for guidance with incision placement, a straight radial approach to the distal radial metaphyseal area is performed. The radial sensory nerve emerging from underneath the brachioradialis is identified and protected. Subperiosteal exposure of the radius is performed while mobilizing the brachioradialis and protecting the radial artery and extensor tendons of the first and second compartment. Smooth convergent wires

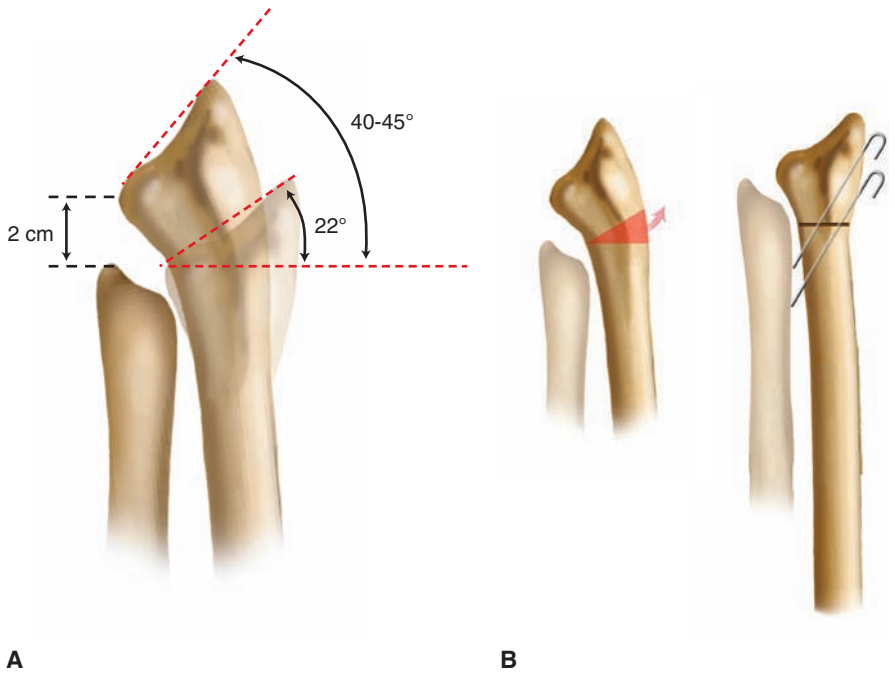

FIGURE 47-6 **A:** Illustration of a preoperative radiograph of adolescent patient with increased radial inclination and foreshortened ulna. **B:** Radial closing wedge osteotomy to level the radial articular surface and rebalance the forearm.

are placed from the radius toward the ulna as guides for the desired closing wedge, as templated on preoperative radiographs. The goal is to restore the radial articular inclination and volar tilt to normal (~22-degree inclination and 11-degree volar tilt in skeletally mature patients). Sharp osteotomes or a small oscillating saw can be used to remove the appropriate wedge. The ulnar cortex and periosteum are left intact. The correction is performed by gently closing the wedge and efficiently placing two oblique radial-to-ulnar, proximal-to-distal smooth wires for fixation. These will pass from the distal radial styloid in a divergent path for proximal fixation. The bone removed can be placed as morselized graft. If adequate, the periosteum can be closed to improve stability and vascularity to the osteotomy site for healing. Various distal radial plating systems can also be used in older patients with more robust bone.

◆ Excision of Distal Ulna OCE, Ulnar Lengthening, and Radial Osteotomy

Sometimes you win, sometimes you lose, and sometimes it rains.
—Bull Durham

There is a subset of MHE or OCE patients with symptomatic malalignment of the wrist and forearm for whom forearm skeletal rebalancing surgery will be beneficial.[22,33,34,36,44] For us, the ideal candidates are older patients in whom one reconstruction will resolve their problem without recurrence. Younger patients are clearly under consideration, but all options are reviewed closely for those children.

The symptomatic and/or motion-restricting OCEs are excised. This is usually from the ulna. If resection leads to loss of bone stock that will negatively impact distal ulna bone fixation for lengthening, the excision and skeletal rebalancing are done in two stages. The ulna lengthening can be done gradually with an external fixator or in a single stage with external fixation lengthening followed by internal fixation plating (Figure 47-7).

The latter is our preference. Exposure is straight longitudinal along the ulnar border. The incision extends from the proximal to distal metaphyseal-diaphyseal junctions of the ulna. A monolateral external fixator is placed proximal and distal to the desired lengthening area. This will be used temporarily to gain desired length before plating. Two pins on either side are usually necessary. A Z-lengthening of the bone is outlined to allow for up to 2 to 3 cm of ulnar lengthening with adequate ulnar bone overlap in the middle for bony stability and timely osteotomy healing. A small oscillating saw is used for the Z-cuts. Gradual distraction is performed. Allowing for soft tissue creep is necessary to achieve the desired length and alignment. Patience and persistence are necessary. Once the DRUJ is reduced and neutral variance achieved, the plate is placed. Proximal and distal neutralization screw fixation is completed, followed by interfragmentary fixation across the Z-overlap. Bone graft or substitutes may be used, but often the osteotomy heals readily in the young. Prophylactic forearm fasciotomies are performed to lessen

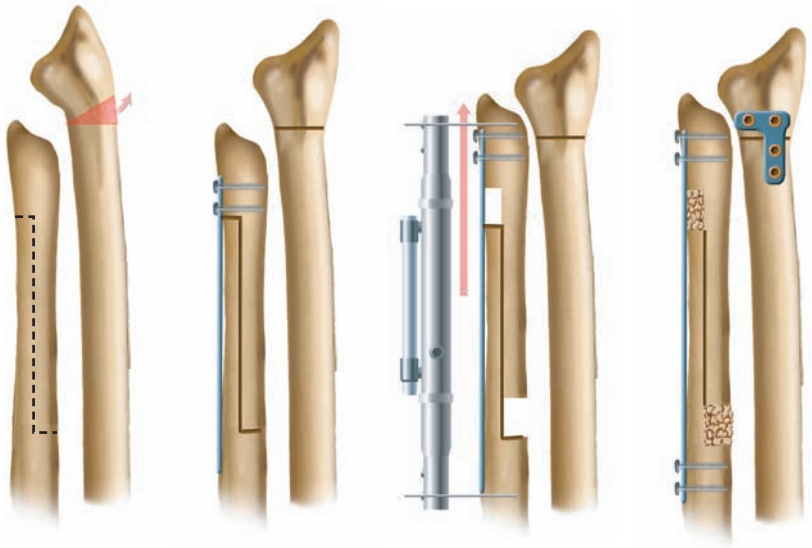

FIGURE 47-7 Illustration of forearm rebalancing in a single stage. The ulna is lengthened through a Z-cut of the bone and intraoperative gradual distraction. The ulna is plated once the desired length is achieved. The radius may require an osteotomy for complete single-stage rebalancing. If a radial closing wedge osteotomy is performed, that bone is morselized and used as graft to the ulnar lengthening.

the risk of compartment syndrome. The external fixator is removed, and ulnar stability and forearm range of motion are tested before closure. Sequential closure over a drain with absorbable suture is performed. An extremely well-padded ("fat and ugly") bivalved cast is applied.

◆ Single Bone Forearm

Every strike brings me closer to the next home run.
—Babe Ruth

The status of the radial head is now a major determinant for us of lengthening versus single bone forearm procedures. If the radial head is dislocated (Figure 47-8), especially in the very young (Figure 47-1), we now opt for a radio-ulnar diaphyseal fusion after proximal radius and distal ulna resection.[37,38,45–47] This procedure has the advantages of (1) a single-stage procedure without distraction lengthening; (2) definitive treatment of the joint dislocations by proximal radial and distal ulnar excision; (3) functional realignment of the forearm in neutral to 20 degrees of pronation with compensatory wrist rotation; (4) restoration of wrist and elbow flexion-extension motion without impingement; (5) continued forearm longitudinal growth through the distal radius without recurrent deformity; and (6) avoiding complex reoperations during growth due to recurrence. The surgery can be performed at any age, regardless of the degree of skeletal maturity.

An extensile exposure to the entire forearm is performed in a dorsal ulnar curvilinear fashion (Figure 47-9A). Proximally the dislocated radial head and neck are exposed through the anconeus-ECU interval. The lateral collateral ligamentous complex is preserved during joint exposure. The radial nerve and its posterior interosseous branch are identified and protected proximally in the brachialis-brachioradialis interval extending distally through the supinator. The biceps insertion into the radial tuberosity is preserved. If more extensive proximal radial

FIGURE 47-8 Radiograph of a skeletally mature patient with EXT1 gene, dislocated radial head, and DRUJ with marked limitations at work and home.

excision is needed to achieve bony alignment and compression, then the biceps tendon insertion is transferred to the proximal ulna. This is performed by detachment of the tendon from the radial tuberosity and insertion into the coronoid with periosteal repair or transosseous suture anchors. With fluoroscopic guidance, extraperiosteal excision of the dislocated radial head and neck is performed. The periosteal excision lessens the risk of recurrent bone formation with growth that could lead to capitellar impingement. The excised bone is stripped of all soft tissues, OCEs, and articular cartilage in preparation for use as intercalary bone graft in the radioulnar fusion.

Distal ulnar dissection is performed in the ECU-FCU interval. The dorsal ulnar sensory nerve is protected. Exposure of the distal ulna is performed from beneath the triangular fibrocartilage meniscal homologue into the DRUJ and ulnocarpal joint. Extraperiosteal excision of the ulna is performed from the metaphyseal-diaphyseal region distally to include all the exostoses. Fluoroscopy aids in choosing the level of excision for deformity correction and fusion. The excised distal ulna is also stripped of all soft tissues, OCEs, and cartilage for use as an additional intercalary graft.

Subperiosteal exposure of the diaphyseal ulna is performed. While protecting the anterior and posterior interosseous neurovascular structures as well as the volar and dorsal musculature, dissection is carried across to the diaphyseal level of the radius. Similar subperiosteal

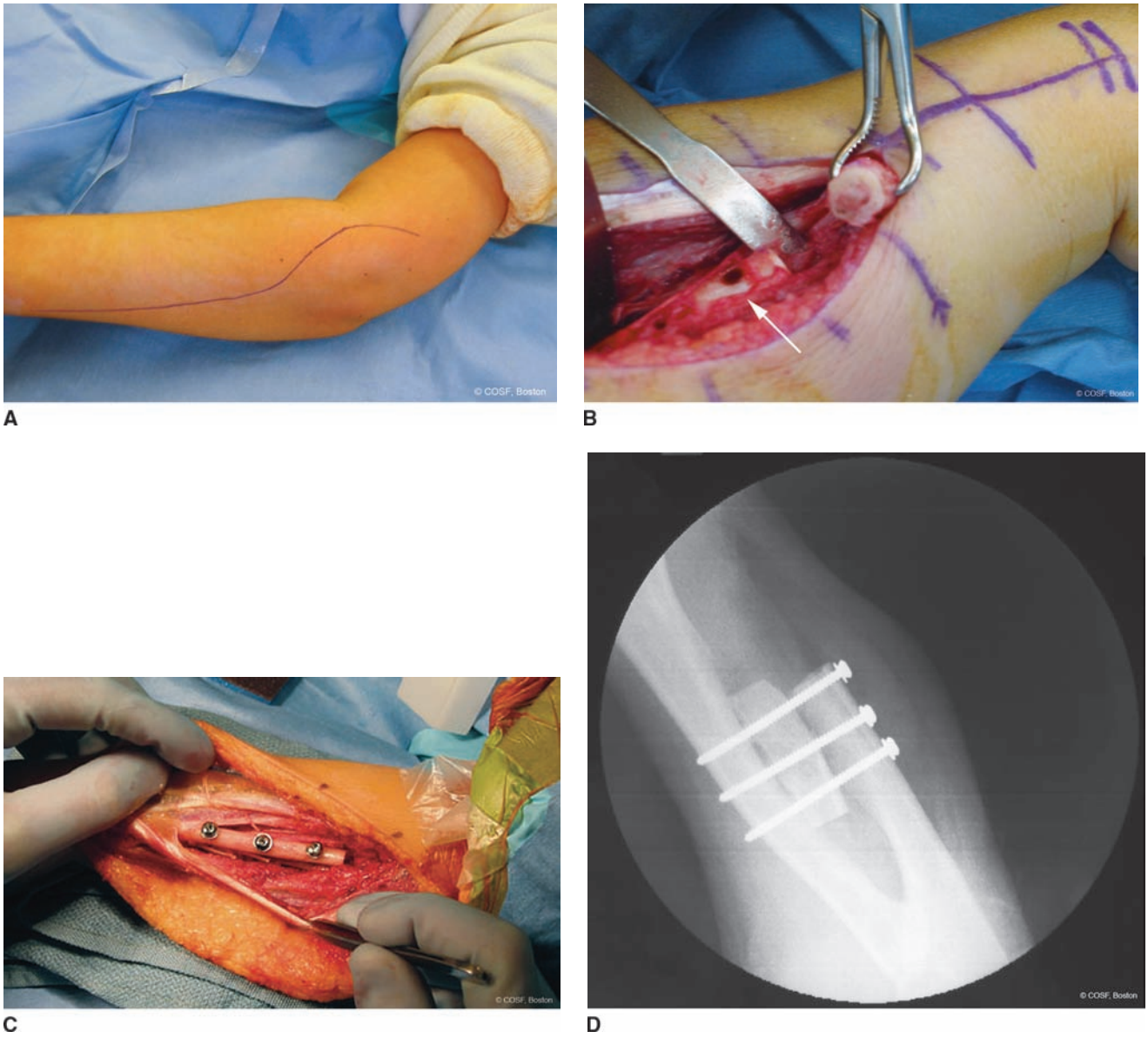

FIGURE 47-9 **A:** Incision outline for extensile exposure of the proximal radius to the distal ulna for single bone forearm surgery. **B:** Subperiosteal of the distal ulna (*clamped*) and proximal radius (*arrow*) in preparation for radius and ulna fusion. **C:** Internal fixation with three screws and washers of radius to ulna. **D:** Radiograph of fixation with intercalary graft.

exposure of the radius is performed, which in essence releases the interosseous ligaments (Figure 47-9B). Intraoperative manual distraction lengthening and bony realignment are performed. The ulna is temporarily fixed to the radius through the intercalary grafts with provisional smooth wires. The other option is end-to-end repair of the proximal ulna to the distal radius. The forearm is placed in 0 to 20 degrees of pronation, which is determined by palpating the position of the radial styloid relative to the proximal ulna and olecranon. The radial articular surface is corrected to the anatomic approximately 20 degrees of radial inclination in the AP plane by fluoroscopy. The radius is maximally lengthened on the ulna to improve growth discrepancy and prevent proximal radial-capitellar impingement. Full flexion-extension motion should be possible at the wrist and elbow. Adjustment of the temporary fixation with fluoroscopic guidance is performed to achieve these goals. The inner diaphyseal cortices of the radius and ulna are burred to bleeding bone to enhance bony fusion. The proximal radius and distal ulnar bone grafts are fashioned for intercalary insertion for stability and bone healing. Internal fixation is performed with appropriate-size compressive screws and washers across all cortices, generally 3.5-mm diameter screws with lag technique (Figure 47-9C). Usually, three screws can be placed across the radius, ulna, and intercalary graft for secure fixation (Figure 47-9D). The remaining bone graft is morselized into corticocancellous pieces and placed between the radius and ulna. The tourniquet is deflated to control hemostasis. Prophylactic superficial volar, dorsal, and mobile wad forearm fasciotomies are performed through the operative incision prior to closure. Long-arm, bivalve cast immobilization is performed until healing is sufficient for protected mobilization. Depending on the age of the patient, complete fusion between the radius and ulna is expected between 6 and 12 weeks.

◆◆ Distraction Lengthening with Radial Head Reduction

They have done studies you know, 60% of the time it works, every time.
—Ron Burgundy (Will Ferrell), Anchorman

Operative reduction of the radial head, distraction lengthening of the ulna, realignment of the radius and ulna to restore forearm rotation, reduction of the DRUJ, and excision of OCEs are components of a complex reconstruction. It is one we no longer do. The authors refer you to other publications and surgeons who advocate for this surgery.

A B

FIGURE 47-10 AP (**A**) and lateral (**B**) radiographs of a patient referred for consultation after previous lengthening of ulna and now with dislocated radial head and forearm growth discrepancy between radius and ulna.

At present, the complication and reoperation rates are too high for us compared to the alternative procedures.[48–50]

POSTOPERATIVE

Postoperative immobilization by cast or external fixator protection is continued until there is sufficient bony healing to allow for forearm, wrist, and elbow motion. However, there clearly is a balance in that the ultimate outcome is dependent on pain-free restoration of motion, strength, and function. This is usually achievable with up to 6 weeks of protection and another 6 weeks of supervised therapy.

ANTICIPATED RESULTS

There are no environments where you are only going to win, because life just isn't like that.
—Bobby Orr

A high majority (more than 90%) of patients will achieve pain relief and improved motion and strength by all the procedures described in this chapter.[51] The key is to pick the right operations for the right patients.

COMPLICATIONS

Never let the fear of striking out keep you from playing the game.
—Babe Ruth

With OCE excision alone, recurrence or growth disturbance are the issues. Neurovascular injury can occur in large and/or multiple OCEs that have displaced and have put the adjacent neurovascular bundles under tension.

With lengthening procedures, nonunion, loss of motion including digits, pin-site infections, joint instability, and/or dislocation are serious concerns. Aggressive therapy and pin tract care are required to lessen the risk of these complications. The biggest risk is recurrent deformity with growth. This is most problematic if it results in radial head dislocation (Figure 47-10).

Nonunion of a radioulnar synostosis is a risk. This is higher in older patients. Compressive fixation and grafting are utilized to lessen this risk (Figure 47-11).

Patients with MHE appear to be at more risk for keloid scarring of their surgical excision as opposed to patients with solitary OCE excision.[52]

A B

FIGURE 47-11 Two radiographic views of nonunion of radius to ulna fusion treated with iliac crest bone graft and revision of fixation.

FIGURE 47-12 Long-term result at 12 years postoperative radius to ulna fusion with AP (**A**) and lateral (**B**) radiographic views.

CASE OUTCOME

This child was treated with a single bone forearm reconstruction. She regained full elbow and wrist flexion-extension arc of motion without pain. At skeletal maturity, she had no functional issues, no pain, no recurrence of deformity, and no intervening operations on her elbow, forearm, wrist, or hand (Figure 47-12).

SUMMARY

MHE is an autosomally inherited disorder due to mutations in the EXT tumor suppression genes. The resultant abnormal endochondral ossification leads to bony deformity with growth that causes pain, impairs motion, and leads to limb and bone foreshortening and joint malalignment. In the upper limb, the most serious consequences are in the forearm. Surgery for MHE/solitary OCE spans the spectrum of simple OCE excision to complex forearm skeletal rebalancing.

COACH'S CORNER

Single-stage Forearm Rebalancing

There are patients for whom a combination of ulnar lengthening and radial osteotomy in forearm skeletal rebalancing surgery is appropriate. In these patients, it is debatable whether this is best done with a progressive lengthening technique or single-stage procedure. If only the ulna is to be lengthened, a single-stage procedure is feasible and preferred by us (Figure 47-7). It lessens the postoperative hassle for the child and family; risk of the ubiquitous pin tract or worse, deep space, infection; hardware complications; and will successfully realign the forearm. If you are lengthening and correcting both bones, have an outstanding professional support team for lengthening surgeries and their expected complications, and ideally have patients and families geographically near you, a progressive technique is feasible and will realign the skeletal elements. The more

COACH'S CORNER *(continued)*

complex and, in some respects, risky the surgery, the more we look for simpler solutions. Dr. John Hall used to advise us "Some problems require anatomic surgeries, and some situations require geographic solutions." Thus, our preference for both (1) single-stage forearm rebalancing when the radial head is anatomically located and (2) single bone forearm reconstruction when the radial head and DRUJ are dislocated.

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CHAPTER

48

Neurofibromatosis

CASE PRESENTATION

A 3-year-old female presents for a second opinion regarding a pathologic fracture of the right ulna (Figure 48-1). She was previously diagnosed with a right ulna fracture after a low-energy fall. Initial treatment with cast immobilization did not result in bony healing. She presents for consultation regarding additional treatment options.

CLINICAL QUESTIONS

- What is neurofibromatosis (NF)?
- What are the clinical criteria by which NF is diagnosed?
- What are the orthopaedic manifestations of NF?
- What are the surgical indications for and principles of neurofibroma excision?
- In cases of pseudarthrosis of the ulna, what are the treatment options for surgical care?
- What are the potential complications of neurofibroma excision? Of free vascularized fibular grafting (FVFG) for congenital pseudarthrosis?

THE FUNDAMENTALS

Also known as von Recklinghausen disease, NF type 1 (NF1) is one of the most common human genetic disorders. Although the primary pathologic process involves altered neuronal cell growth, NF1 may present with a number of musculoskeletal and systemic manifestations. The effect on bones, nerves, skin, and other soft tissues may lead to alterations in growth, development, and function of the upper extremity, presenting a host of challenges to the pediatric hand and upper extremity surgeon.

Etiology and Epidemiology

Historically, NF was first described in 1793 by von Tilenau, though von Recklinghausen is credited with associating the clinical manifestations of this disorder with nerve tumors.[1,2] One of the most common genetic diseases in humans, NF affects approximately 1:3,000 people and is inherited in an autosomal dominant fashion with near complete penetrance. Approximately one-half of all cases are due to sporadic mutation.

Mutations in the neurofibromin gene, localized to chromosome 17q11.2, are responsible for NF1.[3] The NF1 gene locus is comprised of 350,000 base pairs and 59 exons, and its large size has been implicated in the frequency with which sporadic mutations occur.[4] The gene encodes a 280-kDa cytoplasmic G-activating protein that regulates p221-RAS proto-oncogene function.[5–7] While this protein is found throughout the body during development, it later becomes more specifically expressed in neuronal tissues.

These genetic abnormalities are distinct from mutations in the merlin or schwannomin gene, which have been attributed to NF type 2 (NF2) (so-called central NF).[8,9] Diagnostic criteria include the presence of eight or more nerve masses and a positive family history of a first-degree relative with NF2. It affects approximately 1:40,000 individuals and usually presents with hearing loss in young adults. While NF2 typically causes tumors of cranial nerve VIII (including the bilateral vestibular schwannomas resulting in hearing loss), meningiomas, ependymomas, and peripheral nerve tumors, musculoskeletal manifestations are uncommon. As a result, these patients rarely come under the care of the pediatric hand and upper extremity surgeon.

Furthermore, segmental NF represents yet another uncommon variant of NF.[10,11] Segmental NF typically involves multiple plexiform neurofibromas limited to a single body part without crossing the midline and devoid of the systemic clinical manifestations common to NF1.

Clinical Evaluation

Silence is golden when you can't think of a good answer.
—Muhammad Ali

Neurofibromas refer specifically to mixed cell tumors arising from peripheral nerve sheath cells, rich in Schwann cells, fibroblasts, mast cells, and endothelial cells. The

FIGURE 48-1 Anteroposterior and lateral radiographs of a young child with congenital pseudarthrosis of the ulna in the setting of NF. Note is made of the tapered and sclerotic bony ends with dysplastic distal ulnar segment consistent with a congenital pseudarthrosis.

clinical diagnosis of NF1 is made based upon a number of established clinical criteria (Table 48-1).[1,12] In general, NF is diagnosed in the presence of two of the following clinical features: (1) more than six café au lait spots measuring at least 5 mm in diameter in children, (2) two or more solitary neurofibromas or one plexiform neurofibroma, (3) axillary or inguinal freckling (the so-called Crowe sign), (4) the presence of optic gliomas, (5) two or more iris hamartomas (Lisch nodules), (6) characteristic skeletal lesions (e.g., long bone pseudarthrosis), and/or (7) a first-degree relative with NF1.

Histologically, neurofibromas appear as whorls of interlacing spindle-shaped cells, though they stain poorly for S-100 and Leu-7 (Table 48-2). Technically benign, these lesions demonstrate varying morphologies, unpredictable growth patterns, and often infiltrate and involve the nerve fascicles and axons themselves.[13] Clinically, the lesions manifest themselves as solitary palpable subcutaneous nodules, often with overlying discoloration. Although rarely appreciated at birth, neurofibromas usually become apparent in late childhood (e.g., at the end of the first decade of life). Solitary neurofibromas account for roughly 85% of all upper limb cases.

Plexiform neurofibromas, in contrast, are characterized by diffuse, raised, hyperpigmented, cutaneous lesions with boggy or "bag-of-worms"–type consistency. Genetic mutations similar to those seen in NF1 of chromosome 17 are seen in plexiform neurofibromas; indeed, the presence of plexiform neurofibromas is almost always associated with NF1.[14] Although neurofibromas are typically nonpainful, the presence of pain or tenderness—particularly with plexiform lesions—raises the concern of malignant transformation, usually into malignant peripheral nerve sheath tumors (MPNST).[15–18] Indeed, owing to the genetic basis of the disease, patients with NF are at higher risk for other malignancies as well, including melanoma, rhabdomyosarcoma, astrocytomas, and hematologic malignancies.

In addition to these classic and diagnostic clinical manifestations, NF may cause bony lesions resulting in presentation to a pediatric hand and upper extremity surgeon. Perhaps the most common and severe orthopaedic issue related to NF is pseudarthrosis of the long bones, most commonly the tibia, fibula, ulna, and clavicle.[19] While only 5% to 10% of patients with NF will demonstrate bony pseudarthroses, up to 75% with pseudarthroses will have NF1.[13,20,21] These patients typically present with deformity of the affected limb, often with purported

Table 48.1

Clinical diagnosis of NF1

Diagnostic Clinical Criteria for the Diagnosis of NF
More than 6 café au lait spots (>15 mm in diameter in adults, >5 mm in children)
Two or more neurofibromas of any type or one plexiform neurofibroma
Axillary or inguinal freckling (Crowe sign)
Optic glioma
Two or more iris hamartomas (Lisch nodules)
Characteristic bone lesion (e.g., cortical thinning with pseudarthrosis)
First-degree relative with NF!

From Feldman DS, Jordan C, Fonseca L. Orthopaedic manifestations of neurofibromatosis type 1. *J Am Acad Orthop Surg.* 18:346–357.

Table 48.2

Features distinguishing schwannoma from neurofibromas

Clinical Feature	Schwannoma	Neurofibroma
Symptoms	Mass, pain, paresthesias	Mass, pain, paresthesias
Gross pathology	Encapsulated eccentric tumor sparing and displacing nerve fascicles	Fusiform mass within the nerve intimately associated with nerve fascicles
Histology	Interlacing fascicles of spindle cells; no axons within lesion	Interlacing bundles of spindle cells; axons and nerve fibers seen throughout lesion
Immunohistochemistry	S-100 and Leu-7 strongly positive	Neurofilament positive; S-100 and Leu-7 weak
Surgical treatment	Marginal excision preserving nerve fascicles	Excision of mass involves sacrificing neural elements

Adapted from Forthman CL, Blazar PE. Nerve tumors of the hand and upper extremity. *Hand Clin*. 2004;20:233–242, v.

history of prior fracture nonunion. While the exact pathophysiology is unknown, these bone lesions are characterized radiographically by nonunion sites devoid of typical periosteal reaction and callus formation, with dysplasia, sclerosis, and narrowing of the adjacent bony segments (see Coach's Corner) (Figure 48-1). When left untreated, the condition may result in bowing deformities of the limb (particularly the leg). Given the abnormal biology of these lesions, it is common to see persistent "nonunion" after prior attempts at conventional fracture healing, including casting, internal fixation, and autogenous or allograft bone grafting.

Furthermore, given that NF1 is due to a known neurofibromin gene mutation, genetic testing may assist in diagnosis. The so-called protein truncation test is utilized to detect abnormally truncated, or shortened, proteins that result from the inherited or acquired genetic mutation(s).[22] This test, however, is positive in only 70% of patients, making NF still a diagnosis assigned often by virtue of clinical criteria.

In addition to careful clinical history, physical examination, and plain radiography, advanced imaging such as computed tomography or magnetic resonance imaging (MRI) may assist in diagnosis and treatment. Advanced three-dimensional imaging will provide improved localization as well as gross descriptive features of the mass(es) in question. Even with current imaging technology, however, the distinction between nerve tumors and nerve sheath or other neoplasms (specifically, neurofibroma vs. schwannoma) may not be able to be made (Table 48-2).[23]

A number of other hyperpigmentation or overgrowth syndromes may be confused with NF and should be included in the differential diagnosis of these patients. These conditions include but are not limited to McCune-Albright syndrome, Leopard syndrome, and hemihypertrophy due to vascular or lymphatic malformations.

Given the genetic diagnostic testing available, as well as the multiple other organ systems that may be involved, formal genetic consultation is recommended in cases of established or suspected NF.

Surgical Indications

Surgery is generally indicated for pain and functional limitations due to a nodular or plexiform neurofibroma. In cases of patients with increasing pain or tenderness, surgery is indicated to rule out malignant transformation, particularly in cases of plexiform lesions. (Immunohistochemistry looking at ki-67 and S-100 staining has been utilized to distinguish MPNST from neurofibromas.)[24] Finally, surgical excision and/or skeletal reconstruction is indicated in patients with secondary bony deformity or pseudarthroses.

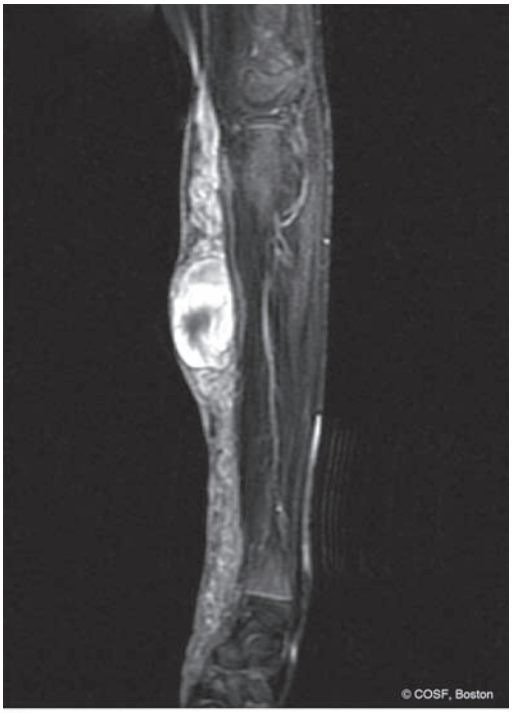
SURGICAL PROCEDURES

Excision of NF Nerve Lesions

The harder you work, the luckier you get.
—Gary Player

In patients with nodular neurofibromas associated with pain, enlarging size, or concern for malignant transformation, surgery is performed under general anesthesia (Figure 48-2). In keeping with oncologic surgical principles, extensile longitudinal surgical incisions are utilized. The normal neurovascular structures are identified proximal and distal to the mass, and the confirmation is made of the peripheral nerve involved.

Surgically, gross inspection of the neurofibroma typically reveals a firm nodularity within the course of the peripheral nerve. As the solitary neurofibroma arises centrally and often envelopes the adjacent nerve fascicles, the nerve appears to be expanded in a fusiform fashion. (This is in contradistinction from schwannomas, which



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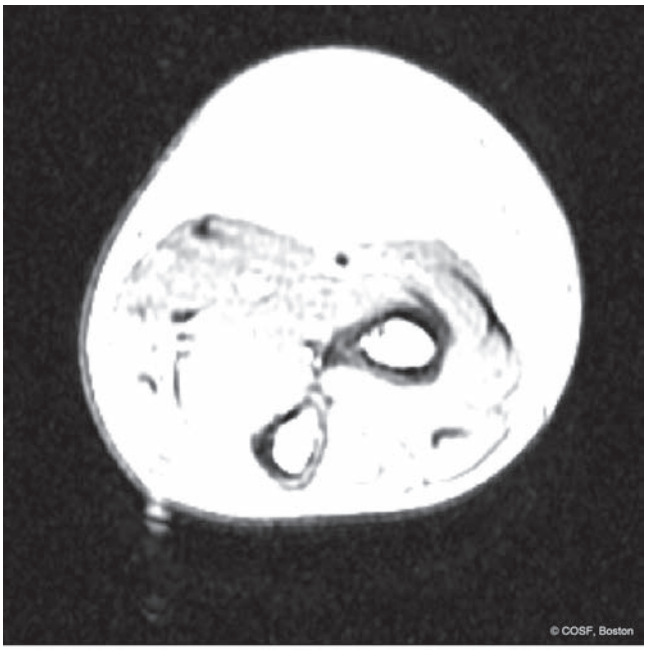

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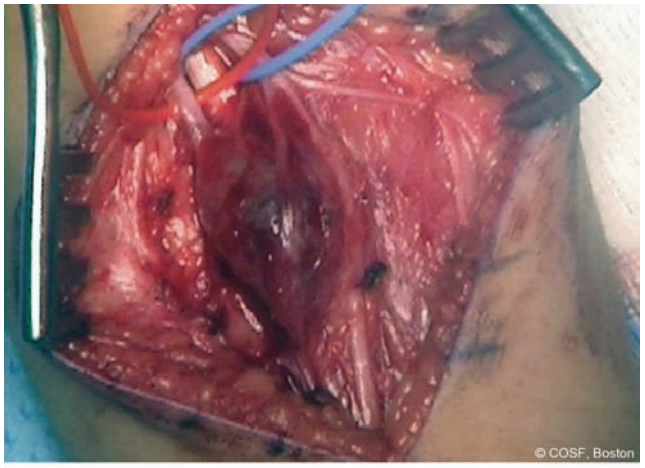
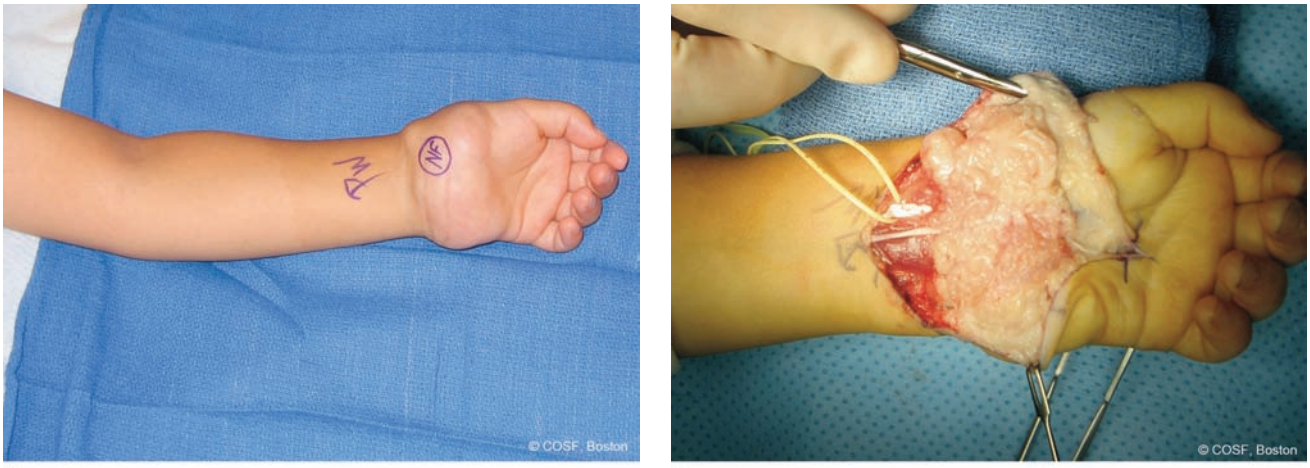


B

FIGURE 48-2 Excision of a solitary, nodular neurofibroma. **A:** Preoperative sagittal (A1) and axial (A2) MRI images of a patient with a large, painful forearm neurofibroma. **B:** Intraoperative photograph demonstrating the lesion in situ.

are more eccentric, globular shaped, encapsulated, and not intertwined with the underlying neural elements.) For this reason, neurofibromas are *not* as easily dissected away from the involved nerve, and neurofibroma excision without compromising nerve function is challenging to say the least. Microscopic dissection is often required in an effort to preserve neural elements, and occasional nerve reconstruction (grafts or nerve transfers) may be needed to restore function in cases where a major peripheral nerve cannot be preserved.[25–27] Patients and families should be counseled about the risk of transient or permanent nerve injury following excision, as well as the high risk of recurrence in cases where more conservative excisions are performed. In cases of proximal major peripheral involvement, complete excision may not be recommended due to the morbidity associated with the resulting neurological deficit(s).[27] However, more often than not, the large neurofibromas can be safely excised by carefully teasing the normal, longitudinal running fascicles off the expansile lesion.

Similar principles are followed for excision of symptomatic or concerning plexiform neurofibromas, though more extensive surgical dissection is required to achieve an adequate visualization of the lesion (Figure 48-3). Careful subcutaneous dissection is required to develop the appropriate plane between the pathological tissue and overlying skin. In cases of redundant tissue and dermal involvement, the affected overlying skin may be excised



A B C

FIGURE 48-3 Excision of a plexiform neurofibroma. **A:** Preoperative clinical images of a patient with plexiform neurofibromas involving the volar base of the left hand. **B:** Intraoperative photograph demonstrating wide surgical exposure of the pathologic tissue. **C:** Gross appearance of the excised specimen.

with the deep tissue provided appropriate skin closure may be performed.

◆ Free Vascularized Fibular Grafting

FVFG with Proximal Fibular Epiphyseal Transfer

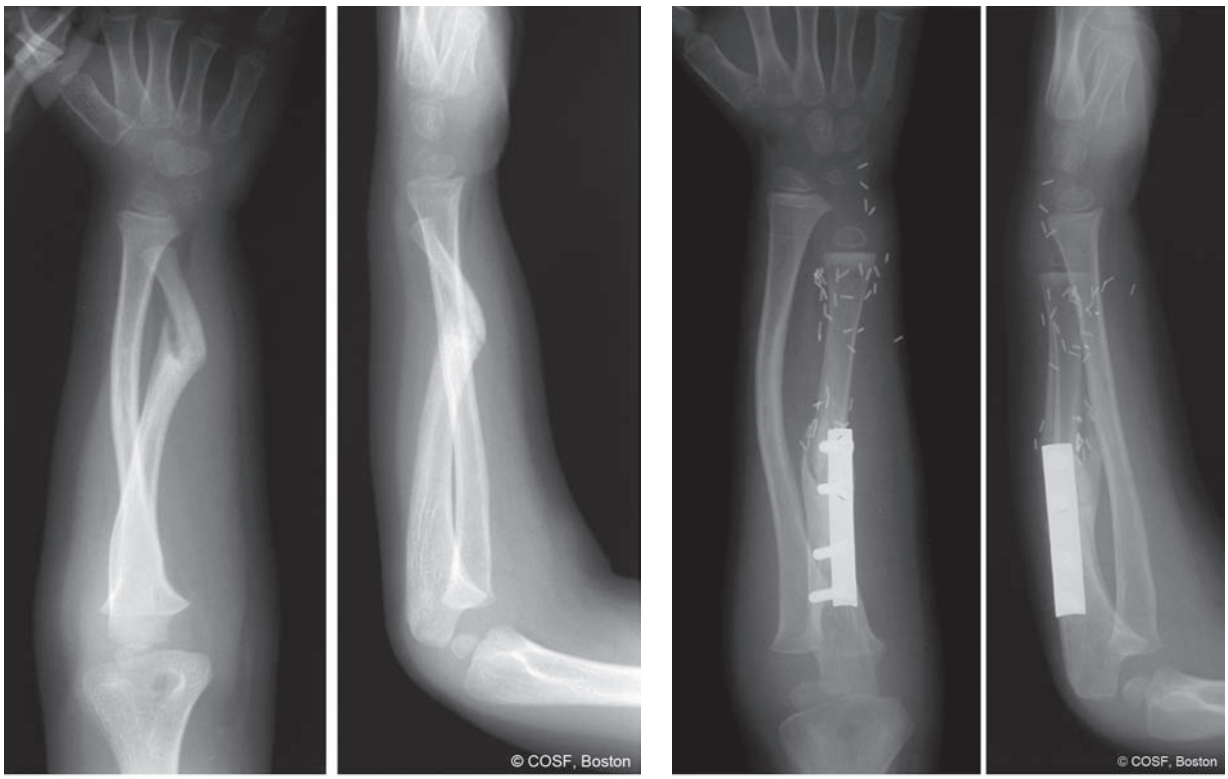
The difference between a successful person and others is not a lack of strength, not a lack of knowledge, but rather in a lack of will.
—Vince Lombardi

Johnston has previously proposed a classification system that provides guidance in the optimal management of pseudarthroses due to NF. This system is based entirely upon two patient factors: (1) the presence or absence of fracture and (2) the age at which the initial fracture or bony injury occurred.[28] While this system was derived from and intended for tibial pseudarthroses, similar considerations may be applied to lesions of the upper limb.

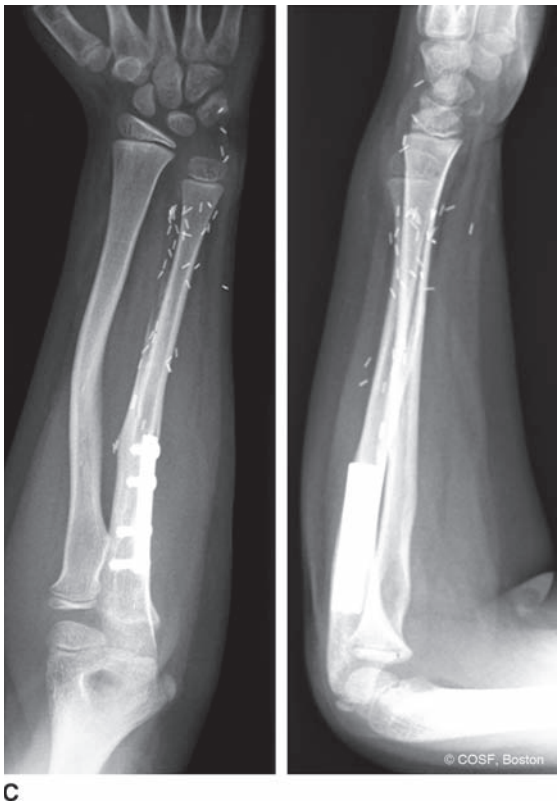
Historically, traditional methods of treating congenital pseudarthroses in the setting of NF were fraught with high rates of failure. Open reduction, plate and intramedullary rod fixation, with or without concomitant autogenous or allograft bone grafting resulted in poor union rates overall.[29–31] Given the pathologic bony involvement and the risk of persistent pseudarthrosis following traditional fracture fixation and nonvascularized bone grafting techniques, vascularized bone grafting is the treatment of choice for cases of congenital pseudarthrosis associated with NF (see Chapter 44) (Figure 48-4).

The surgical procedure is often performed utilizing a two-team approach when possible. The site of ulnar pseudarthrosis is approached directly via an incision along the ulnar border of the forearm, employing the extensor carpi ulnaris and flexor carpi ulnaris intermuscular interval if not otherwise contraindicated based upon previous surgical incisions. The ulnar artery and vein are identified and protected during exposure of the ulna. Extensive debridement of the pseudarthrosis tissue is performed until bleeding bone from the adjacent intramedullary canal is visualized. Tissue specimens are sent for subsequent histopathologic evaluation.

In the more skeletally mature patients, FVFG is performed in an interpositional fashion, with the intention



A B



C

FIGURE 48-4 **A**: Preoperative radiographs of an ulnar congenital pseudarthrosis. Given the dysvascular distal ulnar segment, the decision was made to perform FVFG with concomitant proximal epiphyseal transfer (same as Figure 48-1). **B:** Postoperative radiographs following FVFG with transfer of the proximal fibular epiphysis. The proximal fibula now serves as the new ulnar head. **C:** Postoperative follow-up radiograph demonstrating bony union and continued growth of the transferred fibula.

of providing vascularity to the previously abnormal distal ulnar fragment. The distal radioulnar joint (DRUJ) ligaments and triangular fibrocartilage complex (TFCC) are thus left intact for continued wrist stability. After bony resection is carried out to healthy-appearing margins, the amount of bony resection is carefully measured. The recipient bone ends are prepared in a "Z" or "step-cut" fashion. The appropriate length of vascularized fibular graft is then isolated on its vascular pedicle (peroneal artery and vein) according to standardized techniques (see Chapter 44). Matching step-cut osteotomies are made after fibular harvest. Internal fixation of the fibular graft to the recipient site is performed using small or minifragment interfragmentary screws and/or plates (Synthes USA, Paoli, PA). End-to-side microvascular anastomoses of the peroneal artery and vein into the ulnar artery and vein are then performed, usually distally near the wrist. Careful inspection of the anastomotic sites, in addition to observation of blood flow from the graft itself, confirms vascular reconstitution of the fibular graft.

Special considerations are made in the very skeletally immature patient with a dysvascular distal ulnar segment. Preoperative radiographs may demonstrate atrophy, narrowing, and sclerosis of the entire distal ulna with obliteration of the intramedullary space and paucity of callus formation. This may be corroborated by intraoperative inspection of the ulnar segment distal to the pseudarthrosis site. In these cases, the entire distal ulna is replaced with a free vascularized fibular graft with proximal fibular epiphyseal transfer (see Chapter 44). During resection of the abnormal native distal ulna, the distal radioulnar and ulnocarpal ligaments, along with the TFCC, are preserved for subsequent repair. The proximal fibula is transferred as a vascularized graft including the proximal epiphysis on its peroneal and anterior tibial vascular pedicles. Internal fixation and microvascular anastomoses are performed as described above. In addition, the TFCC and DRUJ are reconstructed via soft tissue repair to the transferred proximal fibular epiphysis.

POSTOPERATIVE

Patients are cast immobilized following excision of solitary or plexiform neurofibromas for 2 weeks for proper wound healing and analgesia. Range-of-motion exercises and scar management, often with the assistance of a therapist, are initiated after confirmation of wound healing, with advancement to strengthening and activities as tolerated.

Following FVFG, patients are treated with intravenous dextran 40 at a dosage of 5 to 10 mL/kg/day for 3 to 5 days, followed by oral aspirin for an additional 2 weeks, for thrombosis prophylaxis. The upper extremity is cast immobilized for 6 plus weeks postoperatively, followed by a removable orthosis or bivalved cast upon the initiation of supervised range-of-motion exercises. It is critical to have sufficient bony healing before stopping protective immobilization in the young child. This can take up to 12 weeks. The lower extremity is placed in a long-leg cast with the ankle in neutral dorsiflexion to prevent equinus and/or flexor hallucis longus flexion contracture(s), followed by short-leg cast immobilization for a total of 6 to 12 weeks. Again, avoid full weight bearing in the young child until the tibia and fibula have healed together.

ANTICIPATED RESULTS

With adherence to the surgical indications and treatment principles outlined above, accurate diagnosis and appropriate surgical excision may be performed in most cases. Persistent pain and nerve dysfunction, however, may occur even with successful lesion excision.[32,33] Given the spectrum of clinical presentation, anatomic distribution, and intraoperative findings, there is a paucity of literature to provide meaningful general statements regarding surgical outcomes.

In cases of congenital pseudarthrosis in the setting of NF, bony healing and restoration of skeletal alignment and function may be anticipated in the majority of cases.[34–36]

COMPLICATIONS

It's a little like wrestling a gorilla. You don't quit when you're tired you quit when the gorilla is tired.
—Robert Strauss

The most frequent complication encountered following surgical treatment for symptomatic nodular or plexiform neurofibromas is recurrence. While aggressive resection may minimize the potential for recurrence, the scope of surgical excision must be balanced against the desire to preserve neurologic function and avoid long-standing functional loss. Indeed, persistent or worsening pain and nerve dysfunction have been reported following surgical excision.[32,33] Patients and families must be counseled about the risk of recurrence and need for continued postoperative surveillance prior to any surgical intervention. New lesions often commonly appear.

In cases in which FVFG is used to achieve bony union and/or continued skeletal growth, there is a risk of progressive ankle valgus and other donor-site morbidity. Preservation of the distal 10% of the fibula and creation of a distal tibiofibular synostosis during fibular harvest will help minimize these risks (see Chapter 44).

CASE OUTCOME

Upon careful clinical history and physical examination, the patient was diagnosed with congenital ulnar pseudarthrosis in the setting of NF1. After thorough discussion

with the family regarding treatment options, the decision was made to proceed with FVFG with concomitant proximal fibular epiphyseal transfer (Figure 48-4). At most recent clinical and radiographic follow-up, there was no evidence of recurrent disease, and the patient had pain-free use of the right upper extremity.

SUMMARY

NF is a common genetic condition resulting in abnormal nerve growth. Patients may present to pediatric hand and upper limb surgeons for evaluation of solitary nodular neurofibromas, plexiform NF, or congenital pseudarthrosis. In cases of pain, enlarging masses concerning for malignant transformation, or pseudarthrosis, surgical treatment may be considered. Careful preoperative counseling, preoperative decision making, and surgical technique will allow for successful outcomes with minimal complications.

COACH'S CORNER

Although uncommon, every pediatric hand and upper extremity surgeon will encounter a congenital pseudarthrosis due to NF in the upper limb during their career. The temptation is to presume these lesions are fractures and treat them as such. Comprehensive clinical examination will reveal other stigmata of NF1. Furthermore, careful radiographic assessment will identify features characteristic of a congenital pseudarthrosis and avoid this mistake.

In cases of congenital pseudarthrosis, the bony ends are typically tapered and sclerotic, with an obliterated or narrowed intramedullary canal. Often the more distal segment is hypoplastic or dysplastic in size and shape. Due to the underlying abnormal biology, there will be no periosteal reaction or fracture callus formation. While easily overlooked, these characteristic features should alert the examiner to the likelihood of a pseudarthrosis and guide the surgeon to the appropriate clinical diagnosis and surgical treatment.

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CHAPTER

49

Benign Lesions of the Upper Limb

CASE PRESENTATION

A 6-year-old female presents for evaluation of a bone tumor. After falling onto her outstretched left upper extremity, the patient had sudden-onset shoulder pain. Subsequent evaluation included radiographs that demonstrated a pathologic proximal humerus fracture (Figure 49-1). The patient was placed in a sling and now presents for pediatric upper extremity consultation. The patient has been otherwise healthy and denies any recent fevers, rashes, or other medical illnesses.

CLINICAL QUESTIONS

- What is a unicameral bone cyst (UBC)?
- What is an aneurysmal bone cyst (ABC)? How does it differ from a UBC?
- What is the risk of malignant transformation with these lesions?
- What are the treatment options for UBCs and ABCs?
- What are the complications from treatment?
- What are the indications and techniques for deformity correction and limb lengthening following proximal humeral physeal disturbance?
- What are the treatment principles and techniques for other common benign tumors of the pediatric upper limb?

THE FUNDAMENTALS

The pediatric hand and upper extremity surgeon will encounter a host of benign tumors of the upper limb. While benign, unicameral bone cysts (UBCs) and aneurysmal bone cysts (ABCs) may cause pain, pathologic fracture, progressive deformity, and/or limb length difference. Other common lesions—including giant cell tumor of tendon sheath, enchondroma, and infantile fibroma, among others—may similarly become symptomatic or cause functionally limiting deformity. Understanding of the principles of treatment and techniques of surgical care will allow for optimization of management and minimization of complications.

Etiology and Epidemiology

Although the exact incidence is unknown, benign tumors of the upper limb are common in children and frequently present to the pediatric hand surgeon for diagnosis and treatment. In a prior retrospective review of 349 children presenting at a tertiary care pediatric hospital for evaluation of a hand or wrist "tumor," the most common diagnoses were retained foreign bodies, ganglion cysts of the wrist, and retinacular cysts of the digits[1] (Table 49.1). Other common entities included vascular (most commonly venous) malformations, epidermal inclusion cysts, and enchondromas. Malignant tumors accounted for 2% or less of all lesions, reinforcing the concept that malignancies of the pediatric hand are quite uncommon. While the differential diagnosis in the evaluation of a benign-appearing mass is quite broad, each will have its own set of characteristic clinical and radiographic features, which help make the diagnosis and guide treatment.

In addition to these benign entities, bone cysts are frequently encountered in the growing upper limb. UBCs refer to fluid-filled lesions that commonly affect the metaphysis of long bones in children and adolescents.[2–4] There is a roughly 2:1 male:female predisposition, and the vast majority of patients will be <20 years of age. Also known as simple bone cysts, the exact prevalence of UBCs is unknown, as many are asymptomatic and therefore never identified or diagnosed. They are thought to comprise 3% of all biopsied primary bone tumors and may be the most common cause of pathologic fractures of the long bones.[2,5–7]

The precise etiology of UBCs has yet to be characterized. Some investigators have proposed that UBCs represent intraosseous synovial cysts, based upon electron microscopy.[8] Others have suggested that UBCs are a result of interstitial fluid accumulation in the setting of abnormal or absent lymphatic or venous drainage of the bone, perhaps due to a local defect in metaphyseal bony growth or remodeling.[9] This elevated pressure may explain success

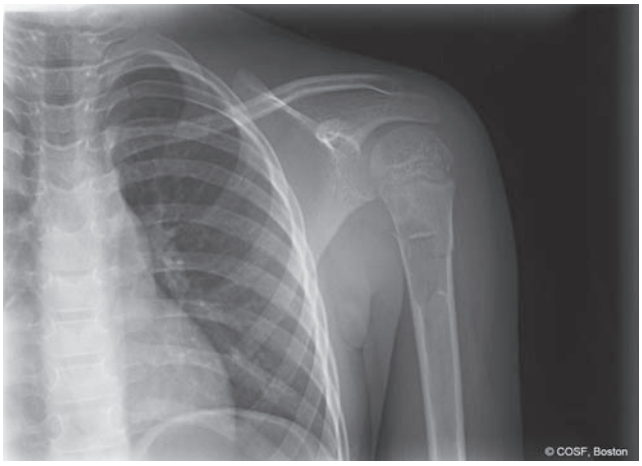


FIGURE 49-1 Anteroposterior radiograph of the proximal humerus depicting a pathologic fracture through a UBC. Note is made of the characteristic "fallen fragment" sign.

in surgical treatment strategies involving decompression and/or restoration of local circulation.[10–13] Still other researchers have identified elevated levels of prostaglandins and oxygen-free-radical scavengers within these lesions, which may cause bone resorption; this observation supports the concept that corticosteroid injection may be used for treatment.[12,14–17]

Histologically, cyst walls are lined with a fibrous membrane comprised of giant cells; no endothelial lining has been identified, and thus the term "UBC" is somewhat of a misnomer. Some authors have identified cells resembling type A and B synovial cells within the membrane.[8]

ABCs are similarly benign cystic lesions that may affect the bones of the upper limb. The lesions contain bloody fluid and are lined with fibroblasts, osteoclast-like giant cells, and reactive woven bone.[18,19] Again, the name is a misnomer, as histologically these lesions resemble neither cysts nor aneurysms.

In the majority of cases ABCs are primary bone lesions, though may appear secondarily from preexisting osseous lesions in up to 30% of cases. With an estimated incidence of 1.4:1,000,000, ABCs are most common during the second decade of life.[20] Indeed, primary ABC rarely occurs in patients over 30 years of age. While the long bones of the lower limb are most commonly affected, ABCs may appear in the humerus and other bones of the upper extremity. In a retrospective multicenter study of 156 children with primary ABC, the humerus was found to be the fourth most commonly involved bone. The clavicle, radius, and metacarpals were less common.[21,22]

The etiology of ABCs remains unknown. A number of theories have been proposed, including the notion that impaired local circulation results in elevated venous pressures and enlarged vascular disturbances within the affected bone.[23] Other theories have implicated prior trauma as an inciting event. It is possible that trauma or changes in local vascularity lead to hemorrhage, inflammation, and increased osteoclastic activity, which in turn results in further bleeding.[24]

Recently there has been further work into the genetics of these lesions. Genetic translocations (17p11-13 and 16q22) have been identified in some ABCs, perhaps resulting in CDH11 or USP6 oncogenic upregulation.[25]

Table 49.1

Common benign tumors of the pediatric hand and upper limb

Foreign bodies
Ganglion and retinacular cysts
Vascular malformations
Epidermal inclusion cysts
Enchondroma
Exostosis
Neurofibroma or schwannoma
Infantile digital fibroma or juvenile aponeurotic fibroma
Lipoma
Glomus tumor

Adapted from Colon F, Upton J. Pediatric hand tumors. A review of 349 cases. *Hand Clin*. 1995;11:223–243.

Clinical Evaluation

In cases of benign tumors, patients will typically present for evaluation of a visible and palpable mass. Often these masses are asymptomatic and of uncertain chronicity. A careful history is taken, with particular emphasis on identifying any prior penetrating or blunt trauma and eliciting any information that might be concerning for infection. Physical examination allows for identification of the mass and characterization of its size, consistency, mobility, tenderness, and association with overlying skin or vascular changes. The diagnosis may often be made based on simple history and examination. For example, a firm, mobile, subcutaneous nontender cystic mass at the palmodigital flexion crease of the digit is characteristic of a retinacular cyst, whereas raised, nontender, papular masses over the dorsal aspects of adjacent digital tips in a toddler is characteristic of an infantile digital fibroma. In cases of bony involvement, such as seen with enchondroma, radiographs will also have distinct features consistent with the underlying diagnosis. Soft tissue lesions, as well as retained radiolucent foreign bodies, may be visualized with ultrasound or magnetic resonance imaging (MRI) (Figure 49-2). With careful clinical evaluation and experience, the diagnosis of most benign tumors can be made based upon clinical grounds.

Patients with a UBC of the proximal humerus do not have palpable or visible masses and therefore present in one

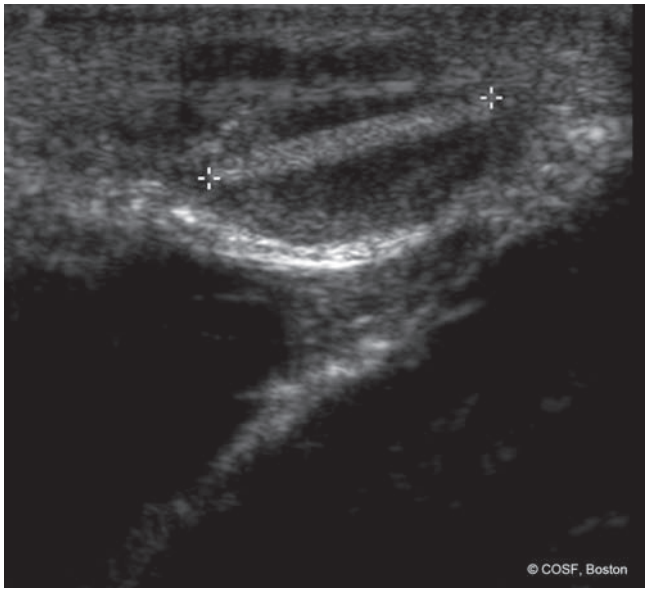


FIGURE 49-2 Ultrasound of the left hand in a 10-year-old boy with a painful first web-space mass. Findings demonstrate a 1.5-cm splinter in the subcutaneous tissues.

of two ways. In some patients, the radiographic diagnosis of UBC is made incidentally on shoulder x-rays taken during the evaluation of an unrelated traumatic event. These patients are typically asymptomatic and unaware that the lesion exists. There is no pain, tenderness, or distal neurovascular compromise. Similarly, these shoulders are usually without deformity or physical impairment. Other patients will present with a pathologic fracture of the proximal humerus through the UBC.

The characteristic radiographic appearance of UBCs makes the diagnosis fairly straightforward. The classic UBC is a centrally located, radiolucent, marginated lesion of the metaphysis. In general, the diameter and boundaries of the UBC do not exceed the width of the adjacent physis. Often, a thin radiopaque line is seen within the cyst, the so-called fallen fragment sign, representing a thin cortical fragment that has fractured and settled into the middle of the cyst[26] (Figure 49-1).

Patients with an ABC similarly present in one of two fashions. Some patients will present with a cystic lesion identified incidentally on plain radiographs taken for evaluation of a traumatic or other unrelated condition. Other patients will present after pathologic fracture through an existing ABC.

While x-rays of ABCs may appear similar to those of UBCs, there are a number of distinguishing radiographic features characterizing ABCs. Lesions are cystic and often expansile, with dimensions exceeding the width of the adjacent physis. Endosteal scalloping and periosteal elevation are common, giving the lesion the so-called soap bubble appearance. Septa and multiloculated lesions are common. Use of MRI will often confirm the diagnosis, demonstrating fluid-fluid levels within the cyst, along with internal septae.[27]

Surgical Indications

In general, surgical indications for benign tumors of the hand and upper limb include (1) persistent mass of unclear etiology for which a histopathologic diagnosis is desired; (2) pain and/or functional limitations due to the hand mass; (3) progressive or functionally limiting deformity; and (4) pathological or impending pathological fracture.

The primary indication for surgical treatment of UBCs is the presence of a large lesion associated with prior or impending pathologic fracture. When UBCs are identified incidentally on plain radiographs, quantification of pathologic fracture risk may be performed via quantitative computed tomography.[28] This information is helpful to patients, families, and providers when weighing the risks and benefits of surgical intervention.

Similarly, indications for surgical intervention for ABCs include the need for diagnostic tissue to establish a diagnosis, pain, and impending or prior pathologic fracture.

SURGICAL PROCEDURES

Nonoperative Treatment of Benign Masses

He had the ability of taking a bad situation and making it immediately worse.
—Branch Rickey, on Leo Durocher

Observation is always the first line of treatment for benign tumors of the pediatric hand and upper limb. For many patients and families, education and observation are all that is needed. In many instances, such as with retinacular and ganglion cysts, spontaneous resolution may occur.[29]

In other situations, the natural history is one of spontaneous resolution, and surgical intervention may only worsen the clinical situation. Indeed, there are some clinical entities that increase in size and spread with surgical stimulus. Infantile digital fibroma is an example of such a lesion. A benign condition thought to be due to proliferation of myofibroblasts, infantile digital fibromas classically present as firm, plaque-like papules over the dorsolateral aspect of the digital tips (Figure 49-3). The presence of paranuclear cytoplasmic inclusion bodies and the clinical observation that these lesions often affect contiguous skin surfaces of adjacent digits have implicated a possible viral etiology for this lesion.[1,30] Still others have theorized that abnormal regulation or expression of transforming growth factor-beta during developmental digital separation may lead to this condition.[30,31] Given the propensity of this benign condition to regress spontaneously during the first decade of life, as well as its tendency to recur after

FIGURE 49-3 Infantile digital fibroma. **A:** Dorsal aspect of a 2-year-old child with infantile digital fibroma. Note the characteristic contiguous lesions affecting the dorsoradial aspect of the small and dorsoulnar aspect of the ring finger. **B:** Alternate view depicting the size of the lesion.

attempted surgical excision, observation is the preferred treatment. In rare situations, biopsy may be performed to confirm the diagnosis.

Nonoperative Treatment of a UBC

Nonoperative management of a UBC is appealing. In the asymptomatic patient with an incidentally diagnosed UBC, observation is often the treatment of choice, particularly given the expectation of UBC resolution with continued skeletal maturity.[32] Indeed, most believe these cysts will progress from an active to quiescent to involutional stage as a part of their natural history.

In patients with symptomatic UBCs or those presenting in the setting of pathologic fracture, there are some instances in which the cysts will spontaneously resolve during or after fracture healing. However, these instances of spontaneous healing are rare, occurring in <15% of cases.[2,33,34] Perhaps this is due to the fact that only a minority of fractures occur during the involutional stage.

Ultimately, the clinical decision making regarding nonoperative treatment is clouded by the lack of information regarding the natural history of these lesions. Little reliable prognostic information can be obtained by cyst (size, location, associated fracture) or patient (age, gender, skeletal maturity) characteristics.[32] This is further complicated by the recurrence rates seen after attempted surgical treatment.

Similarly, observation of ABCs may be considered for asymptomatic patients.[27,35] This should be an active process, however, involving serial clinical examinations and radiographs to monitor for symptoms and/or radiographic progression. Furthermore, when the diagnosis remains unclear, biopsy for tissue diagnosis should be considered. This is particularly relevant given that ABCs may arise from or resemble other malignant tumors (e.g., telangiectatic osteogenic sarcoma).[36]

Aspiration and Injection of UBC

If at first you don't succeed, you are running about average.
—M. H. Alderson

Although the true cause of UBC remains unknown, the elevated prostaglandin levels found have supported the concept that steroid injection may be used for treatment. Even with the encouraging data regarding steroid injection, multiple injections may be required to achieve cyst resolution, and the recurrence rate remains.[14,37–40]

Indeed, the risk of persistent or recurrent cyst has been cited between 41% and 84% after single injection.[14,41–45]

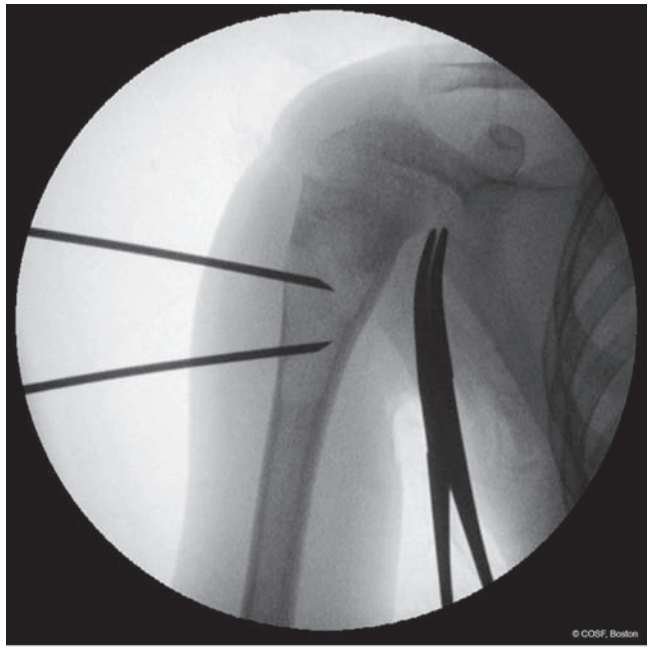
In addition to aspiration and corticosteroid injection, other adjuvant measures have been proposed to increase the success rates. Mik et al.[46] have proposed aspiration, intramedullary decompression, and packing the lesion with medical-grade calcium sulfate pellets. Autologous bone marrow injections have also been used, with reported success rates of up to 75%.[44,47–50] Still others have utilized autologous bone marrow aspirate and demineralized bone matrix in addition to steroid injection.[45,51] Indeed, with this combination of agents, success rates approach 50% after a single treatment.

Bone morphogenetic protein is *not* used, based upon prior reports of profound pain, swelling, and inflammation after injection for bone cysts.[52]

Currently, we use steroid injection combined with bone marrow aspirate and demineralized bone matrix for first line UBC treatment.

The procedure is performed under general anesthesia with fluoroscopic guidance (Figure 49-4). Patients are placed in the supine position on a radiolucent table, and the entire upper limb and ipsilateral iliac crest region are prepped and draped into the surgical field. After localization of the lesion, two 13-gauge bone marrow aspiration needles (Lee-Lok, Lee Medical, Plainsboro, NJ) are placed percutaneously through the humeral cortex into the cyst: one proximal and one distal. Aspiration of the intralesional fluid is performed, and, if the diagnosis is in question, the

A



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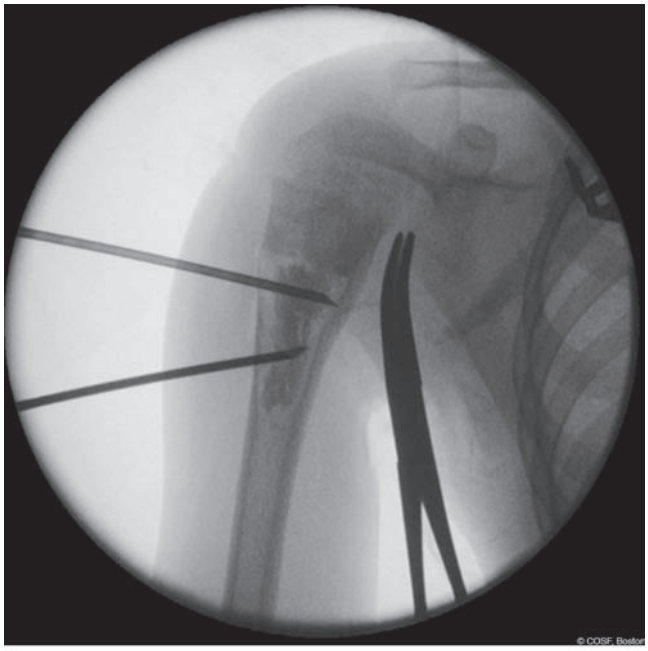


C

FIGURE 49-4 Aspiration and injection of a proximal humeral UBC. **A:** Preoperative radiograph of a 7-year-old male who had sustained three prior pathologic fractures through a bone cyst, with no radiographic resolution after fracture healing. **B:** Intraoperative fluoroscopy depicting placement of needles into the proximal and distal aspects of the cyst. **C:** Radiopaque contrast is placed, confirming appropriate needle placement and ruling out the presence of septae/loculations. The cyst was subsequently injected with a combination of corticosteroid, autogenous bone marrow aspirate, and demineralized bone matrix.

fluid is sent for cytology and pathohistological evaluation. Half-strength radiographic contrast (Optiray) is then injected into the cyst, both to confirm accurate needle placement and to characterize the morphology of the lesion. Particularly in the setting of prior pathological fractures, these "unicameral" lesions may be loculated and septated. Following this, 40 to 80 mg of methylprednisolone acetate (Depo-Medrol, Pfizer, New York, NY) combined with 5 mL of demineralized bone matrix (Grafton DBM Gel, Osteotech, Inc., Eatontown, NJ) and 5 to 10 mL of bone marrow aspirate harvested from the iliac crest is mixed and injected into the cyst. Simple adhesive bandages may be placed, and sling immobilization is utilized for comfort only postoperatively.

Steroid injections have not been shown to be successful in cases of ABC.[14,24,27] Some early reports have suggested that alcohol or calcitonin injections may be efficacious for ABCs; however, we do not currently utilize injections for the treatment of ABCs.[53,54]

Mass Excision

There are a host of situations in which simple mass excision is indicated and will provide confirmation of diagnosis as well as improvements in pain and functional limitations. While each clinical entity and individual patient is different, a number of unifying surgical principles apply. First, longitudinal incisions should be used whenever the diagnosis is in doubt. Second, critical neurovascular structures should be identified proximal and distal to the mass and protected whenever possible. Furthermore, every effort should be made to obtain a complete marginal excision in cases of benign lesions, to maximize clinical results and minimize recurrence risk. In our experience, simple excisions of benign ganglions, retinacular cysts, vascular malformations, and other well-circumscribed soft tissue lesions are done effectively with <10% risk of recurrence (Figure 49-5).

Curettage and Bone Grafting of Enchondromas

Enchondromas are benign cartilage tumors affecting both short and long tubular bones. Enchondromas are exceedingly common, represent the most common primary bone tumor of the hand and the second most common cartilaginous neoplasm overall, with the peak incidence during the second decade of life.[55] While enchondromas are usually solitary, syndromes of multiple enchondromas include Ollier disease (nonhereditary form of multiple enchondromatosis) and Maffucci syndrome (multiple enchondromas associated with soft tissue hemangiomas

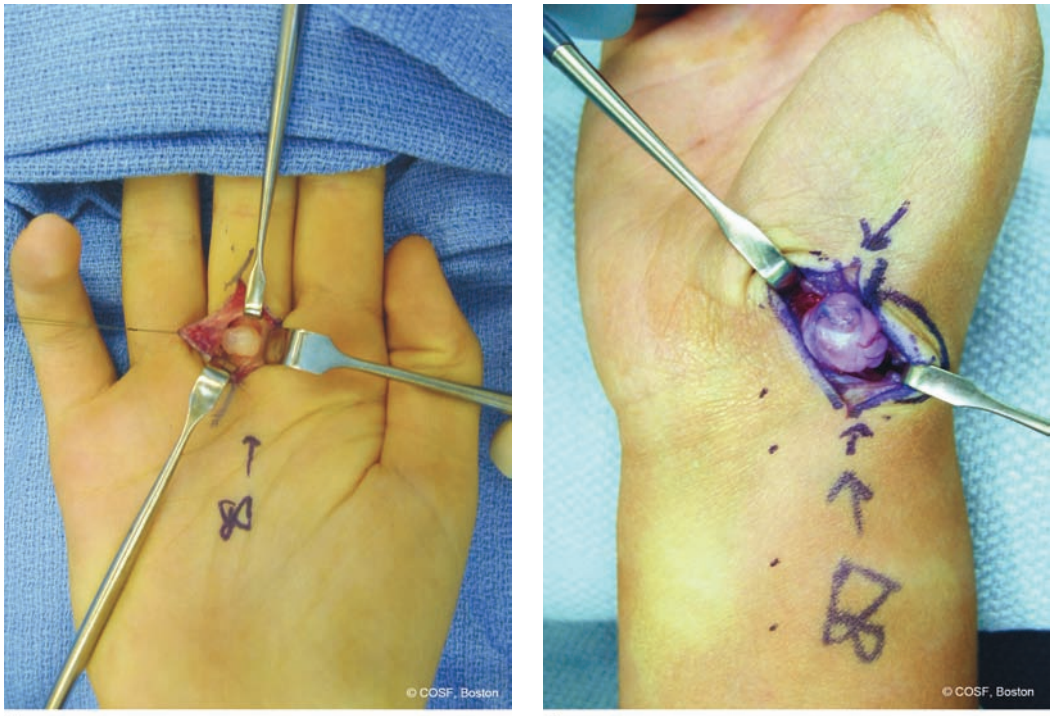
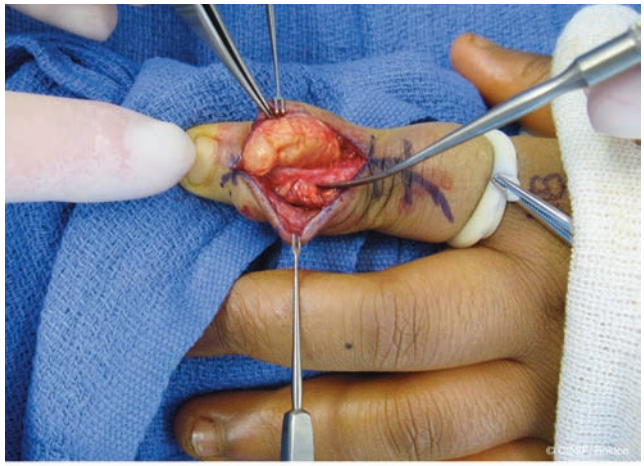


FIGURE 49-5 Clinical examples of surgical excision of common benign hand and upper limb masses. **A:** Intraoperative photograph of a symptomatic retinacular cyst of the long finger in a 14-year-old right hand–dominant rower and lacrosse athlete. **B:** Large volar radial wrist ganglion cyst, excised due to persistent symptoms of pain and difficulty resting the pronated hand on flat surfaces.

C



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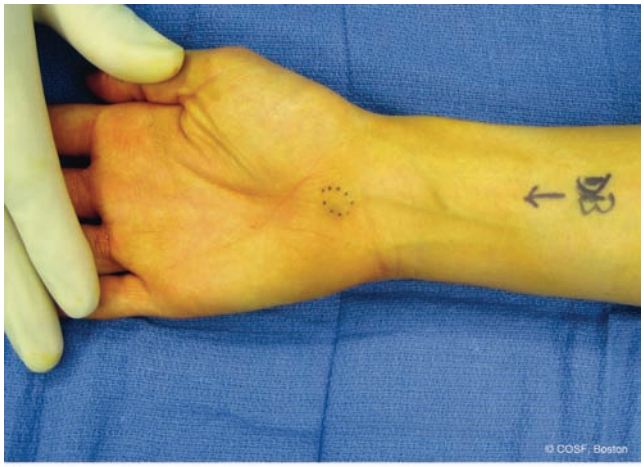

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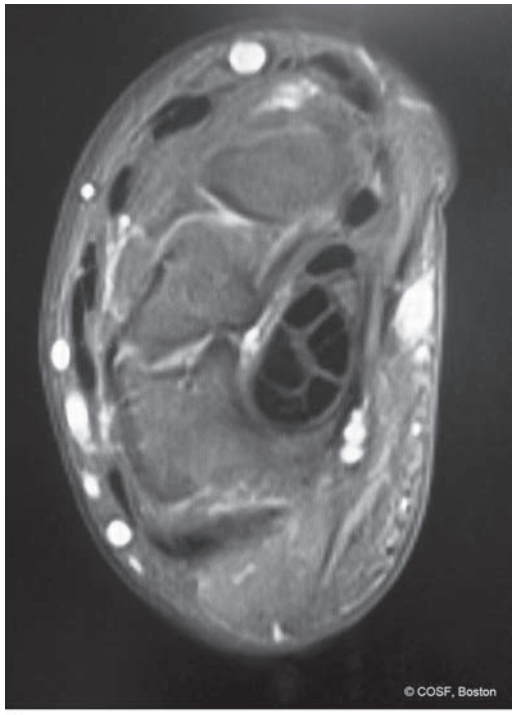


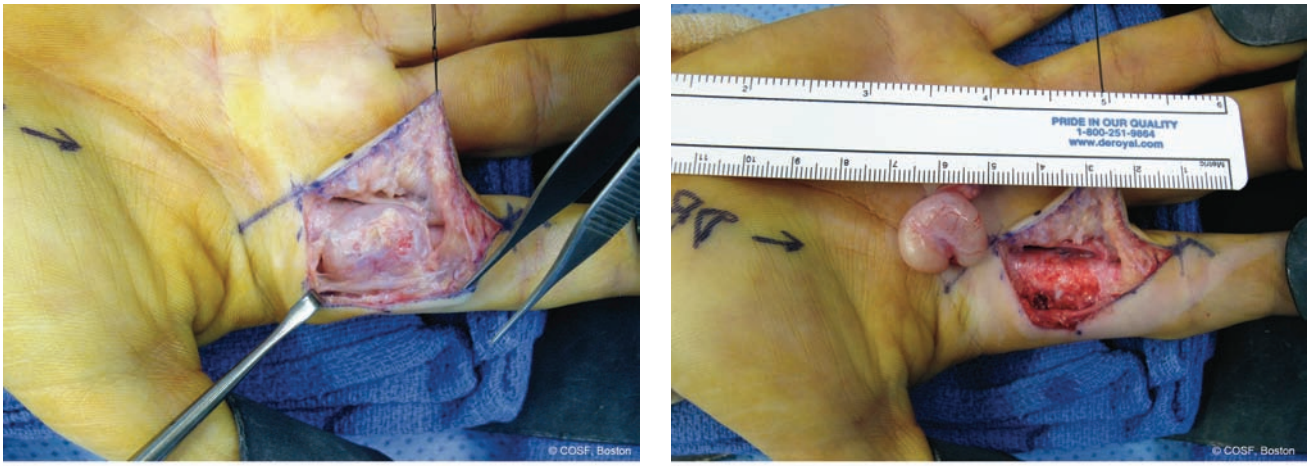
F

G

FIGURE 49-5 *(continued)* **C, D:** Preoperative clinical and intraoperative appearance of a giant cell tumor of tendon sheath, which affected the extensor mechanism of the index finger in a 6-year-old male. **E, F:** Clinical photograph and preoperative axial MRI image of a symptomatic subcutaneous vascular malformation. **G:** Intraoperative appearance during surgical excision of the superficial venous malformation.

and lymphangiomas). Affected digits will typically have firm bony enlargement or nodular masses (Figure 49-6). Radiographs will depict central radiolucencies with smooth, thin sclerotic margins and endosteal scalloping. The cortices may be slightly expansile. Intralesional punctuate mineralization is common. Associated periosteal reaction or soft tissue masses are absent. Patients will typically present for evaluation of abnormal radiographic findings seen incidentally on x-rays or for evaluation of hand pain with or without pathological fracture.

In patients with large or symptomatic enchondromas, treatment consists of curettage and bone grafting. Via a



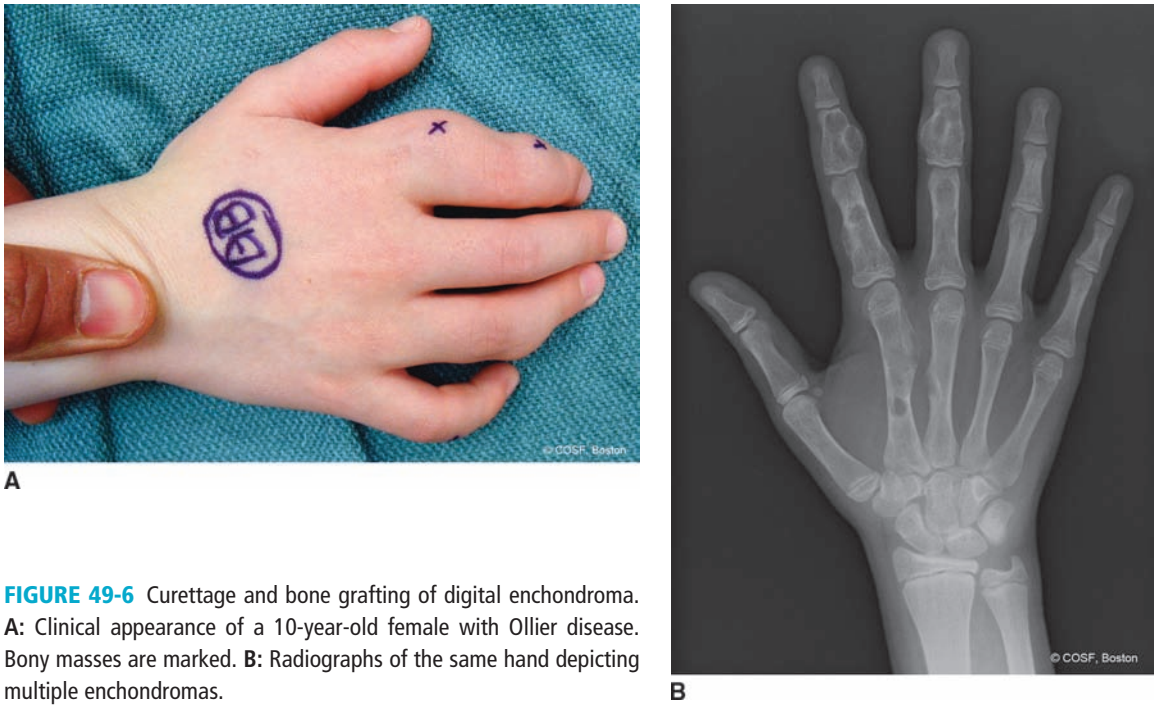
H I

FIGURE 49-5 *(continued)* **H, I:** Intraoperative photographs during excision of a symptomatic mass of the index finger. Subsequent pathology was consistent with a peripheral schwannoma. Note that the mass could be removed while preserving the radial digital nerve to the index finger.

midaxial approach, skin flaps are elevated and the interval between the lateral bands and central slip incised. Careful subperiosteal elevation is then performed around the affected phalanx, with care not to cause an iatrogenic fracture in the region of the thin, expansile cortex. An oval cortical window is created, often by simple pressure applied with a forceps or small curette. The cartilaginous enchondroma has a shiny, glassy white appearance and may be easily curetted out at this time. Intraoperative fluoroscopy may confirm adequacy and completeness of curettage. Following this, the cavity is filled with corticocancellous allograft. At present, we do not use autogenous bone grafts for the standard enchondroma. The wound is closed in layers and the digit immobilized in a splint or cast for a period of 2 to 3 weeks.

Bone Grafting of Bone Cysts

In theory, more invasive methods of cyst excision and curettage reduce recurrence rates but also impart greater morbidity and complication rates.[56]



A B

FIGURE 49-6 Curettage and bone grafting of digital enchondroma. **A:** Clinical appearance of a 10-year-old female with Ollier disease. Bony masses are marked. **B:** Radiographs of the same hand depicting multiple enchondromas.

C

D

FIGURE 49-6 *(continued)* **C:** Another patient with an isolated enchondroma of the ring finger middle phalanx. **D:** Radiographs following curettage and bone grafting, depicting bony incorporation without evidence of enchondroma recurrence.

Patients are positioned supine on a radiolucent table or in the modified beach chair position, with the affected shoulder and upper limb extended off the edge of the table to allow for adequate intraoperative fluoroscopic visualization (Figure 49-7). Typically a deltopectoral approach is utilized, which may be extended distally into a standard anterolateral approach to the humerus. An oval cortical window is created in an effort to avoid creating a stress riser in the already weak and thin humeral cortex. While osteotomes, burrs, or smooth pins may be used, typically the bone is so thin and compromised that a simple curette may be utilized to breach the cortex.

The cyst fluid is evacuated and the fibrous membrane curetted from the cyst wall. Intraoperative imaging is employed to confirm adequate curettage of the entire cyst. The lesion may then be packed with corticocancellous allograft chips, which have been shown to be effective

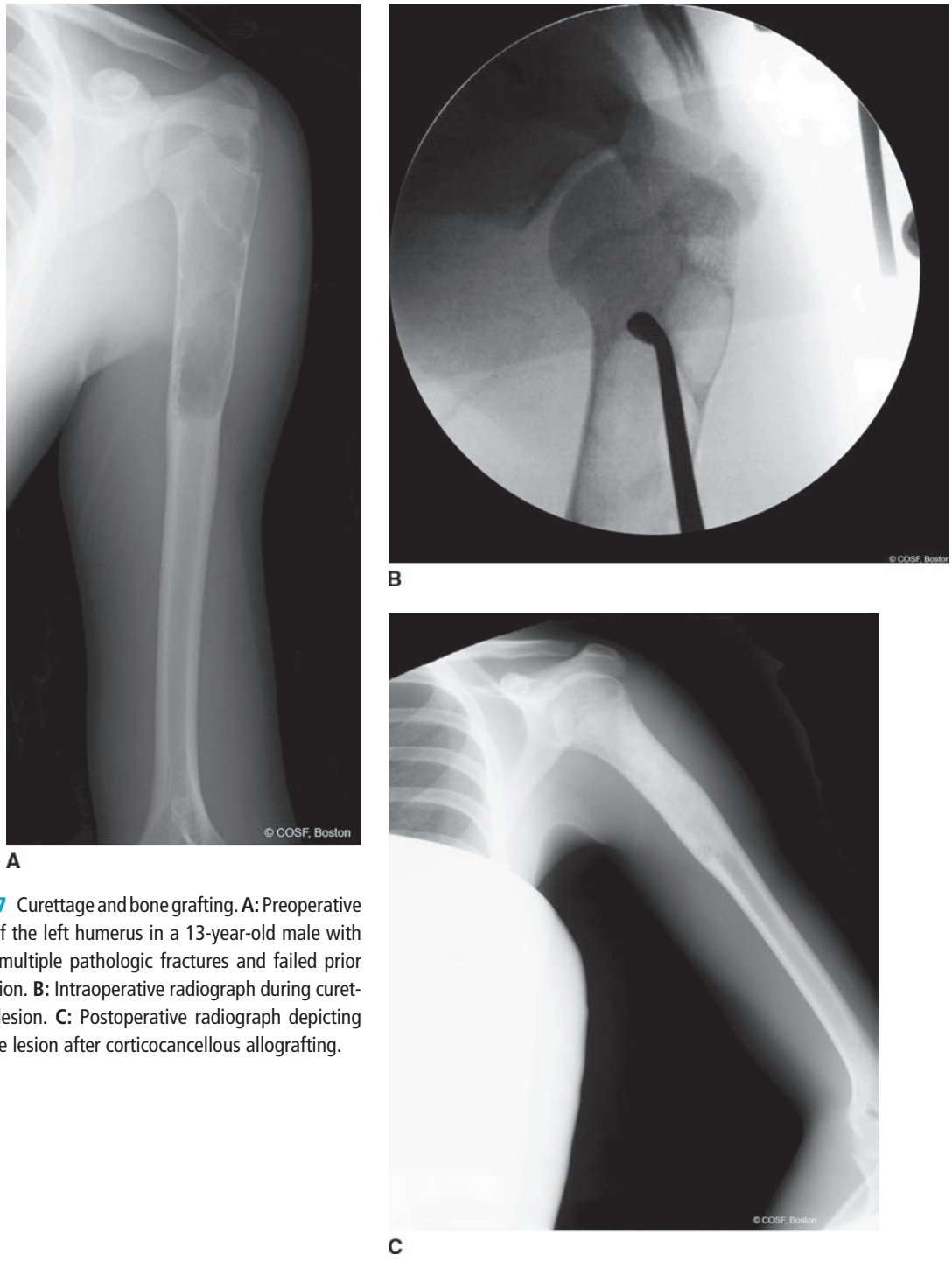


FIGURE 49-7 Curettage and bone grafting. **A:** Preoperative radiograph of the left humerus in a 13-year-old male with a history of multiple pathologic fractures and failed prior steroid injection. **B:** Intraoperative radiograph during curettage of the lesion. **C:** Postoperative radiograph depicting healing of the lesion after corticocancellous allografting.

and eliminate the morbidity associated with autogenous iliac crest bone graft harvest.[57–59] We do not currently utilize phenol or other chemical ablative materials when performing this procedure. Following bone grafting, the soft tissues are closed in layers, and the patient is placed in a sling for postoperative comfort.

While others have proposed "continuous cyst decompression" via placement of an intramedullary rod or cannulated screw, we do not currently utilize this technique.[60–62]

Curettage and bone grafting similarly remains the procedure of choice for ABCs and is performed in a similar fashion as with UBCs. The risk of recurrence remains between 20% and 70% however, with most studies demonstrating an approximately 30% recurrence rate.[27,63,64] In an effort to improve success rates following curettage, a number of adjuvants have been considered, including pre- or perioperative embolization, local phenol administration, cryotherapy, and even polymethylmethacrylate packing.

Ultimately, surgical treatment with en bloc resection of the entire affected bony region results in the lowest recurrence rates, though certainly is fraught with increased morbidity and technical complexity. This may be considered the final salvage procedure for non-weight-bearing bones that may be sacrificed to eliminate the lesion. As with UBCs, great care must be taken with juxtaphyseal lesions so as to avoid iatrogenic growth disturbance. Even in cases where curettage and grafting is performed, the risk of recurrence with incomplete curettage is accepted to preserve physeal integrity and growth potential.[65]

◆ Valgus Closing Wedge Osteotomy for Humerus Varus

Humerus varus is commonly associated with UBCs and ABCs of the proximal humerus. First described by Kohler[66] in 1935, humerus varus is defined radiographically by a proximal neck-shaft angle of <140 degrees, a greater tuberosity elevated above the level of the superior articular surface of the humeral head, and a reduced subacromial space (Figure 49-8A). Although a host of causes have been implicated, including post-traumatic and postinfectious etiologies, static or progressive varus deformity of the proximal humerus has been described in the setting of UBCs.[67–75] This may be due to the deleterious effect of a cyst abutting the proximal humeral growth plate or from iatrogenic injury to the physis during curettage procedures. The final common pathway is partial growth disturbance of the proximal humerus, resulting in progressive varus angulation. Clinically, patients with humerus varus will have limitations in forward flexion and lateral abduction due to abutment of the greater tuberosity against the acromion.

Surgical treatment of humerus varus involves a corrective osteotomy to improve proximal humeral alignment and diminish impingement. In children and adolescents, this may be successfully achieved with lateral closing wedge osteotomy and tension band fixation[76,77] (Figure 49-8B). Indications include radiographic humerus varus with progressive, painful, or functionally limiting restrictions in shoulder motion.

Patients are placed in the modified beach chair position. The affected shoulder and entire upper extremity are prepped and draped into the surgical field. Care is made to ascertain that appropriate intraoperative fluoroscopic imaging of the proximal humerus can be performed. The proximal humerus is exposed via a deltopectoral approach. The insertions of the pectoralis major and deltoid are reflected in a subperiosteal fashion. Care is taken not to disrupt the proximal humeral physis. Two parallel 2-mm (K-) wires are introduced into the lateral cortex of the humeral shaft at the site of the deltoid insertion and directed proximally toward the humeral head perpendicular to the planned osteotomy site for preliminary fixation of the distal fragment. Ideally, K-wires are positioned to cross perpendicular to the planned osteotomy site.

Tension band fixation is prepared using no. 1 Ethibond (Ethicon, Inc., Somerville, NJ) or other nonabsorbable suture passed in a figure-of-eight fashion between the insertion of the rotator cuff at the greater tuberosity and K-wires at the humeral shaft. Under direct vision, an oblique closing-wedge osteotomy is performed. Angled guides similar to those used for intertrochanteric osteotomies of the hip may be used during surgery to help achieve the desired angular correction as determined from the preoperative radiographs. The osteotomy is made just distal to the physeal plate in the region of the metaphyseal deformity.

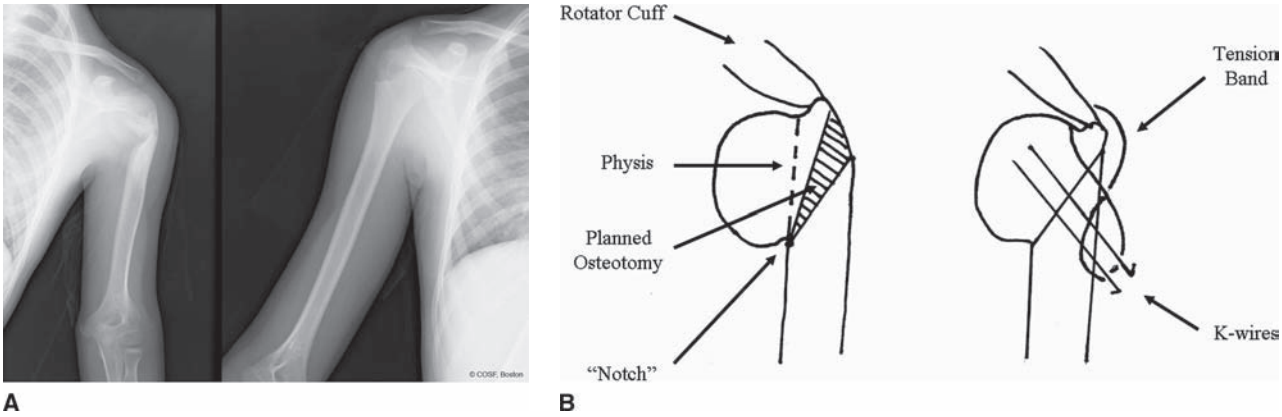


FIGURE 49-8 Secondary procedures following treatment of a UBC of the proximal humerus. **A:** Preoperative radiographs of the affected left humerus and unaffected right humerus depicting left humerus varus. This patient had previously undergone curettage and bone grafting of a large UBC abutting the proximal humeral physis. **B:** Schematic diagram depicting the technique of lateral closing wedge osteotomy and tension band fixation.

C

D

E

F

FIGURE 49-8 *(continued)* **C:** Postoperative radiograph depicting restoration of more normal proximal humeral anatomy and tension band fixation. **D:** While there was clinical improvement in pain and shoulder motion, this patient went on to develop progressive upper limb length discrepancy and recurrent humerus varus. The predicted discrepancy at skeletal maturity was 12 cm. Clinical photograph depicts the discrepancy at the initiation of limb lengthening. **E:** Radiograph of the humerus 2 weeks after proximal humeral osteotomy, distal humeral osteotomy, and application of a unilateral fixator. Note is made of correction of the humerus varus, though some translation at the distal osteotomy site is seen. **F:** Following lengthening there was good clinical restoration of upper limb length.

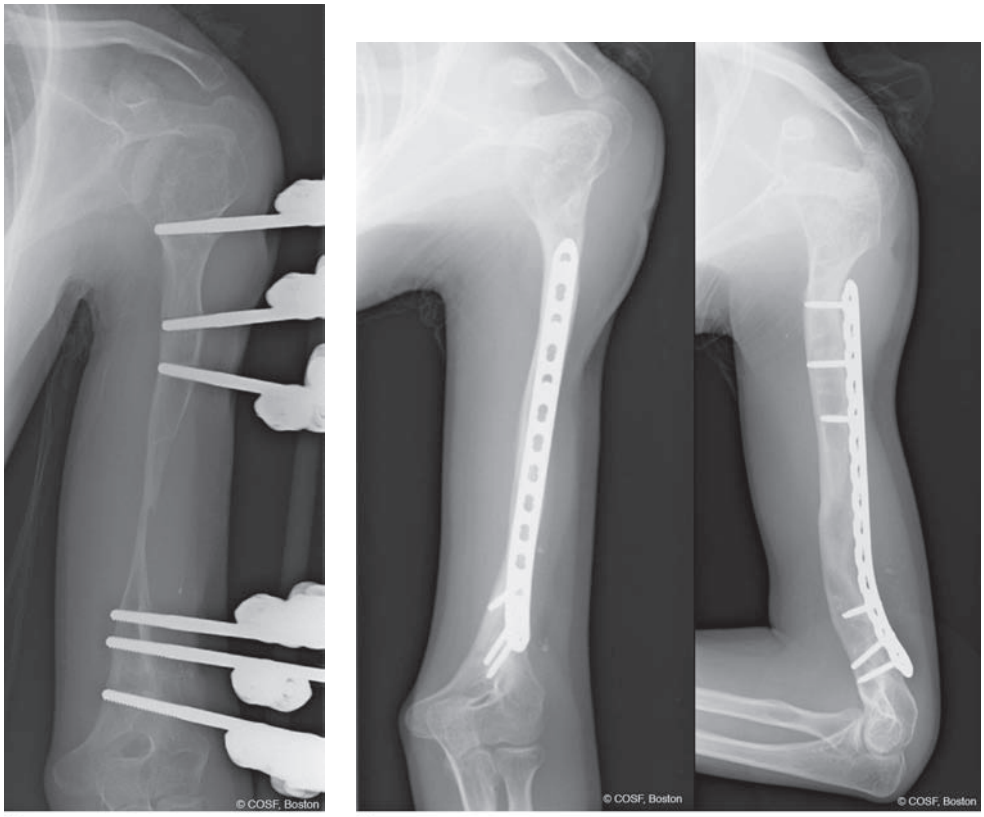


FIGURE 49-8 *(continued)* **G:** Radiographs demonstrated incomplete regeneration and consolidation. **H:** The patient subsequently underwent iliac crest bone grafting and plate fixation with progression to radiographic healing.

Osteotomy cuts are made to converge at the radiographic "notch," corresponding to the point of medial physeal arrest. To avoid iatrogenic injury to the ascending branch of the anterior humeral circumflex artery and thus minimize the risk of humeral head osteonecrosis, the osteotomy is created laterally and care is taken to preserve the far medial humeral cortex. The medial humeral cortex and periosteum are left intact during the osteotomy, also allowing it to serve as a hinge during closure of the osteotomy, providing additional rotational control at the osteotomy site, and protecting the medial neurovascular structures. At this stage, closure of the osteotomy is performed, followed by immediate passage of the smooth K-wires into the humeral head. Fluoroscopic visualization is used to ascertain appropriate K-wire placement and avoid intra-articular penetration. The tension band sutures are then tightened across the osteotomy site, providing compression and stability at the osteotomy site (Figure 49-8C).

After surgery, older compliant patients are placed in a sling and swathe and may begin gentle pendulum exercises immediately. Very young children and those likely to be noncompliant with activity modification are placed in a shoulder spica cast or abduction splint. The sling, spica cast, or splint is discontinued by the fourth postoperative week, when there is radiographic evidence of healing across the osteotomy site. Active range of motion is begun at this time. Strengthening exercises are initiated after complete clinical and radiographic healing, typically 6 to 8 weeks postoperatively. After confirmation of radiographic healing, K-wires are removed as a day surgical procedure in the young or in the office under local anesthesia in older patients.

◆ Limb Lengthening

Success is the sum of details.
—Harvey Firestone

In addition to angular deformities of the proximal humerus, physeal arrest may result in upper limb length discrepancies following treatment of UBCs and ABCs, as well as after physeal fractures and infections.[78] While much more limb length discrepancy is tolerated in the upper limb compared with the lower extremities, surgical limb lengthening may be considered in patients with over 6 cm of predicted limb length difference at skeletal maturity.[79–83] It is clear that sizable upper limb length discrepancies, though aesthetically noticeable, often result in no functional limitations; in light of this and the complications often associated with lengthening procedures, it should be

understood that the indications for humeral lengthening are relative and highly individualized.

Calculation of the ultimate limb difference at the completion of skeletal maturity may be challenging. Recent work by Paley et al.[84] have provided methods of calculating predicted discrepancies (Figure 49-9; Table 49.2).

While multiple techniques of humeral lengthening have been proposed, we favor distraction osteogenesis with the assistance of a unilateral external fixator (Limb Reconstruction System, Orthofix Inc., Richardson, TX).

Patients are positioned supine on a radiolucent table, allowing access to the entire upper limb and adequate intraoperative fluoroscopic visualization. Site of lengthening is dependent upon the nature of the deformity, but we typically favor monofocal lengthening at the distal humeral metadiaphysis. Typically, two to three points of fixation proximal and distal to the planned osteotomy and lengthening site are sufficient. The unilateral frame (rail and clamps) is assembled to allow for the desired position and lengthening potential. Under fluoroscopic guidance, stab incisions are made in the skin over the lateral aspect of the humerus, and blunt spreading is performed through the subcutaneous tissues to the level of the bone. Hydroxyapatite (HA)-coated threaded pins (OsteoTite Bone Screws, Orthofix Inc., Richardson, TX) are then inserted into the humerus, with care taken to engage both the lateral and medial cortex. These pins may be inserted through the holes in the preassembled clamps to ensure appropriate positioning and collinear trajectory to fit the planned frame. It is recommended that the most proximal and most distal pins are inserted first. Once two to three threaded pins have been inserted proximal and distal to the planned osteotomy site, the osteotomy may be performed.

Although percutaneous techniques have been proposed, we favor an open approach to the humerus, due to the proximity of the radial nerve to the usual osteotomy site. Via a small lateral longitudinal incision, dissection is performed to the humeral metadiaphysis, protecting and retracting adjacent soft tissues. Minimal periosteal stripping is performed to preserve the biological healing potential. The humeral cortex is then perforated with a K-wire or drill, and the osteotomy is completed with an osteotome. Careful distraction is performed under direct visualization and fluoroscopic imaging to confirm the osteotomy is complete. The segments are then reapproximated and stabilized using the unilateral frame. The incision is closed in layers.

Lengthening is not initiated for 5 to 7 days postoperatively, and is performed by 0.25 mm distraction performed four times per day until the desired length is achieved. Serial radiographs are obtained to ensure appropriate lengthening, alignment, and distraction osteogenesis. Patients are encouraged to maintain elbow motion with daily range-of-motion exercises and are instructed regarding pin care (half-strength hydrogen peroxide applied at the pin sites twice daily with a cotton swab).

In cases where both lengthening and valgus correction of humerus varus need to be performed, the same unilateral frame may be used in the setting of both a distal osteotomy (for lengthening) and proximal lateral closing wedge osteotomy (for correction of varus). In these situations, the proximal lateral closing valgus osteotomy is stabilized by one HA-coated pin above and two pins below the osteotomy site (Figure 49-8E–G).

POSTOPERATIVE

Following aspiration and injection of humeral UBCs, a simple bandage will suffice, and sling immobilization is provided for comfort. Range-of-motion and upper limb use is advanced as tolerated, and serial radiographs are obtained over the ensuing months to assess for healing.

Following curettage and bone grafting of bone cysts, sling immobilization is utilized for the first 2 postoperative

$$\Delta_{maturity} = \Delta_{present} + I \times G$$

$$I = \text{inhibition} = 1 - (S2 - S1)/(L2 - L1)$$

$$G = \text{growth remaining} = L_{maturity} - L = L\,(M-1)$$

Δ = limb length difference
S = length of affected limb
L = length of normal bone
M = multiplier
1 and 2 denote measurements taken at two timepoints

FIGURE 49-9 Formula to calculate anticipated limb length discrepancies at skeletal maturity for developmental conditions (e.g., physeal arrest, Ollier disease). The limb length difference at skeletal maturity ($\Delta_{maturity}$) is calculated by adding the current limb difference ($\Delta_{present}$) to the predicted additional growth difference. The additional growth difference is calculated by multiplying the inhibition factor (*I*) by the amount of growth remaining (*G*). The inhibition factor is calculated by serial radiographs of the bilateral upper limbs. Growth remaining is calculated by multiplying the current length by (M – 1), where M is the gender and age-appropriate multiplier. (From Paley D, Gelman A, Shualy MB, et al. Multiplier method for limb-length prediction in the upper extremity. *J Hand Surg Am.* 2008;33:385–391.)

Table 49.2

Upper extremity multipliers (*M*) in females and males used to predict limb length discrepancies, adapted from Paley et al.

Age (Years + Months)	Upper Extremity Multiplier (Females)	Upper Extremity Multiplier (Males)
1	2.79	3.01
1 + 6	2.49	2.70
2	2.29	2.49
2 + 6	2.14	2.33
3	2.02	2.20
3 + 6	1.91	2.09
4	1.82	1.99
4 + 6	1.74	1.91
5	1.68	1.83
5 + 6	1.61	1.77
6	1.56	1.70
6 + 6	1.50	1.65
7	1.46	1.60
7 + 6	1.41	1.55
8	1.37	1.51
8 + 6	1.34	1.47
9	1.30	1.43
9 + 6	1.27	1.39
10	1.24	1.36
10 + 6	1.20	1.33
11	1.17	1.30
11 + 6	1.14	1.27
12	1.11	1.24
12 + 6	1.08	1.21
13	1.06	1.18
13 + 6	1.04	1.15
14	1.02	1.11
14 + 6	1.01	1.08
15	1.01	1.06
15 + 6	1.00	1.03
16	1.00	1.02

Adapted from Paley D, Gelman A, Shualy MB, et al. Multiplier method for limb-length prediction in the upper extremity. *J Hand Surg Am*. 2008;33:385–391.

weeks. Range of motion is encouraged, but heavy lifting and strengthening are not allowed until 6 weeks postoperatively. Serial radiographs are again obtained until radiographic healing and bony consolidation are confirmed.

After lateral valgus osteotomies of the shoulder, older compliant patients are placed in a sling and swathe and may begin gentle pendulum exercises immediately. Very young children and those likely to be noncompliant with activity modification are placed in a shoulder spica cast or abduction splint. The sling, spica cast, or splint is discontinued by the fourth postoperative week, when there is radiographic evidence of healing across the osteotomy site. Active range of motion is begun at this time. Strengthening exercises are initiated after complete clinical and radiographic healing, typically 6 to 8 weeks postoperatively. After confirmation of radiographic healing, K-wires are removed as a day surgical procedure in the young or in the office under local anesthesia in older patients.

Following distraction osteogenesis and limb lengthening, extended time with the fixator left in place is needed until bony consolidation is achieved. The frame and pins may then be removed in the office or under brief sedation or general anesthesia in the operating room.

ANTICIPATED RESULTS AND COMPLICATIONS

Do not perform complex operations on simple patients.
—James Kasser, MD

The most common complication following observation or surgical treatment of UBCs of the proximal humerus is cyst recurrence. Multiple reports suggest the recurrence risk following treatment is up to 50%.[2,5,85,86] The risk of recurrence is just as high with formal curettage and bone grafting procedures as with less invasive aspiration and injections.[2,6] Factors associated with higher risk of recurrence include age <10 years, larger cysts, multilocular cysts, and cysts in the setting of unimpacted fractures.[2,3,34,85]

At present, we have imperfect solutions to this seemingly simple but clinically vexing condition. Patients and families should be counseled regarding the risk of recurrence prior to any surgical intervention.

Lateral closing wedge osteotomies for humerus varus are safe and reliable overall. As the osteotomy is performed through the proximal humeral metaphysis, bony union rates are high. Significant though imperfect improvements in shoulder abduction and forward flexion may be achieved, with marked improvement in radiographic alignment.[77] Patients are typically symptomatic from the smooth pins used for tension band fixation, and a second surgical procedure for implant removal is common. When these osteotomies are performed in very young patients with partial physeal bars and skeletal growth remaining, deformity may recur.

Upper extremity limb lengthening is subject to similar complications as other lengthening procedures, including pin loosening and pin tract infections, incomplete lengthening due to premature consolidation of the regenerate, refracture, nerve palsies, and adjacent joint (elbow) contractures.[79–81] Patients and families should be extensively counseled about the risks of lengthening preoperatively, and great care should be taken in patient selection.

CASE OUTCOME

The diagnosis of pathological fracture through a UBC was made, based upon the characteristic radiographic appearance of the lesion. After fracture healing, though the patient was clinically asymptomatic, there was a large radiolucency in the proximal humerus, consistent with persistent UBC. After discussion with the family about potential treatment options, including the risks of physeal injury with curettage and bone grafting, the decision was made to proceed with aspiration and injection with marrow aspirate, corticosteroid, and demineralized bone matrix. Radiographic resolution was seen after 6 months.

SUMMARY

UBCs and ABCs are common, benign bony lesions encountered by the pediatric hand and upper limb surgeon. In cases of pain and/or prior or impending pathologic fracture, surgical treatment is indicated. Although a host of treatment options exist, the risk of recurrence remains considerable. Late sequelae of proximal humeral lesions—including humerus varus and limb length discrepancy—may be amenable to surgical correction in appropriately selected patients.

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CHAPTER

50

Malignant Lesions of the Upper Limb

CASE PRESENTATION

A 2-year-old female presents with a firm, nontender mass situated dorsally between and over the ring and long finger metacarpals (Figure 50-1). It was noted about 6 weeks before by the parents during bathing. There was no clear history of trauma, though the patient is an active child and falls and bumps into objects frequently. An orthopaedic exam and radiograph led to a diagnosis of nondisplaced diaphyseal fracture healing with noted periosteal reaction on the ring finger metacarpal (Figure 50-2). Despite casting for 3 weeks, the mass appears to be getting larger.

CLINICAL QUESTIONS

- What are the common tumors of the pediatric upper limb?
- What differentiates a benign from a malignant tumor on physical exam and radiologic evaluation?
- What are the indications for CT scan, MRI scan, bone scan, and ultrasound in a diagnostic workup of a suspected tumor of the hand and upper limb?
- When is biopsy alone the appropriate first surgical treatment?
- When is excisional biopsy the preferred treatment?
- What are the indications for terminal segment resection versus ray resection?
- When is limb salvage an appropriate surgical treatment?
- What are the surgical options for limb salvage?

THE FUNDAMENTALS

Etiology and Epidemiology

It's not the disability that defines you, it's how you deal with the challenges the disability presents you with. We have an obligation to the abilities we DO have, not the disability.
—Jim Abbott

Soft tissue and bony masses of the hand and upper limb in children almost always raise serious concerns among parents and primary caregivers about malignant potential. Fortunately, malignancies of the hand are exceedingly rare in children and uncommon in the upper limb. Benign lesions predominate, but malignancies do occur. Differentiation between benign and malignant lesions requires careful attention to detail on physical exam, radiologic evaluation and interpretation, and surgical decision making. It is necessary to keep a high awareness of the very real possibility of malignancy when assessing all palpable masses and radiographic lesions (Figure 50-3). Inappropriate reassurance can be disastrous for one and all.

Common primary malignancies of bone include osteogenic sarcoma and Ewing sarcoma. Chemotherapeutic advances improved 5-year survival significantly and led to limb salvage rather than amputation as the orthopaedic surgery treatment of choice in most tertiary medical centers.[1,2] Neoadjuvant chemotherapy can lessen the surgical resection and improve limb salvage options. A positive response to preoperative chemotherapy is a clear positive prognostic factor.[3] Metastatic and recurrent disease have a poor prognosis. Thoracotomies and tumor resection of pulmonary metastases can improve survival.

Soft tissue sarcomas are rare in children and adolescents. Infantile fibrosarcoma is the most common sarcoma in children <1 year of age but represents <1% of all childhood cancers. Survival of infantile fibrosarcoma with a combination of surgery and chemotherapy is better than adolescent or adult fibrosarcomas.[4,5] Rhabdomyosarcoma (embryonal is the most frequent type in children, but alveolar type occurs most often in limbs), primary neuroectodermal tumors, synovial sarcoma, and neurofibrosarcomas are the most common of the rare soft tissue sarcomas in children and adolescents.[6,7] Radiation therapy is frequently used in the treatment for pediatric and adolescent sarcomas, particularly in cases of limited marginal resections.[8] Long-term consequences of the radiation therapy in survivors include poor bony growth, pathologic fracture, and secondary malignancy.[9,10] Defining the biologic behavior of a pediatric sarcoma includes the histologic response to chemotherapy and chromosomal analysis for specific translocations and resultant fusion genes.[11]

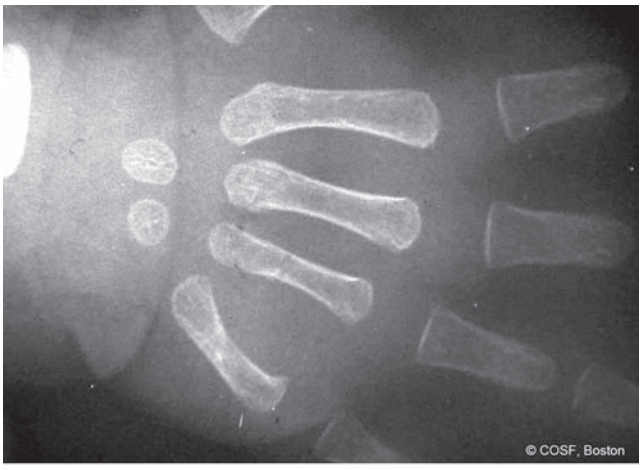
FIGURE 50-1 Photograph of dorsal hand mass centered between ring and small finger metacarpals.

Clinical Evaluation

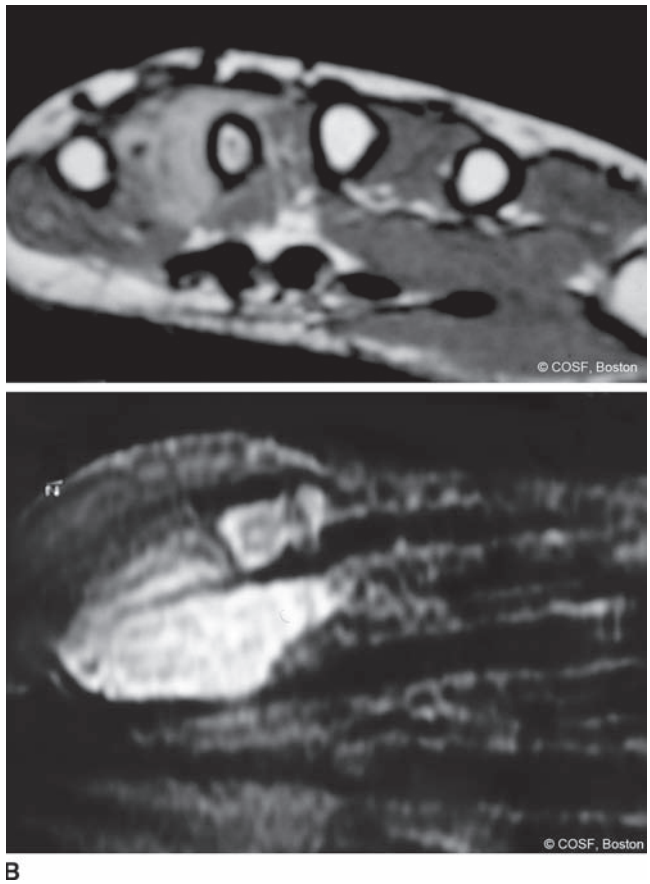
In general but not always, lesions of bone and soft tissues play by the following rules: (1) benign soft tissue lesions are well circumscribed, often encapsulated, grow slowly, and do not metastasize and (2) malignant lesions are expansile, have poorly defined borders, grow rapidly, and can spread to other anatomic sites. Size is not a reliable diagnostic discriminator (i.e., ganglions can be gigantic; malignancies can be barely palpable), nor are symptoms always helpful (not every malignancy hurts in the nighttime; some benign lesions are very painful). Thus, physical exam is useful but not perfectly precise in distinguishing benign from malignant lesions.

In the evaluation of an upper limb mass in a child, fractures, infections, and their sequelae are important parts of the differential diagnosis. So too are metabolic bone disease, systemic disorders, and inflammatory processes. Laboratory testing with complete blood count and differential, erythrocyte sedimentation rate, C-reactive protein, serum calcium, phosphate, blood urea nitrogen, creatinine, alkaline phosphatase, lactate dehydrogenase, rheumatoid factor, antinuclear antibody, and Lyme titers is commonly indicated to help discriminate among diagnoses.

Musculoskeletal imaging is critical. Short of biopsy and histologic exam, imaging can usually differentiate benign from malignant lesions and lead to an accurate diagnosis. Plain radiographs provide excellent anatomic information about the degree and type of bony involvement (Figure 50-4A). All concerning soft tissue and musculoskeletal



A



B

FIGURE 50-2 **A**: Radiograph revealing soft tissue mass effect on ring metacarpal. Unfortunately, this was initially interpreted as fracture callus. **B:** MRI scans of lesion confirming malignancy.

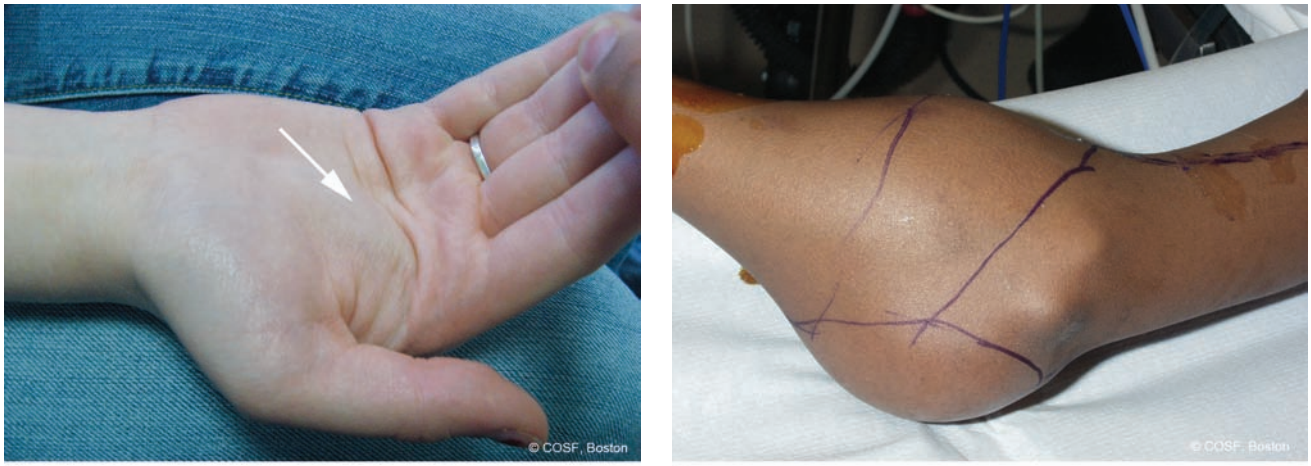
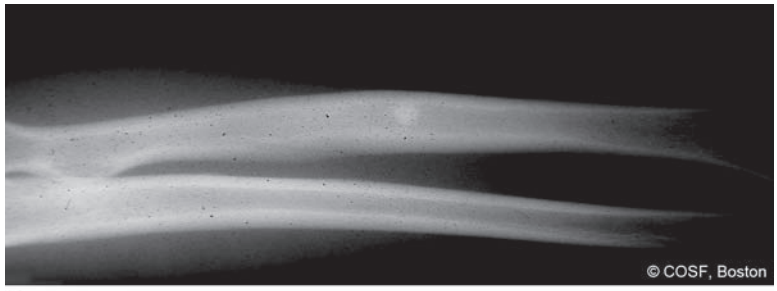


FIGURE 50-3 **A**: Accessory lumbrical muscle presenting as a mass in the palm, a worrisome anatomic area for possible malignancy. **B:** A very late presentation for a massive lesion about the elbow of obvious concern for malignancy. This case was a synovial sarcoma.

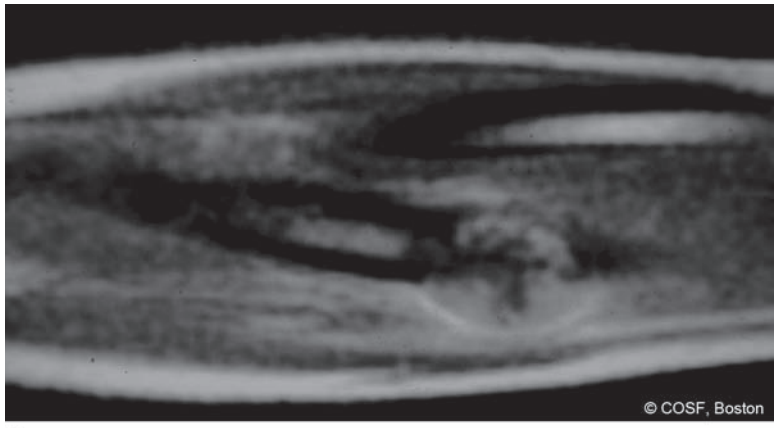
lesions should have at least two perpendicular plain radiographs to define size, what the lesion is doing to the bone, how the bone is reacting to the lesion, and if there is soft tissue involvement. High-resolution ultrasounds are relatively inexpensive and easy compared to computed tomography (CT) and magnetic resonance imaging (MRI) scans. Ultrasounds can distinguish cystic from solid lesions, and, in some cases (e.g., unclear ganglion), this may be all that is necessary. CT scans allow visualization of intramedullary canal, cortical and soft tissue involvement, and usually provide an accurate diagnosis of the lesion. MRI scans better define soft tissue extension and intramedullary skip lesions (Figure 50-4B). These scans are used not only for diagnosis but also for staging and surgical resection decisions.[12]

If the diagnosis is still unclear or worrisome for malignancy, biopsy is indicated. The biopsy incision needs to be judiciously created so as not to jeopardize later limb salvage or segmental resection options. Consultation with, or transfer of care to, an orthopaedic oncologist is often appropriate and wise. Surgical staging is now standardized

FIGURE 50-4 **A**: Expansile lesion of proximal phalanx consistent with an aneurysmal bone cyst (ABC). **B:** MRI scan of same lesion with fluid-fluid level consistent with ABC.



C



D

FIGURE 50-4 *(continued)* **C:** Plain radiograph of forearm with sclerosis and periosteal reaction of diaphyseal radius. **D:** MRI scan revealing primary bone malignancy, which by biopsy was Ewing sarcoma.

(grades I to II) by Enneking criteria[13] (Table 50.1) for grade low (G1), high (G2), regional or distant metastases (M), and compartment involvement (intra- [T1] or extra- [T2]).

In the end, the pediatric hand and upper limb surgeon needs to be aware of and provide appropriate care and consultation for, among others, any of the lesions noted in Table 50.2. Depending on your situation, your oncology practice may be limited to diagnosis, workup, and referral to the appropriate subspecialist, or you may participate in surgical care and patient management. For us, upper limb and hand malignancies are managed using a team approach, with our surgical expertise being utilized for the surgical access and complex reconstructions. Benign lesions often receive complete care by us.

Table 50.1

Modification of Enneking criteria

Enneking Stage	Histological Grade	Anatomic Extent
IA	Low	Intracompartmental
IB	Low	Extracompartmental
IIA	High	Intracompartmental
IIB	High	Extracompartmental
III	Any	Any with metastasis

Adapted from Enneking WF. Staging of musculoskeletal neoplasms. In: Uhthoff UK SE, ed. *Current Concepts of Diagnosis and Treatment of Bone and Soft Tissue Tumors*. New York, NY: Springer-Verlag; 1984:1–21.

Surgical Indications

Biopsy of potential malignant lesions needs to occur after completion of the medical oncology evaluation and diagnostic laboratory and radiographic workup. The biopsy is performed in conjunction with the surgical pathologist to plan frozen section microscopy (often with pathologist, oncologist, and surgeon reviewing together), permanent histology, and tissue typing studies. Remember to always obtain cultures because infection is a great mimicker. If there is any question about the ability to safely obtain the proper specimen and accurately diagnose the patient's condition, referral for biopsy is strongly advised.

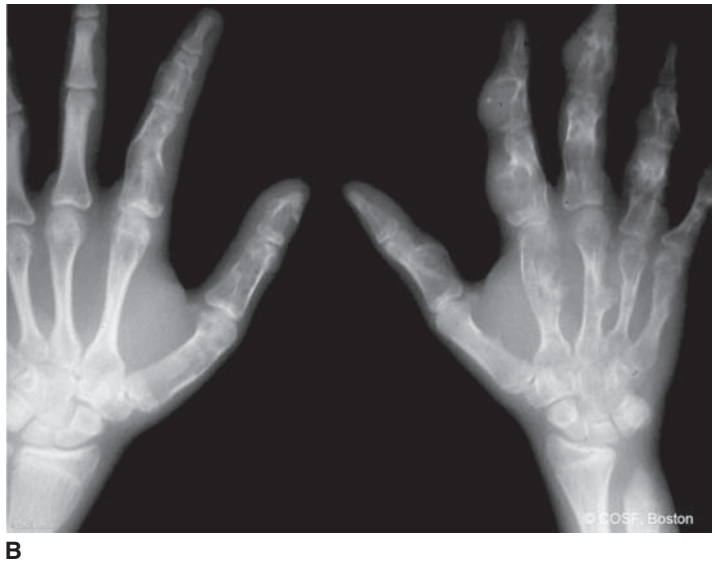
Timing and planning for surgical reconstruction is done once an unequivocal diagnosis is made. Tumor board conferences aid the entire team, with medical oncologists, radiation therapists, musculoskeletal radiologists and pathologists, and surgical subspecialists discussing each case. Protocols are reviewed; plans and timing for chemotherapy, radiation, and surgery are made.

Table 50.2

Benign lesions

Benign lesions	Foreign bodies
Osteochondroma (Figure 50-5A)	Annulare granulare
Enchondroma > Ollier's > Maffucci's (Figure 50-5B)	Melanocytic lesions of nail bed
Chondromyxoid fibroma	Glomus tumors (Figure 50-5H)
Osteoid osteoma	
Infantile fibroma (Figure 50-5C)	**Malignant lesions**
Fibromatosis	Congenital fibrosarcoma
Fibroma (Figure 50-5D)	Synovial sarcoma
Juvenile aponeurotic fibroma	Epithelioid sarcoma
Annulare granuloma	Melanoma
Giant cell tumor of tendon sheath (Figure 50-5E)	Rhabdomyosarcoma
Ganglion of the wrist (Figure 50-5F)	Osteogenic sarcoma
Cyst of tendon sheath	Ewing sarcoma
Vascular malformations (Figure 50-5G)	Chondrosarcoma

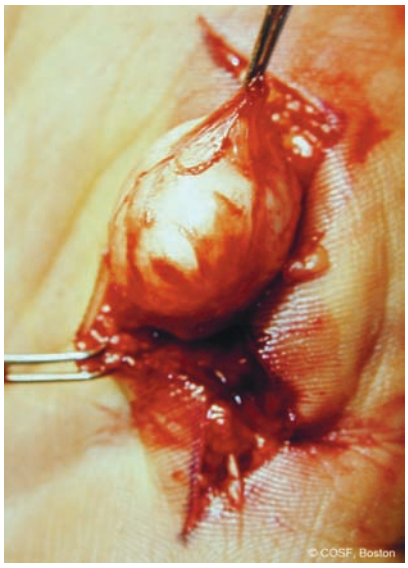
A



B

C

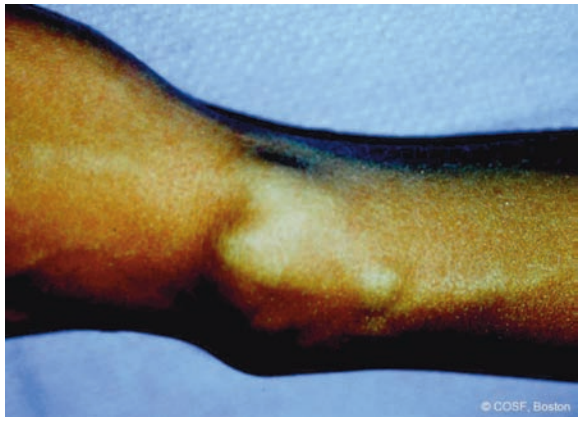
FIGURE 50-5 Various benign masses of the hand that need to be distinguished from malignant masses. **A:** Large distal ulna osteochondroma in a 2 year old. **B:** Multiple enchondromas from Ollier disease. **C:** Infantile fibroma.



D

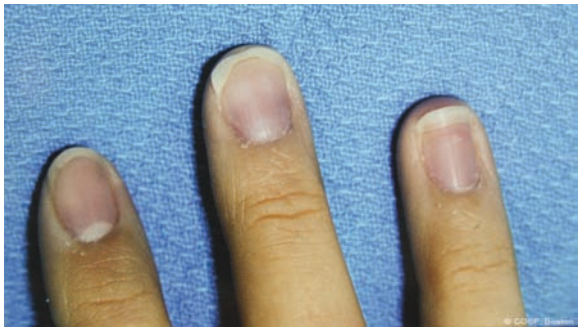
E

F



G1

G2



H1

H2

FIGURE 50-5 *(continued)* **D:** Fibroma of the hypothenar eminence. **E:** Giant cell tumor of tendon sheath. **F:** Ganglion of the wrist **G:** Vascular malformation of the wrist preoperatively (G1) and intraoperatively (G2). **H:** Glomus tumor of nail bed prior to and during excision.

SURGICAL PROCEDURES

Biopsy

In the 8th inning you can't hear the roar of the 9th, all you can do to hold yourself together, and trust.
—Jim Abbott

Planning the biopsy incision is critical. Poorly planned or executed incisions can prevent limb salvage due to compartment contamination of malignant cells. The name of the game is to avoid surprises. Needle biopsies are rarely performed in the upper limb and hand. Open biopsies are the norm. Longitudinal incisions that can be excised completely with definitive tumor resection and reconstruction are mandatory. Biopsies need to be performed under tourniquet control but not with compressive exsanguination, as this will spread tumor cells. Elevation of the limb for a few minutes before tourniquet inflation is recommended. Dissection to the tumor is done within the compartment of the tumor, so later en bloc resection of the entire biopsy path from skin to lesion can be performed. Dissection through muscle rather than with muscle elevation or retraction reduces contamination. Multiple specimens are obtained for frozen section biopsy. Microscopic sampling and preliminary analysis while the patient is still under anesthesia will determine the adequacy of the specimens obtained for diagnosis and special tissue typing. Frozen section microscopy does not determine final diagnosis but usually does distinguish malignant from benign. Most biopsies for malignancy are incisional biopsies, with planned definitive excision and reconstruction occurring later after all the information gathering, subspecialty consultation, and family discussions are complete. Excisional biopsy is performed for benign lesions. Excisional biopsies can be intralesional (curettage of enchondroma) (Figure 50-6) or marginal (fibromatosis). Wide excision is required for all malignancies and may include vital structures (nerves, tendons, bones, joints, arteries) that need complex reconstruction. Prereconstruction chemotherapy and/or radiation therapy can often shrink the size of the lesion, allowing for less radical wide margins and more potential for functional limb salvage rather than amputation. Ultimately, preservation of life always trumps preservation of limb, but if you and your team of experts can get both, the more satisfying is the work you do.

Segmental Hand Resections

Don't give up at half-time. Concentrate on winning the second half.
—Coach Paul "Bear" Bryant

Digital and hand malignancies are rare. Therefore, your index of suspicion needs to be very high at all times so as not to miss the rare one that presents to you. Complete hand amputation is a major loss of function. The compartments of the hand actually extend into the proximal forearm, so strict intracompartmental resection requires a high-level amputation. Local sarcoma recurrence carries a poor prognosis. Therefore, the decision for a segmental resection of a hand malignancy needs to be made in careful consultation with the family, oncologists, and orthopaedic oncologists. These patients often seek multiple opinions at many high-level centers if they can afford the time and money costs. Our role as pediatric hand and upper limb surgeons is most often as high-level technician and anatomist after the other experts have figured out what is the best combination of life and limb preservation for each patient.

Distal phalangeal lesions, such as epithelioid sarcoma or melanoma, may allow for segmental amputation at the middle phalangeal level or more conservatively, a single ray resection (Figure 50-7). More proximal lesions in the middle or proximal phalanx can often be dealt with surgically by single ray resection. Metacarpal-level malignant

FIGURE 50-6 Ollier disease with multiple enchondromas and pain from recurrent pathologic fractures treated with curettage and bone grafting.

FIGURE 50-7 Preoperative photograph of epithelioid sarcoma. This was treated several times by dermatologist with local cauterization. Figure 50-9 details definitive surgical treatment.

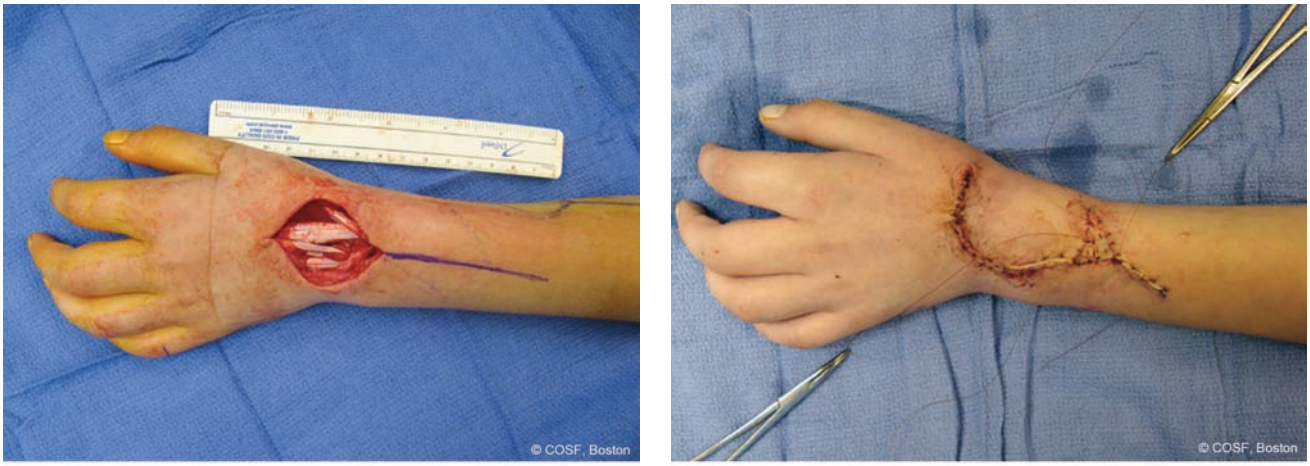


FIGURE 50-8 **A:** Intraoperative photograph after resection of a soft tissue sarcoma of the dorsal hand. **B:** Soft tissue coverage was provided by local rotation advancement flap.

lesions, such as rhabdomyosarcoma, may require multiple ray resections into the carpus or complete hand amputation. Volar carpal lesions usually require distal forearm amputation. Dorsal carpal level hand lesions may be amenable to en bloc resection and reconstruction leaving the palmar neurovascular and distal digital structures intact (Figure 50-8). Each tumor has its unique biology dependent on type and staging, and decisions for surgical care are made based on that important information.

People do not count fingers. Therefore, ray resection is both a very functional and very aesthetic operation. The narrower palm does decrease grip strength, but complete ray rather than partial digital resection has the advantage of no digital gapping. Each ray has some variation on technique of resection. For example, index ray amputation does not require transverse metacarpal ligament reconstruction. Small finger ray resection requires hypothenar muscle flap reconstruction or resection and ulnar nerve protection to maintain intrinsic strength to the remainder of the hand. Long or ring finger resection requires transverse metacarpal ligament reconstruction and potential index or small finger central transposition, respectively.

A dorsal to volar elliptical incision is outlined around the metacarpophalangeal base(s) (Figure 50-9A). The incision is carried out longitudinally volar and dorsal to the metacarpal base(s). The transverse metacarpal ligaments are released with sufficient length left for subsequent reconstruction of the central digits. The neurovascular bundles are identified as the common to proper digital bifurcation. The arteries to the resected digit(s) are ligated and the nerves sharply divided. The nerves and arteries to the retained digits are preserved and protected. The intrinsic muscles are resected for a wide resection of the tumor with a healthy muscle cuff of tissue. The flexor and extensor tendons to the involved digit(s) are transected as proximally as possible out of the contaminated field. The bone resection is at the metacarpal base, through the carpometacarpal joint or with a carpal wedge to have a wide resection and maximize reconstruction. The entire specimen from skin to bone(s) and back is lifted cleanly out of the wound and sent to pathology. Clean margins are checked by frozen section biopsies with exact markings. Closure involves ligament, intrinsic muscle, skin flap, bone, and joint reconstruction as appropriate for each ray resection(s). Careful assessment of digital rotation and passive range of motion is necessary for completion of closure. Smooth pin fixation for 3 to 4 weeks with transverse metacarpal pins is common as long as there are no worries about incomplete tumor resection and local contamination (Figure 50-9B).

◆◆ Allograft, Vascularized Fibular, and Prosthetic Implant Reconstruction

To give yourself the best possible chance of playing to your potential, you must prepare for every eventuality.
—Steve Ballesteros

Intercalary resection and reconstruction of primary upper limb malignancies after appropriate neoadjuvant chemotherapy is considered if there is an appropriately positive chemotherapeutic response, cell type and stage, and anatomic location that is amenable to reconstruction rather than amputation. Allograft, nonvascularized[14,15] and vascularized fibula grafts (alone, together, or in sequence if there is an allograft fracture),[16–19] endoprosthesis,[20,21] or composite grafts are used for reconstruction in various centers and for primary bone tumors (Figure 50-10). This is complex surgery, often performed in teams that utilize hand, orthopaedic oncology, vascular, and plastic surgery expertise. The orthopaedic oncology surgeon is obviously the leader and main decision maker with family and oncologist regarding care. Some double black diamond surgeons can perform all the roles, some more than one, and some need double black diamond surgeons for each element of the surgical care. Surgical care requires maximum preoperative planning; consultation; and certainty that all the necessary equipment, grafts, implants, and surgeons are available at the time of planned reconstruction. You have to expect

A

B1

B2

FIGURE 50-9 **A**: Elliptical incision for ray resection for epithelioid sarcoma. **B:** Full extension (B1) and flexion (B2) after ray resection. People do not count fingers, and the lack of five digits often goes unnoticed in public.

surprises and have the ability to adapt. It is the nature of this type of work. The ability to think clearly under stress is imperative. Having smart friends to think together with you helps a lot. Since each operation is different enough and extremely detailed, we will not go through all the surgical options here for each malignancy in each location.

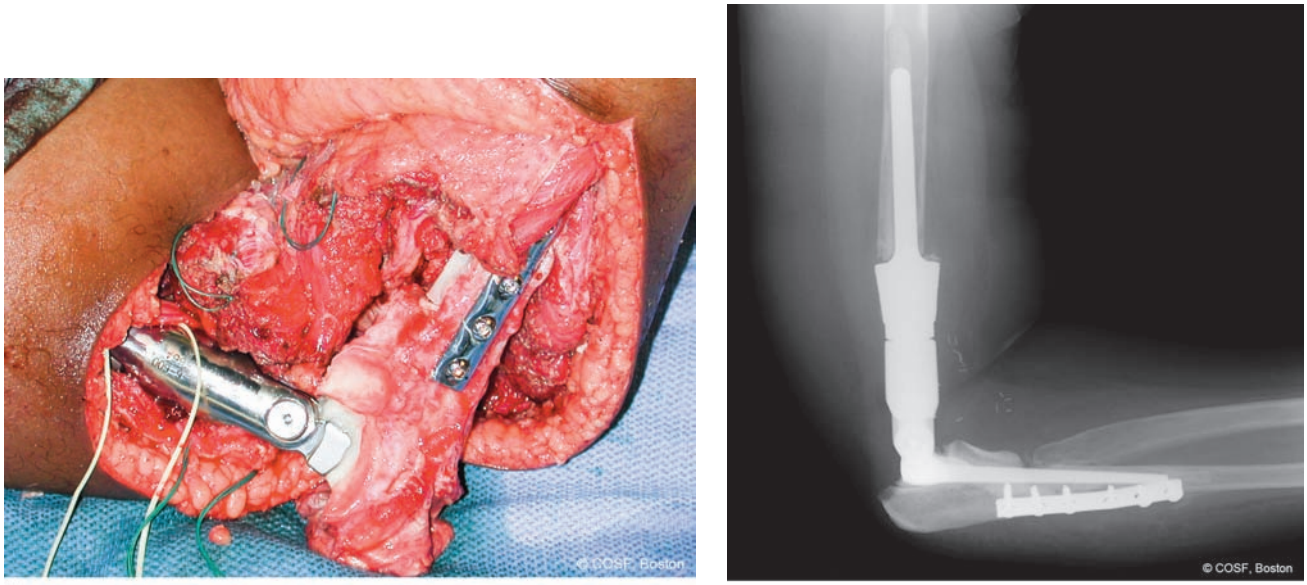
POSTOPERATIVE

The postoperative care varies widely depending on the lesion and reconstruction. Obviously, biopsy is simple wound care and maximum emotional support and knowledge exchange as you progress to treatment recommendations. Complex reconstructions require significant protection and highly skilled therapy to prevent complications from stiffness, functional loss, and fracture or dislocation. Systemic chemotherapy and local radiation can negatively impact wound healing.

ANTICIPATED RESULTS AND COMPLICATIONS

The real glory is being knocked to your knees and then coming back. That's real glory.
—Vince Lombardi

With appropriate patient selection and attention to diagnostic and reconstructive principles, malignancies may be diagnosed and treated in a timely fashion, offering the best



A B

FIGURE 50-10 **A:** Intraoperative composite reconstruction with allograft and hinged elbow prosthesis after resection of synovial sarcoma. **B:** Postoperative radiograph of composite reconstruction with allograft, hinged prosthesis, and radial head resection.

SIDEBAR

Vascularized Fibula for Allograft Fracture Nonunion

Intercalary segment reconstruction with allograft bone/joint, endoprosthesis placement, and composite reconstruction are among the limited number of choices for limb salvage surgery for primary bone tumor patients (predominately osteogenic sarcoma and Ewing sarcoma). The advances in MRI imaging and therapeutic chemotherapy have led to limb salvage surgery rather than amputation as the treatment of choice for primary bone cancers in most medical centers. The allografts are either strut or osteoarticular depending on the location, size, and histology of the tumor. Infection and allograft fractures are the major postreconstruction complications. Up to 25% of the allografts will develop a fracture nonunion. Some of the nonunions will respond to repeat internal fixation and cancellous and/or cortical bone grafting. However, many will require vascularized bone grafting to achieve bony stability and healing[24] (Figure 50-11). Successful vascularized fibular grafting of an allograft nonunion will lead to limb preservation, improved function, and pain relief. The vascularized fibula graft provides both mechanical stability and biologic stimulus for healing. Mechanical realignment surgery can occur at the same time as the vascularized fibular grafting.

FIGURE 50-11 Postoperative reconstruction of allograft fracture nonunion with intercalary segment vascularized fibular graft bridging allograft fracture nonunion in a patient with disease-free osteogenic sarcoma.

hope for disease control and limb salvage. While resection of pathologic lesions can be successful, serial clinical examinations and imaging are needed to monitor for recurrence. The worst complications are those that make patient survival or limb salvage less likely. These include missed or inaccurate clinical or radiographic diagnosis, poor biopsy techniques, incorrect pathologic diagnosis, local recurrence, and metastatic lesions due to untimely care.

Limb-length discrepancy and angular deformity both occur after limb salvage reconstruction. Distraction osteogenesis and/or angular corrective osteotomy may be indicated.[22]

Pathologic fracture can occur through the primary bone tumor, allograft reconstruction, or adjacent to the endoprosthesis. A pathologic fracture can lead to a more complex reconstruction with a vascularized fibula (see Sidebar), revision endoprosthesis, or composite construct. Pathologic fracture through the primary bone tumor does indicate a worse prognosis in osteogenic sarcoma.[23]

CASE OUTCOME

After extensive tumor board consultation and family discussion, a two-finger ray resection was performed to preserve pinch and grasp (Figure 50-12).

A

B

FIGURE 50-12 **A:** Intraoperative photograph of two ray resection for rhabdomyosarcoma. **B:** Postoperative wound closure after resection.

SUMMARY

Malignancy of the hand is very rare. Firm palmar lesions are of the highest concern. Rapidly growing masses warrant clinical and radiographic investigation including MRI and CT scan imaging. Parents are appropriately worried about malignancy when they feel and/or see a mass in their child's arm or hand. We need to be certain we accurately diagnose and treat all soft tissue and bony lesions.

COACH'S CORNER

What Is This Bump on My Child's Arm?

Inevitably when parents present with their child for evaluation of a mass, their spoken or unspoken worry is cancer. The child may have similar concerns. It is best to recognize their cancer concern openly and early. Most of the time, the differential and diagnosis are clear. History, physical exam, and plain radiographs are the cornerstones for evaluation for all musculoskeletal pathology. A thorough history, careful examination, and standard radiographic studies will eliminate most concerns on your and the families' parts.

Cost containment by limiting unnecessary MRI scans is a mandate in the present health care system. However, short of biopsy, MRI scan is the test of choice for diagnosis of worrisome masses and lesions. Table 50-2 contains a list and some associated figures of many of the nonmalignant and malignant lesions and masses that will present to you for evaluation. A clear understanding of all the benign and malignant possibilities will bring accuracy of diagnosis and proper treatment. The consultation then follows the correct discussion of either: "Most parents who bring their child in for evaluation of a mass like this are worried about cancer, but rest assured this is not a cancer. It is…." versus "I am concerned about this mass, and I advise we obtain an MRI scan to know more. Depending on the results of the MRI, I may have to consult with one of my partners who specializes in bone tumors."

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