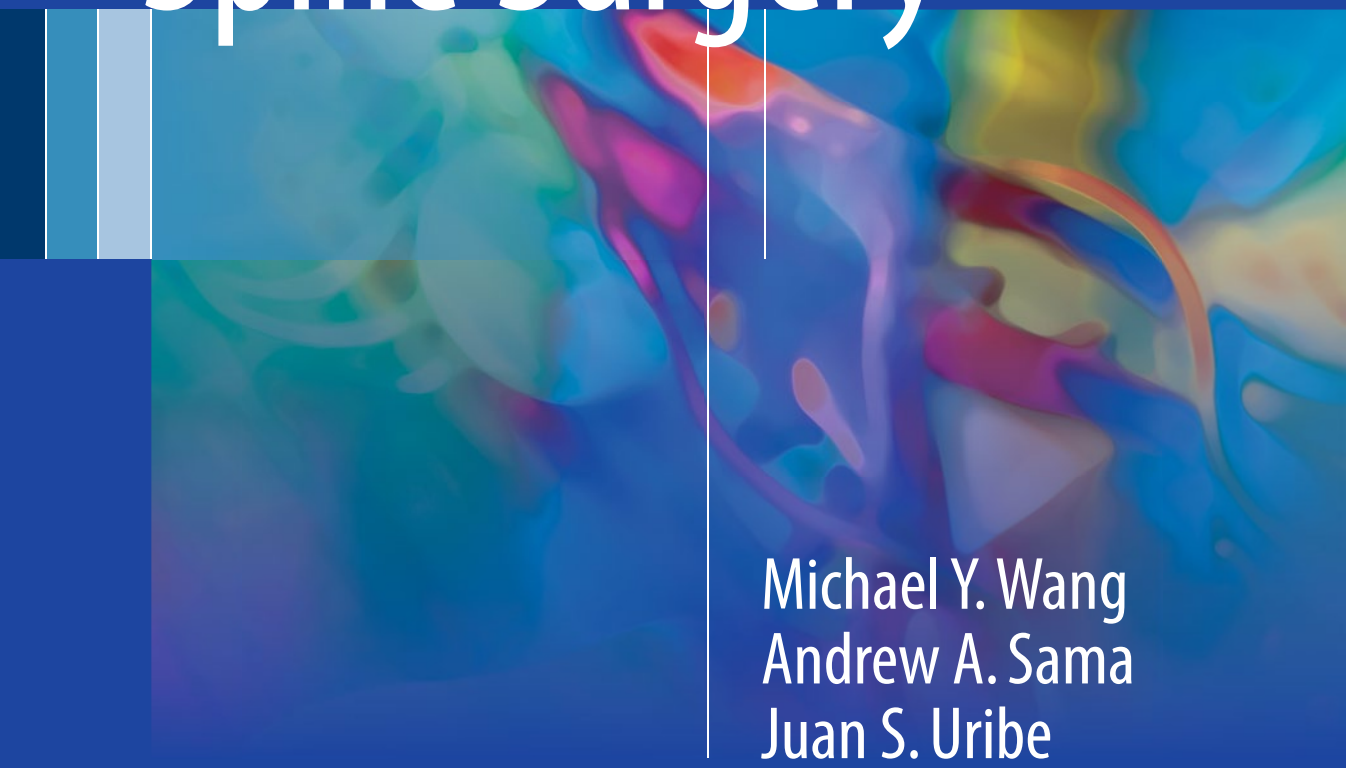
Lateral Access Minimally Invasive Spine Surgery



Michael Y. Wang
Andrew A. Sama
Juan S. Uribe
Editors

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Foreword

It is both an honor and a pleasure to introduce and highlight this excellent contribution in the field of spine surgery. Drs. Wang, Sama, and Uribe have assembled a world-class field of experts to describe the current understanding of the minimally invasive lateral approach to the spine. This truly novel technique has gained traction over the past decade and now clearly is part of the spine surgeons' armamentarium in the treatment of multiple spinal pathologies. The lateral technique has endured and stood the "test of time," with reproducible results improving patient outcomes in the properly selected patients. This technique has gained widespread credibility in degenerative, deformity, traumatic, and neoplastic conditions. With experience, surgeons are learning how to weave this technique into their skill set, how and when to apply it, and combine this technique with posterior open, minimally invasive, or hybrid posterior procedures.

The authors have chosen a cogent and thorough format to present these concepts. Foundational concepts are presented initially, with subsequent sections devoted to approach, navigation, and monitoring. Soft tissue pearls are addressed in great detail, as this technique is "all about the details." Individual pathologies are discussed, with a following section on technical nuances, complications, and their management. The authors clearly make the point that this technique requires strict adherence to detail, planning, and access to facilitate a reliable, reproducible outcome. The lateral technique has proven critical in obtaining spinal alignment, so critical of durable clinical outcomes.

My colleagues have approached this topic with honesty, highlighting current controversies and points of discussion. The lateral technique is here to stay. It is not experimental and can be safely performed by any surgeon willing to address the learning curve. However, there are "advanced" techniques, such as anterior longitudinal ligament sectioning, that carry potential significant complications, and thus should be done in the hands of experts. Like any surgical experience, as we gain more familiarity with the nuances of the technique, a greater facility will emerge; what was once unusual, will become commonplace.

In the past few decades, we have seen significant evolutionary transformations in spinal surgery: pedicle screws, cervical lateral mass screws, anterior spinal plating, navigation, etc., and it is clear that the lateral technique is transformational. This procedure, with both its simplicity and complexity, has clearly advanced the field of spinal surgery. "Knowledge is Power."

This text provides a great breadth and depth of knowledge about the current state of the lateral technique. With this knowledge, surgeons have gained greater control and power in taking care of our patients. That is why we practice medicine. This book is an excellent contribution to our field.

Atlanta, GA, USA Regis W. Haid Jr., MD

Preface

Traditional posterior spinal surgery has been criticized because of the extent of disruption of normal tissues in order to provide access to the spine. With the development of enabling technologies, less-invasive approaches to the spine have been established allowing for the ability to minimize damage to uninvolved collateral structures without compromising the ultimate surgical goals. Numerous studies have shown the value of less-invasive approaches not only in terms of reducing patient morbidity and expediting recovery but also in providing cost-effectiveness.

Over the past decade, lateral lumbar interbody fusion (LLIF) has been popularized as a less-invasive, tissue-sparring approach in the treatment of a variety of spinal disorders. Initially applied primarily for degenerative lumbar pathologies, the technique has evolved to be valuable in the management of spinal trauma, tumors, and complex spinal deformity. The technique has been shown to be versatile, reliable, and reproducible with an acceptable safety profile. Dr. Wang has assembled many of the experts and taught leaders in the field and has developed a long overdue text dedicated to the field of LLIF. *Minimally Invasive Lateral Spine Surgery* provides a detailed discussion of patient selection, surgical indications and techniques, and complication avoidance from many of the foremost "lateral" spinal surgeons. In addition, a frank assessment of the risks and complications of the procedure are presented. Wherever possible the authors have relied on the evidence base to discuss outcomes and shortcomings.

Lateral lumbar fusion is clearly "here to stay," and it is beholden on the proponents and experts in this field to provide teaching and instruction to those willing to learn. This book succeeds in that goal as well as in providing a valuable resource to surgeons experienced with LLIF. Central to discussion of any surgical technique is the patient who trusts the surgeon to make an evidence-based decision regarding the optimal solution for their particular condition. This is not lost on Dr. Wang who has done a terrific job of keeping the patient front and center in this book.

I believe that *Minimally Invasive Lateral Spine Surgery* should be read and studied not only by spine surgeons with a focus on less-invasive techniques but by all spine surgeons. LLIF has become an essential spine surgical option that should be a part of our armamentarium as we strive to optimize our patient care.

Chicago, IL, USA
May 3, 2016

Frank M. Phillips, MD

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Part I

Introduction

History and Rationale for the Minimally Invasive Lateral Approach

1

Luiz Pimenta, Luis Marchi, Leonardo Oliveira, Fernanda Fortti, Etevaldo Coutinho, Rubens Jensen, and Rodrigo Amaral

1.1 Introduction

The minimally invasive lateral approach, since its first technical report [1], has been shown to be a less invasive alternative to access the anterior column of the thoracolumbar spine, providing direct visualization of the spinal structures while reducing adjacent vascular, sympathetic, and visceral trauma associated with open anterior approaches. In addition, less blood loss, less postoperative pain, shorter hospital stay, and faster return to daily activities are associated with this technique [2–5]. The lateral approach has been utilized in an increasingly number of surgical indications. It was first described to treat low back pain associated with degenerative disc disease above L5 level, avoiding patients with severe central canal stenosis [6]. Over the years, indications were extrapolated, showing that indirect decompression of the neural structures can be achieved by disc height restoration [7], and ligamentotaxis can derotate the vertebral body, providing coronal alignment [8–12]. Other published indications, with or without posterior supplementation, are adjacent level disease, pseudoarthrosis, trauma, infection, sagittal alignment, spondylolisthesis revision surgeries, and total disc replacement [13–25]. The scientific evidence has been growing and being highlighted in high-impact publications in the literature, showing its advantages, efficacy, and safety related to this technique. These advances make surgeons responsible for learning and using these new techniques and technologies in order to provide their patients better clinical and radiological results with less complications.

1.2 Historical Approaches to the Lumbar Spine

The first description of a lumbar laminectomy dates from 1829, by Smith, to treat progressive paresis following a lumbar fracture [26]. Thenceforth, new approaches and surgical indications emerged in the literature, being the early reports of fusion published in 1930s [27] for the treatment of spondylolisthesis, what would later be called anterior lumbar interbody fusion (ALIF) [28]. This technique allows the surgeon to prepare a greater surface area, with better blood supply and better load distribution in comparison to the posterior column, essential in the process of fusion [29]. Obviously, the anterior approach has inherent

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Fig. 1.1 Comparison of cage contact area for PLIF, LLIF, and TLIF (*Left* to *right*)

disadvantages, as abdominal muscle dissection, mobilization of the great vessels and abdominal content, dissection of the presacral plexus, retrograde ejaculation, and urinary retention. An access surgeon is often in collaboration with the spine surgeon. Nowadays, the anterior approach progressed and the utilization of laparoscopic techniques allowed the surgeon to perform the surgery with smaller incisions, what is now considered a mini-open technique [30]. The procedure consists of blunt dissection of the abdominal musculature, manual dissection of the retroperitoneal space, while self-retaining retractors allows direct visualization of the anterior spinal column, enabling a large cage insertion for interbody fusion.

On the other hand, the minimalization of the posterior approach to herniated discs and spondylolisthesis have led to less disruptive techniques, in attempt to decrease tissue trauma and enhance clinical outcomes. Jaslow [31] and Cloward [32] initially described the posterior lumbar interbody fusion approach (PLIF) separately in the 1940s. This approach has the advantage to directly decompress the neural structures during interbody cage placement. However, it requires cauda equina retraction and higher risk of nerve roots injury [33]. A modification of this technique was proposed by Harms in 1982 [34], with a unilateral approach that theoretically require less tissue trauma, less bone resection and dural retraction, called transforaminal lumbar interbody fusion (TLIF). Both PLIF and TLIF do not allow inserting large implants, generating less contact between the endplates and the graft, which may impair fusion (Fig. 1.1).

In an attempt to minimize tissue trauma and improve biomechanical support, an anterolateral retroperitoneal approach was described, with posterior dissection and retraction of the psoas muscle [35–37]. However, iatrogenic neural deficits and muscle hypotonia subsequent to lumbar plexus compression due to psoas retraction may occur [38]. The psoas traverse minimizes nerves compression, but carries an inherent risk of direct nerve injury. Early attempts to surpass this issue include evoked EMG monitoring, but with a 60-degree approach and patient in prone position [39]. This orientation routinely incarcerates nerves of the lumbar plexus, hindering safe access to the intervertebral disc and placement of intervertebral devices (Fig. 1.2). Nevertheless, this experience provided advances in the use of EMG monitoring in spine surgery, despite the little usefulness, safety, and effectiveness of this surgical approach.

1.3 Development of Lateral Access Surgery

The complications and technical challenges associated with anterior endoscopic surgery led to the development of a new trajectory to the intervertebral discs (Fig. 1.3). It was described as lateral endoscopic transpsoas retroperitoneal approach (LETRA) and was first presented in 2001 [40]. This technique utilized a blunt finger dissection of the retroperitoneal space, insertion of tubular portals with endoscopic visualization, but without EMG monitoring. The first clinical report on

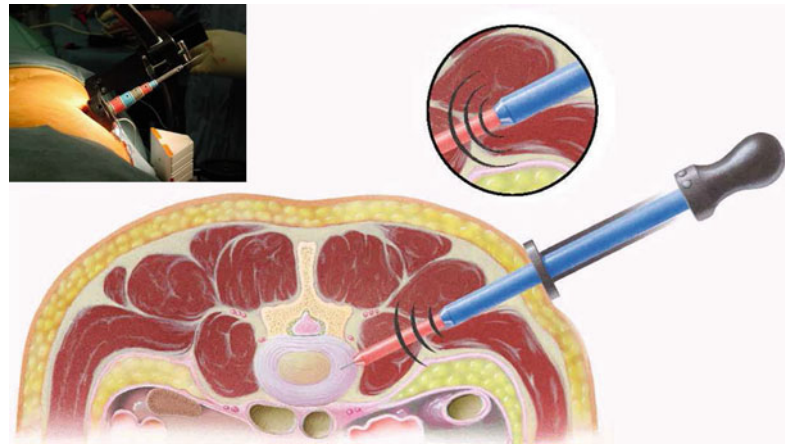


Fig. 1.2 60-degree approach with the patient in prone position, with routinely incarcerated nerves of the lumbar plexus during access

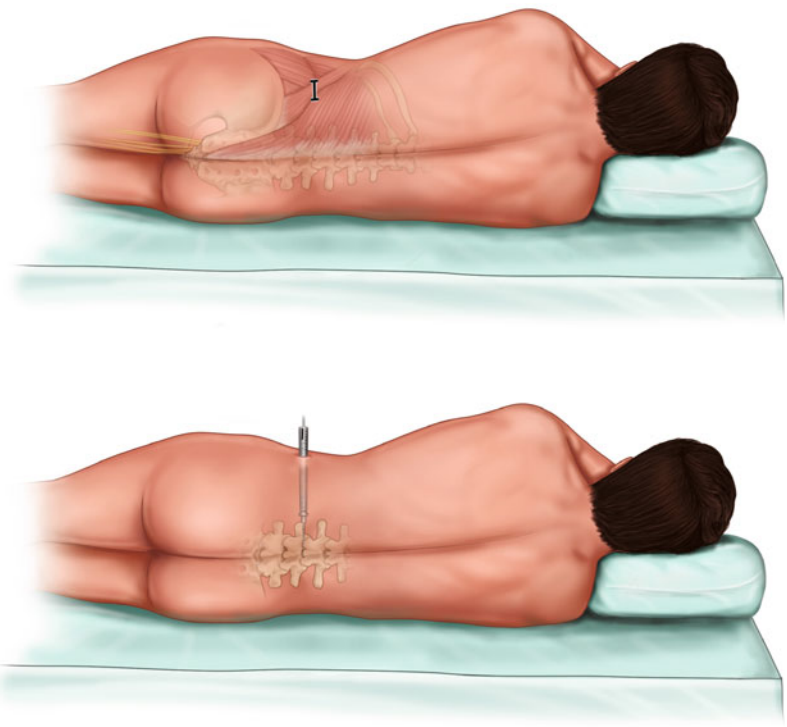


Fig. 1.3 Very first drawing of the initial idea of a 90-degree approach to the lumbar spine, what would become in the future the LLIF

85 consecutive patients has shown 14 % incidence of postoperative psoas weakness and 3.5 % incidence of slight thigh atrophy [1].

Thus, there was a need to develop tools that allow secure lateral access to the lumbar spine, overcoming the disadvantages and preventing iatrogenic neurological injuries. An expandable retractor was developed (NuVasive®, Inc., San Diego, CA) to provide direct visualization of the surrounding structures, improving visibility achieved by endoscopic viewing. To guide the passage through the psoas muscle, an EMG neuromonitoring prevented the blind traverse of the psoas muscle, protecting the integrity of the neural structures. Thereby, the lateral lumbar interbody fusion (LLIF) is defined as a 90-degree

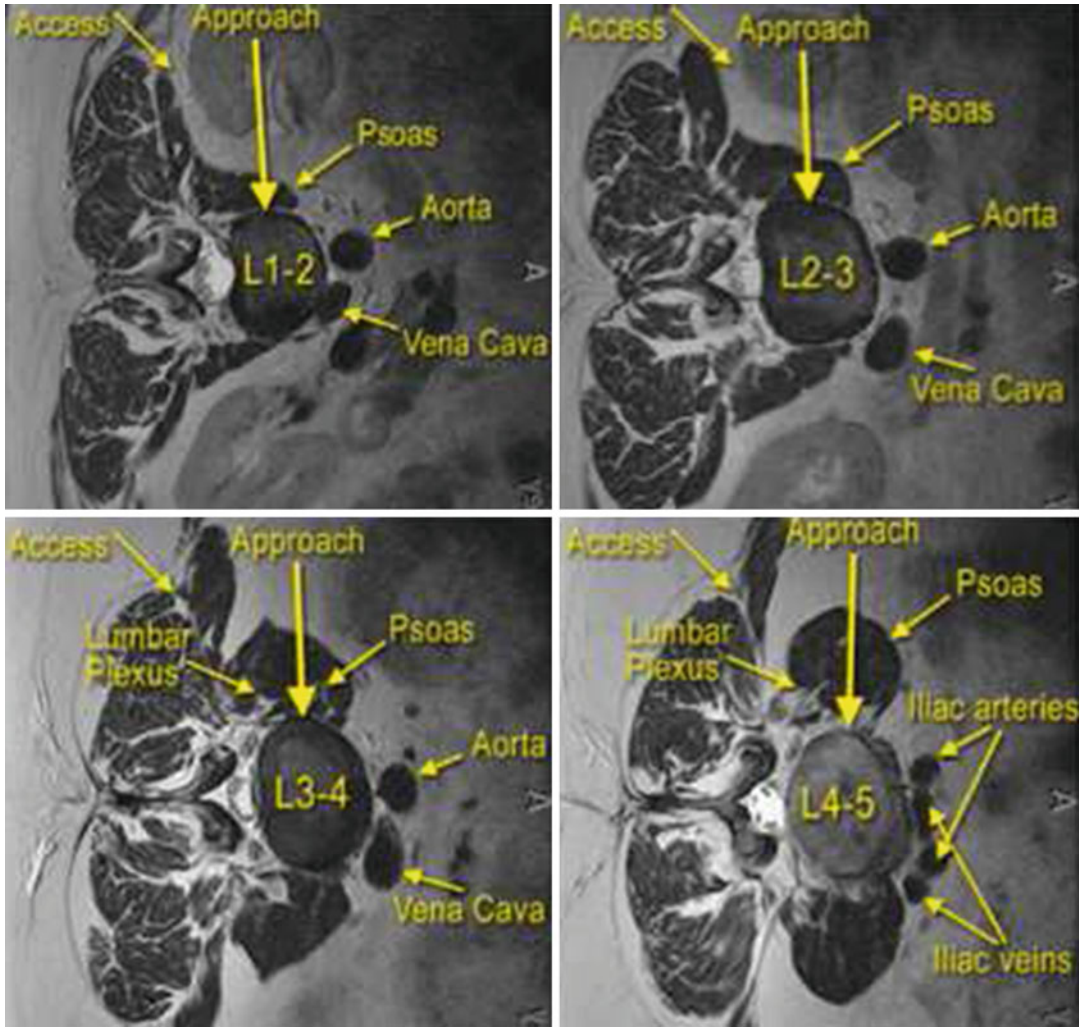


Fig. 1.4 Relevant anatomy for lateral access surgery of the lumbar spine

lateral, retroperitoneal transpsoas approach to the anterior spinal column, with minimum tissue trauma by use of blunt finger dissection of the retroperitoneal space and tactile guidance of the first dilator to the psoas surface. Figure 1.4 shows the relevant anatomy for lateral access surgery in lumbar spine. The utilization of a split-blade retractor generates a customizable working portal that allows direct visualization, with the opportunity to insert a wider cage implant in comparison to other anterior interbody devices. The bilateral annular release allows the device to reach both sides of apophyseal ring, generating a more stable construction and greatest biomechanical advantage. The technique also permits the restoration of the normal disc and foraminal heights, allowing indirect decompression of the neural structures through an anterior intervertebral fusion, correcting sagittal and coronal alignment, stabilizing the targeted level and facilitating bone ingrowth without the morbidity of open surgeries.

1.4 Validation of the Technique

The initial experience in lateral access surgery included less complex surgical indications, like 1- or 2- level interbody fusion for degenerative conditions [5, 41]. As the procedure maintains

intact all ligaments that play a role in ligamentotaxis, the slippage reduction in spondylolisthesis [16, 23] and vertebral derotation in degenerative scoliosis [10–12, 42], added to minimal collateral muscle and bone damage, with decreased risks and complications, demonstrated the superiority in several aspects of lateral access surgery over open traditional techniques [43].

The technical and technological advancement have led to the development of different tools and devices, expanding the range of indications. The polyetheretherketone (PEEK) spacers adapts on patient's necessities, with different width, length, sagittal angle, coronal angle, integrated fixation, like lateral plating that allow supplemental fixation by the same lateral approach, and advancements in working portal, allowing greater safety and effectiveness through better visualization of the targeted structures, minor damage to adjacent tissues, and greater integration with the new instruments. This leads to a more efficient surgery with less risks and complications for patients.

Since it first description, the published literature into lateral access surgery brought to light greater knowledge regarding applications and outcomes of the procedure. This includes dozens of peer-reviewed articles, and hundreds of abstracts and posters presented at the most important scientific meetings all over the world. These scientific evidences have allowed the expansion of surgical applications. Currently, the applications of lateral approach include pseudoarthrosis, discogenic low back pain, degenerative back and leg pain, trauma, infection, tumor, coronal and sagittal alignment, revision, spondylolisthesis, motion preservation, adjacent level disease, and others that require access to the anterior column of the thoracolumbar spine [15, 18, 20, 25, 44–52]. These results will be discussed throughout the book and so are not addressed in this present moment.

1.5 Future Steps on Lateral Approach

There is a continuous need in keeping medical education, maintaining efforts on development and research, and improving individualized patient care. Multicenter studies and data collection are essential for continued validation of new applications. The lateral approach extended the look on various pathologies of the spine, with more safety, effectiveness, and better clinical outcomes besides significant less morbidity. It is imperative that surgeons and medical societies continually assess the value of the care we deliver using methods that allow us to offer to our patients the best quality of care. This is the new environment that we live in, and we must always be up to date about new techniques and technologies and its validation in evidence-based medicine. The lateral access surgery has revolutionized how interbody fusions can be done, and the involvement of the spine surgeons will be critical in the continued advancement of this technique.

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Biomechanics of Lateral Spinal Reconstruction

2

Paul Porensky, E. Emily Bennett, and Edward Benzel

2.1 Introduction

The lumbar spine exists in a unique anatomical and surgical environment, with biomechanical and load-carrying characteristics distinct from those within the cervicothoracic spine. The ability to approach lumbar elements with a relatively facile lateral trajectory affords new augmentation and fixation opportunities. Though our understanding of lumbar biomechanics in both physiological and pathological settings is well appreciated, the vast majority of investigations of lumbar surgical intervention have evaluated posterior and anterior approaches. The growing popularity of lateral lumbar surgery will undoubtedly lead to additional lumbar biomechanical inquiry. A number of important questions need to be considered with respect to lateral surgery: defining the benefits of maintenance of posterior elements, the effects of disengaging load-bearing facets, and the outcomes of vertebral interspace height and alignment augmentation. The goal of this chapter is to provide a review of normal lumbar anatomy and biomechanics, as well to review and extrapolate what is already known to altered mechanics in the setting of lumbar pathology and lateral lumbar intervention.

2.2 Lumbar Anatomy

An understanding of lumbar spine anatomy is essential to both appreciate the relevant biomechanics in the physiological and pathologic settings, as well as to understand the effects of lateral surgery. A complex interplay of multiple elements defines the lumbar region, including osseous structures such as the vertebral body and endplate, strong and mobile facet joints, and active and passive soft-tissue components – including muscles, ligaments, and intervertebral discs. Select components contain mechanoreceptors, proprioceptors, and pain receptors that communicate with the central nervous system to maintain stability and avoid injury. The combination of these elements serves four main functions, including bracing viscera and the appendicular skeleton, nerve root and thecal sac protection, extremity control, and mobility. Each lumbar

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element must maintain stability, as well as support mobility and control. Our bipedal evolutionary trajectory has resulted in the development of structures that are capable of impressive force-resistance, as well as efficient and fluid movement. The lumbar spine is itself a widely mobile bridge to the lower extremities [1]. These lumbar structures not only carry a greater load than the cervical and thoracic spines but also lack the stabilizing effect of the ribcage and must support the oversized lever arms required to maintain upright posture [2].

2.2.1 Vertebra

The vertebral body is the basic functional unit of the spine. The five lumbar vertebral bodies are all comparatively more massive than their thoracic and lumbar counterparts, owing to their increased force-carrying requirements. The bodies themselves become progressively larger from cranial to caudal, with each level absorbing the majority of the rostral axial load strain. A honeycombed cancellous architecture, akin to the inner support of an airplane wing, achieves a high strength to weight ratio – approximately four times that of cortical bone. Vertical struts connect from one endplate to the other and absorb the axial loads; outward bowing is contained by orthogonally oriented transverse struts, thereby converting forces from vertical to horizontal [3]. Transverse elements also absorb shear forces. These oblique struts sweep together at the pedicles to resist the localized high tensile forces, then vertically to the facet masses where vertical forces are again deflected, and finally to the lamina and spinous process to resist further tensile and bending forces [1].

The ratio of cortical to cancellous bone is directly related to weight-bearing status, with a more complex cancellous arrangement within the body and facet masses and a greater cortical concentration at the pedicle [2]. Fortunately this arrangement provides greater pedicle screw pull-out resistance, with the notable exception of the sacrum. The pedicles assume a progressive increase in mass from rostral to caudal. The transverse diameter increases and the pedicle height progressively decreases as the spine is descended. The transverse pedicle angle also increases with more caudal direction, while the opposite is true in the sagittal plane [4, 5].

2.2.2 Intervertebral Discs

Intervertebral discs are specialized structures that have both the tension-resisting properties of a ligament and load-carrying element akin to joint cartilage [3]. Healthy discs provide spine mobility while also absorbing immense axial and shear loads. Each disc has two distinct elements, the nucleus pulposus and annulus fibrosus. The former, a remnant of the primitive notochord, is composed of water (a 90 % majority), collagen, and highly hydrophilic proteoglycans. The annulus is a circumferential bundle of laminated collagen sheets, each sheet overlaying the previous in a different orientation and fusing with adjacent layers [1, 6]. The annulus is most robust ventrally and weakest in the posterolateral margins. The disc is bounded cranially and caudally by vertebral endplates, each composed of a thin layer of cortical bone (~1 mm, though thinnest in the center adjacent to the nucleus pulposus) and hyaline cartilage. Healthy endplates are no longer perforated by vascular feeders by the age of skeletal maturity, though they become revascularized in the setting of discal degeneration. The discs, therefore, are the largest structures in the body that rely on diffusion for nutrition and metabolic exchange [7].

Axial loading results in increased intradiscal pressure. These hydrostatic forces are transferred to radial forces that are contained by the high tensile strength annulus as well as ridged and inelastic endplates [1, 2, 7]. Hyperflexion and torsional loading lead to maximal strain at the posterolateral annulus margins, which can result in progressive annular tear and subsequent back pain. Complete failure of the annulus leads to nucleus herniation and nerve root compression [1, 6]. Senescence of the disc complex includes progressive nucleus desiccation and stiffening of the circumferential annulus fibers, the combination

of which leads to altered load sharing and transference of forces to the facets and the disc-endplate periphery. Together with decreased bone mineral density and thinning of the cancellous trabecular architecture, weakened vertebral bodies can fail under stress and lead to compression fracture [2, 8].

2.2.3 Facets

The facets are diarthrodial joints that extend bilaterally from the lamina to articulate with corresponding facets of the level above and below. These osseous pillars have opposing cartilage surfaces and a synovial connective tissue lining that provides lubrication to create a low friction environment [9]. A strong ligamentous capsule envelopes the joint. The capsule resists deformation, rotation, and translation, and a rich receptor innervation enables robust central nervous system communication to prevent joint overload or injury. The facets not only increase in mass from L1 to L5, but the orientation also progresses toward a more sagittal position with caudal descent (though the L5–S1 facet abruptly assumes a coronal orientation). Together they share in axial load bearing with the intervertebral discs, with 25% of the load transmitted through the facets in the normal spine and a greater percentage with disc pathology or lumbar extension [1]. The oblique lumbar joint geometry means that they are excellent stops to rotatory, translational, and lateral bending movements and are less effective during flexion [9]. The facets ultimately guide and constrain movement at adjacent segments to prevent motions that could put the disc and neural structures at risk [10].

2.2.4 Muscles and Ligaments

Lumbar muscles are intimately involved with coordinating the impressive degree of physiologic motion of the spine along with constraining motion to qualities and quantities that do not put anatomical structures at risk. Flexors include the psoas muscle, as well as indirectly the rectus abdominus muscle. The latter balances the long extensors, as well as creating a rigid cylinder around the spine by increasing intra-abdominal pressure and tensing the lumbodorsal fascia [3]. The lumbar extensors consist of the upper erector spinae (longissimus and iliocostalis lumborum) and lumbar erector spinae muscles (multifidus and lumbar portions of the longissimus and iliocostalis). The upper erector spinae muscle arises from the thoracic spine, spans the entire lumbar region, and inserts on the sacrum and posterior superior iliac spine. The lumbar longissimus and iliocostalis muscles have an oblique orientation which results in large posterior translation forces during lifting, counteracting ventral shear forces. The multifidus muscle consists of multiple overlapping fibers, with each fascicle arising from a single tendon connected to a spinous process and inserting on a caudal mammillary process, sacrum, and iliac crest. Multifidus muscle orientation and attachment points permit powerful extension and rotation [11].

A series of vertically oriented ligaments span dorsal and ventral vertebral segments. The posterior longitudinal ligament, supraspinous ligament, interspinous ligament, and ligamentum flavum resist hyperflexion. This latter ligament is infused with a high proportion of elastic fibers that resists buckling during extension. The anterior longitudinal ligament resists hyperextension through a continuous attachment along the ventral vertebral bodies and fewer attachments to the annulus fibrosus [4].

2.3 Lumbar Geometry and Stability

The various anatomical elements of the lumbar spine must interact seamlessly to ensure fluid and efficient motion while protecting adjacent structures from injurious forces and motions. Spinal stability, in essence, is the ability to safely engage in such physiologic movements; conversely, instability is defined by the inability to protect neural and mechanical elements under physiologic loads, leading to neural decline, incapacitating pain, or deformity [12, 13]. A stable lumbar spine is expected to maintain a lordotic posture,

engage in efficient energy expenditure during movement, participate in force transfer to control limb movement, and neutralize noxious forces. A three-component system works to maintain stability: passive tensile forces such as osseous elements, ligaments, facets, and intervertebral discs; active forces are the muscles and tendons that work to maintain position within safe ranges of motion; last is the system of peripheral to central receptors and nerves that coordinate such safe movement and attempt compensation for force stresses [3].

2.3.1 The Neutral Zone

Spinal stability is better understood when considering displacement of lumbar elements while subjected to increasing loads. Neutral posture and small but incremental load carrying is characterized by a zone of high laxity (flexibility) with low stiffness. The neutral zone (NZ) is manifest when movements are highly energy efficient, and ligaments, tendons, and muscles are under very little tension [4, 14]. As loads increase the terminus of the NZ is reached and the spine begins to stiffen, and individual spinal elements are placed under tension. Hence, a region of linear increase on the load-displacement curve known as the elastic zone (EZ) is entered. The EZ in a stable spine marks the end of pain and injury-free range of motion. The biphasic lumbar load-displacement curve, composed of the NZ followed by the EZ, allows for the dual and contradictory goals of movement and element protection (Fig. 2.1). The two zones permit energy-conserved motion and increase spinal stiffening near the terminus of physiologic motion; additional forces beyond these zones result in permanent deformation and eventually complete failure. Active spinal forces and central nervous system communication are taxed with maintaining posture within this range of motion [3].

Instability is thus further defined by a decrease in the capacity of spinal stabilizing systems to maintain the neutral zone within physiologic ranges, that is, within quantitative and qualitative ranges of motion that do not cause neurologic dysfunction, pain, or deformity. The neutral zone is naturally floppy. Rigidity for the maintenance of the upright posture is sustained by active muscle contractions. The neutral zone is therefore dynamic, with both physiologic and pathologic behaviors augmenting its size. Stretching or ligamentous, disc, or other passive system injuries, including destabilizing surgery, expand the zone. The lumbar musculature stiffens the spine to prevent injury. Core strengthening (including the strengthening of the lumbar musculature) shrinks the neutral zone, as does surgical fixation [12, 14].

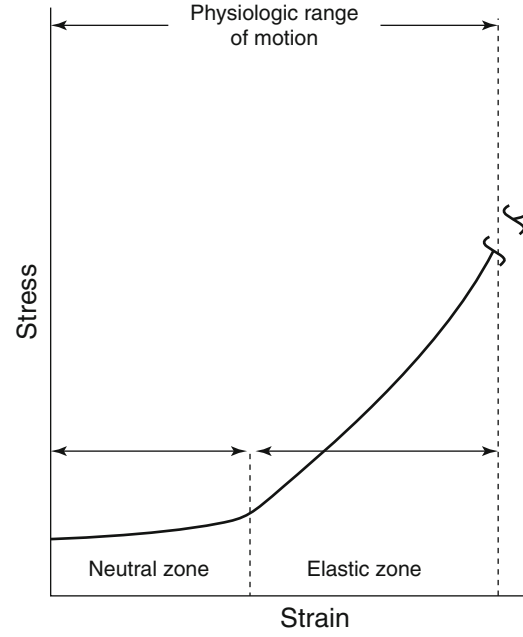


Fig. 2.1 A load-deformation curve illustrating the neutral and elastic zones (deformation or strain on the x-axis, load or stress on the y-axis) (With permission from Thieme Publishing, New York, NY; in Biomechanics of the Spine (editor/author: Edward C. Benzel), 2001)

2.3.2 Bending Moments and Load Carrying

The maintenance of stability requires resistance to deforming forces. These can be divided into

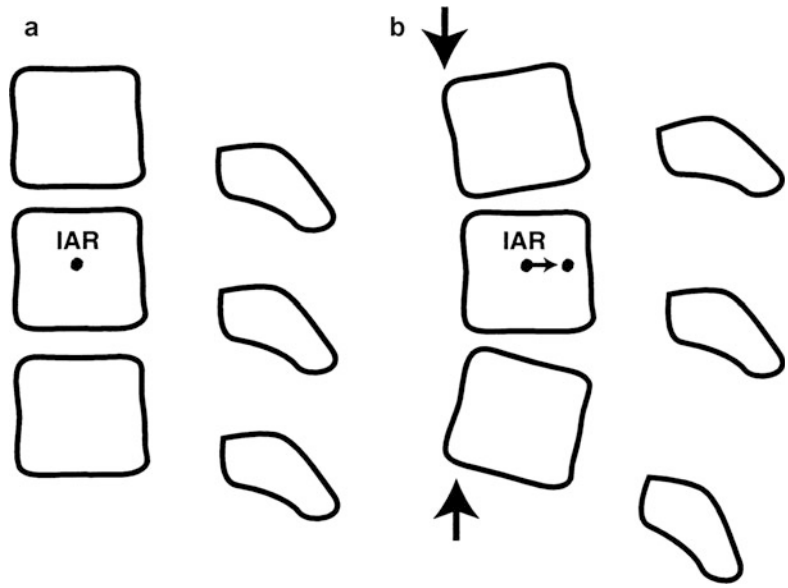


Fig. 2.2 Translation of the IAR from preload (**a**) to a more dorsal position (**b**) after application of a ventral bending moment (With permission from Thieme Publishing, New York, NY; in Biomechanics of the Spine (editor/author: Edward C. Benzel), 2001)

component force vectors that have a well-defined direction in space. To determine the effect of a vector on an individual vertebral body functional unit, the point at which the vertebral body pivots at any given time (IAR, instantaneous axis of rotation) and the orthogonal distance from the IAR to the force vector (the moment arm) are defined. When a spine segment moves, the IAR typically passes through or close by the vertebral body. The IAR is dynamic, moving dorsally with flexion in the sagittal plane and more ventral with extension (Fig. 2.2). Its position can be predicted with flexion-extension radiographs. There are twelve potential movements around each IAR, encompassing both translation and rotation with respect to the *x*/*y*/*z* axes [3, 12]. To determine the amount of force at a spinal level, one must calculate the force that a vector generates on the IAR by means of torque on the "imaginary lever" of the moment arm. The product of the moment arm length (*D*) and the vector force (*F*) applied to the moment arm is the bending moment (*M*) (Fig. 2.3).

$$D * F = M\left[12\right]$$

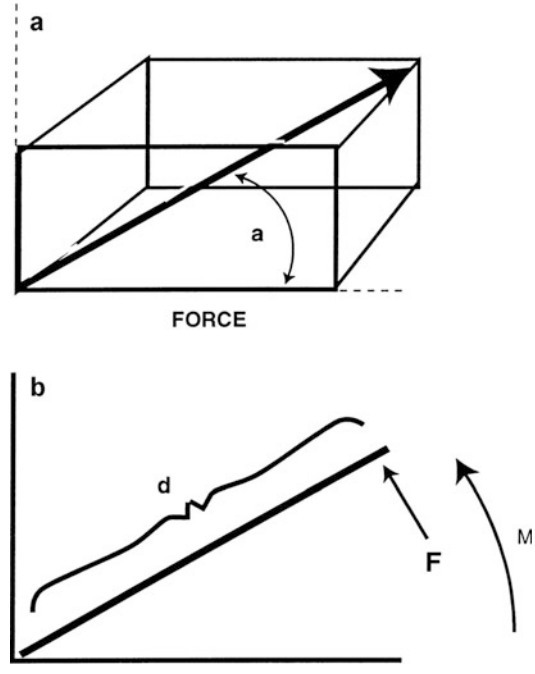


Fig. 2.3 (**a**) Force vector defined in three-dimensional space; (**b**) a bending moment (*M*) is created when a force (*F*) is applied at a distance (*d*) from a fulcrum (the IAR) (With permission from Thieme Publishing, New York, NY; in Biomechanics of the Spine (editor/author: Edward C. Benzel), 2001)

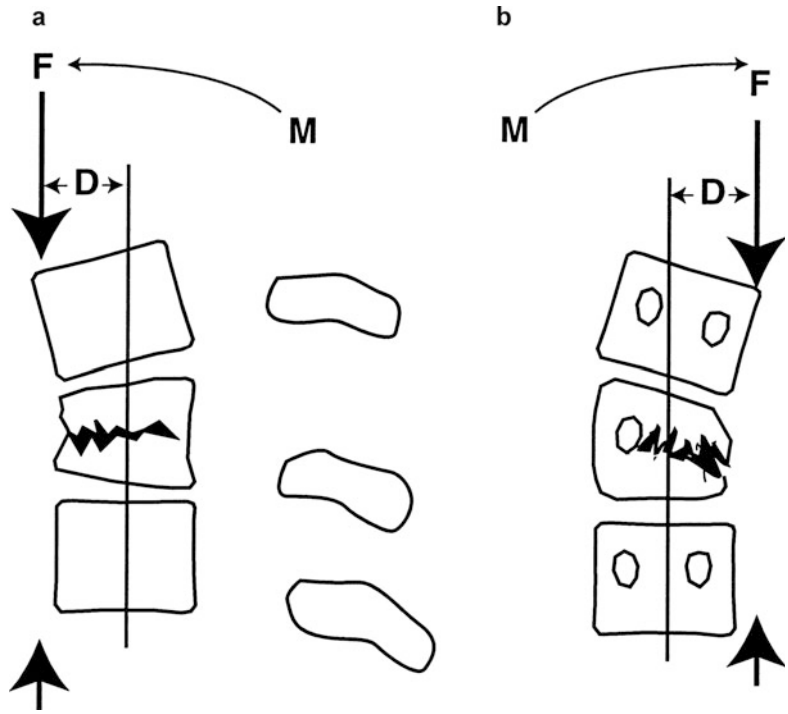


Fig. 2.4 The maximum bending moment (*M*, a product of force (*F*) and moment arm length (*D*)) is at the center of the circle created by the radius of its arc. (**a**) Lateral view of vertebral body failure from an excessive bending moment; (**b**) anteroposterior view (With permission from Thieme Publishing, New York, NY; in Biomechanics of the Spine (editor/author: Edward C. Benzel), 2001)

The bending moment results in rotation about the IAR. Counteracting forces positioned to produce bending moments equal in quantity though opposite in direction result in zero net motion, in keeping with Newton's second law of motion. The bending moments produced by forward flexion of the thoracic spine are counteracted by extension bending moments in the lumbar spine.

2.3.3 Lumbar Lordosis

The lordotic curve of the lumbar spine is an evolutionary adaptation to facilitate stability during upright posture and bipedal gait. Humans are born with a pan-kyphosis and assume cervical and lumbar lordosis with ambulation. The curves combine to center the trunk over the femoral heads and increase the resistance to vertical loads by deforming in ordered directions that are maintained by the active and passive spinal elements [3]. The exaggerated lordosis of the lower lumbar spine places the IAR in-line with major force vectors, resulting in only small bending moments. This protective factor results in a lower rate of fracture with supranormal forces; fractures that do occur here result in more pure axial loads and a higher relative rate of burst fractures. In contrast, the straightening and slight kyphosis of the thoracolumbar junction shifts the IAR dorsally and increases the subsequent flexion bending moment, imparting significant stress on the discs and anterior vertebral bodies. Supranormal vectors, as occurs during trauma or repetitive flexion, predispose to compression fracture and disc degeneration [12] (Fig. 2.4). Lumbar hyperflexion during lifting also shifts the IAR dorsally, drastically increasing the flexion bending moment. Together with offloading the facets onto already stressed discs and vertebral bodies, such posture considerably increases ventral shear forces and the potential to damage spinal elements at lower compressive loads [11].

Maintaining lumbar lordosis, or augmenting lordosis in the setting of a flat back, decreases the moment arm and ventral stress. Interbody lordotic cages or posterior osteotomies can achieve this effect surgically [15]. Furthermore, a greater flexion moment arm must be counteracted by the active and passive elements of lumbar extension

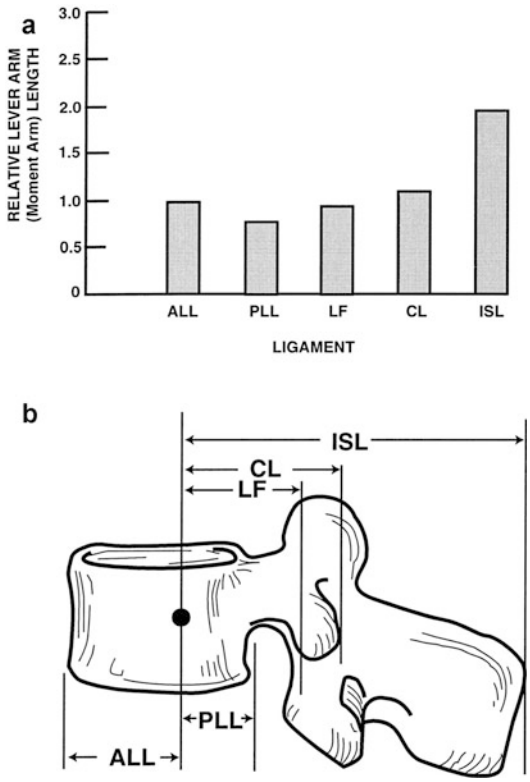


Fig. 2.5 The relative lever arm lengths of lumbar ligaments. (**a**) The moment arms of lumbar ligaments (yielding flexion or extension). (**b**) Ligament distance from the IAR. (*Dot* IAR, *ALL* anterior longitudinal ligament, *PLL* posterior longitudinal ligament, *LF* ligamentum flavum, *CL* capsular ligament, *ISL* interspinous ligament) (With permission from Thieme Publishing, New York, NY; in Biomechanics of the Spine (editor/author: Edward C. Benzel), 2001)

to maintain sagittal balance within the physiologic neutral zone. Posterior ligaments vary in their capacity to resist flexion based on their intrinsic strength and their moment arm length from the IAR. The supraspinous and intraspinous ligaments have superior mechanical advantage and a proportionally high bending moment compared to the PLL, and thus their disruption can lead to progressive kyphosis. Capsular ligaments have superior strength and a moderate-length moment arm [12, 16] (Fig. 2.5).

Lumbar muscular extensors are most efficient while in lordosis. Lumbar flexion reduces the lever arm length of the erector spinae and the muscles must operate at a mechanical disadvantage when resisting the forward flexion of the trunk. Sustained and more forceful contractions lead to inefficient energy expenditure and back pain, fatigue, and poor posture. Multifidus loses optimal fascicle orientation with lumbar flexion, impairing its ability to resist flexion, translation, and shear forces [11].

2.4 Biomechanics of Lumbar Pathology

Common lumbar pathology, including stenosis, degenerative disc disease, and spondylolisthesis, results in anatomic changes that alter normal biomechanics. Furthermore, traditional surgical interventions designed to treat these conditions can themselves disrupt mechanics and lead to progressive lumbar instability. Lumbar stenosis is a progressive degenerative process defined by canal, lateral recess, and foraminal narrowing. It is frequently a result of ligamentous and osseous hypertrophy in response to pathologic motion within degenerative lumbar functional units [17]. Direct decompression of effected neural elements is the treatment of choice, including laminectomy, laminotomy, and foraminotomy.

Degenerative disc disease (DDD) is one of the most common causes of low back pain. Several interrelated degenerative changes can lead to derangement of normal biomechanics, including annular tears, endplate fissuring and ossification, and loss of disc height through decreased water content and proteoglycan degradation. These degenerative changes increase the likelihood of nucleus extrusion, decreased weight bearing by the nucleus pulposus, and shifting of force carrying onto adjacent articular surfaces and facet joints [7]. Therefore, facet joint degeneration is almost always associated with or preceded by degeneration of the intervertebral disc [9]. Furthermore, decreased hydrostatic pressure diminishes tension along the longitudinal ligaments and inner annulus, compromising the ability of the disc to resist shear forces and forward displacement [18]. The lumbar discs and vertebral bodies are wedge shaped, and decreased disc height together with osseous compression in

weakened cancellous bone yields a progressive loss of lordosis. As described above, active and passive lumbar extensors function most efficiently in physiologic lordosis. DDD not only results in pain at the overloaded facets and deranged endplate but also from progressive kyphosis and the biomechanical disadvantage of overburdened lumbar extensor musculature. Surgical restoration of disc height and reestablishment of a lordotic curve addresses these pain generators.

Spondylolithesis describes the translational motion of one vertebral body on another. Classification includes dysplasia from a congenitally incomplete neural arch, traumatic, pathologic, isthmic, and degenerative. Pathologic and traumatic etiologies imply a localized trauma or generalized osseous condition that permits forward slip. Isthmic spondylolithesis is the result of pars interarticularis incompetence (spondylolysis), while a degenerative etiology is associated with facet joint spondylosis and DDD [19]. The latter is associated with an increased female prevalence and most commonly occurs at the L4–5 level [6]. From a biomechanical perspective, forward flexion increases shear stress on the ventral disc, which is counteracted by extensor muscles and ligaments. The application of these force vectors places a maximum amount of stress along the pedicle and pars, ventral disc, and facet; eventual failure of one or all of these structures results in translation of one vertebral functional unit over another. Progression of spondylolithesis is associated with disc degeneration and is highly correlated with loss of disc height [18]. Spondylolithesis is clinically manifest most commonly by mechanical back pain, and displacement of the neural arch can lead to compression of nerve roots and the thecal sac. Surgical intervention targets decompression and fixation/fusion to arrest and possibly correct listhesis.

2.4.1 Lumbar Surgery

Many biomechanical considerations should be appreciated during a posterior approach to the lumbar spine for decompression and posterolateral fixation and fusion [20]. Extensive soft-tissue dissection during exposure risks muscle denervation and disruption of the active stabilizing systems. Resection of the interspinous ligaments weakens the passive extensor stabilizers and diminishes their large bending moments that counteract flexion vectors. Facet capsules, associated with strong ligamentous complexes with moderate moment arms, resist flexion and are easily injured during exposure and decompression. The facet joints themselves are important for guiding and constraining motion as well as for axial load bearing. Excessive facet joint resection places increased loads on adjoining joints and discs and results in accelerated degeneration. Aggressive resection of the pars interarticularis disassociates functional units and increases shear stress on ventral structures, leading to iatrogenic spondylolisthesis (Fig. 2.6).

Because anterior column degeneration is a primary cause for spondylolisthesis, surgical management is aimed at restoration of anterior column support. Insertion of interbody spacers allows tensile strain restoration, disc height augmentation, correction of anterior column alignment, and subluxation reduction [21]. Indirect decompression of the neural foramen may also occur [22]. If posterior elements are also affected, as with isthmic spondylolysis, anterior interbody instrumentation must be followed by posterior instrumentation.

Traditional treatment options for lumbar interbody fusion include anterior lumbar interbody fusion (ALIF), transforaminal lumbar interbody fusion (TLIF), and posterior lumbar interbody fusion (PLIF). PLIF and TLIF use a posterior approach and therefore the biomechanical considerations of a posterior approach must be considered. Facet joint resection mandates posterolateral fixation and fusion to ensure stability. The ALIF approach spares the posterior elements, though sacrifices the anterior longitudinal ligament (ALL) when creating a ventral annulotomy. The ALL is a strong tension band in extension [4]. After disruption of this ligament, the PLL and dorsal elements alone must recreate this tension band effect, although placement of an anterior plate restores stability in extension [23]. Stand-alone interbody spacers risk over

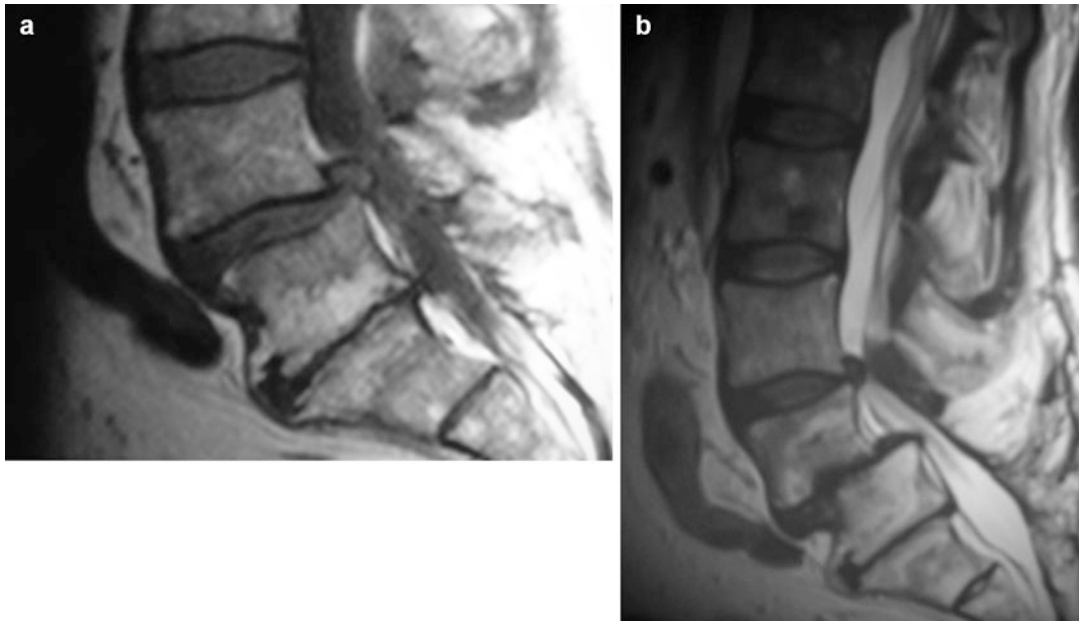


Fig. 2.6 Iatrogenic progressive L4/5 spondylolisthesis after lumbar laminectomy. (**a**) T1-weighted MRI prior to laminectomy; (**b**) T2-weighted MRI post-laminectomy

distraction of the facet joints, leading to shifting of load sharing ventrally and impaired resistance to forward flexion.

2.5 Lateral Lumbar Fixation

A lateral lumbar approach avoids many of the destructive changes that accompany anterior or posterior approaches [24] and may offer further biomechanical advantage by nature of the interbody graft and fusion. All three major tensile ligaments, including the ALL, PLL, and interspinous ligament complex, are left intact during dissection and discectomy, maintaining inherent stability. Denervation of the erector spinae muscle is circumvented, though the transpsoas technique does place temporary traction on a major lumbar flexor, the psoas muscle. The facet joint and capsule are not disturbed, thus avoiding iatrogenic instability from posterior bony element resection.

Lumbar spine biomechanics are augmented in several ways by the lateral interbody method. Placement of a large intervertebral graft with accompanying disc space distraction permits indirect decompression of the foramen and spinal canal via ligamentotaxis and unbuckling of the PLL and ligamentum flavum. Restoration of anterior column height and tensioning of the ligaments may reduce spondylolisthesis and restore physiologic lordosis [18, 21]. Correction of sagittal kyphotic deformity places each element of the vertebral functional unit into the most efficient orientation for maintenance of stability within the neutral zone; it also may reduce the incidence of adjacent level disc degeneration [11, 15, 25, 26]. Compared to other techniques, a larger interbody cage can be used that covers the entire transverse dimension of the endplate and creates a larger area for fusion [27]. Larger implants that cover greater endplate surface area may also reduce the rate of cage subsidence and the risk of ventral loss of height [28].

Restoration of disc height and fusion with a large interbody implant may be sufficient for correction of degenerative spondylolisthesis [21]. Conversely, an incompetent posterior ligamentous or osseous complex (i.e., spondylolysis) must be supplemented with dorsal fixation in order to avoid progressive instability [18, 20]. Cage shape, bone density, and simultaneous use

of dorsal instrumentation determine compressive strength of cages used in interbody techniques [20]. Cylindrical cages provide less implant-endplate contact area than rectangular grafts and therefore resist motion to a lesser extent than rectangular grafts [27, 29]. Since larger grafts create a larger surface area for fusion and provide more stability, rectangular grafts are preferred.

As mentioned earlier, excessive disc space distraction with an oversized interbody implant risks facet joint distraction and a diminished ability to resist flexion. Care must be taken to avoid this potentially destabilizing maneuver, and the goals of indirect foraminal decompression and disc height restoration must be balanced with the integrity of the facet joints. Supplemental posterior fixation should be considered to ensure a high rate of fusion [30, 31].

Conclusions

The lumbar spine relies on a complex interplay among ligamentous, osseous, and muscular structures to coordinate physiologic motion while maintaining stability. While many degenerative conditions alter normal anatomy and disrupt spinal biomechanics, surgical interventions can themselves accelerate instability during dissection and through aggressive decompression. Lateral lumbar exposures circumvent many of the lumbar stabilizing elements, thus avoiding much of the iatrogenic biomechanical morbidity of posterior and anterior approaches. Moreover, lateral reconstruction may offer further advantage through robust disc height restoration, reestablishment of lordosis through ventral lengthening, and a large surface area for fusion across the endplates.

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3 Physiologic Benefits and Impacts of Minimally Invasive Spine Surgeries

Gisela Murray, Chun-Po Yen, and Juan S. Uribe

3.1 Goals of Minimally Invasive Spine Surgery

Minimally invasive spine surgeries (MIS) are percutaneous or mini-open techniques utilized for spine decompression, fusion, instrumentation, or malalignment correction akin to their open counterparts with the benefits of reducing intraoperative blood loss, postoperative pain, infection, and complications. MIS surgery achieves these goals through minimizing dissection and crush injury to the paraspinal musculature and preserving posterior tension band. Introduction of tubular or expandable retractors and refinement of long and bayoneted instruments allow the spine surgeons not only able to perform the routine posterior decompressive procedures but also posterior lumbar interbody fusion (PLIF) or transforaminal lumbar interbody fusion (TLIF) [1, 2].

Another innovative breakthrough in the past decade is the minimally invasive lateral approach to the thoracic and lumbar spine utilizing the natural retroperitoneal or retropleural corridors [3, 4]. Originally used for degenerative spinal disorders, the lateral approach has expanded its indications to treat pathologies involving anterior and middle column of the spine such as trauma, neoplasm, and deformity. It replaces more morbid procedures, which often involve thoracotomy, laparotomy, or extensive posterolateral dissection [5–8]. Percutaneous pedicle screws and rods have been another powerful addition in the MIS spines surgeons' armamentarium to stabilize and realign the spine [9].

3.2 Physiological Benefits

Many physiological benefits have been described for MIS in general. The most important are reduced blood loss, lower infection rates, and soft tissue envelope preservation.

3.2.1 Blood Loss

This has been the most consistent benefit of the MIS. In a prospective study of 61 patients undergoing single level PLIF through MIS or open approach, the authors found no clinical or radiological difference between the groups at 1 year minimum follow-up. However, there was significantly less blood loss and a lower transfusion rate in the MIS group [10]. In our experience, the average blood loss for a single level lateral interbody fusion (LIF) is approximately 50 ml

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per level [11]. This benefit is more obvious when the technique is used in complex spine pathologies. For example, in the case of thoracic corpectomies, the published average blood loss for MIS ranges from 543 to 1,857 mL in contrast to 2,100–3,136 ml when open surgeries were performed [6]. In the setting of scoliosis surgery, the difference is also conspicuous. In a recent publication for surgical correction of adult spine deformity, MIS averaged 669 ml of blood loss vs. an average of 2,322 ml with open techniques [12]. Less blood loss leads to lower allogeneic blood transfusion and lower risks of transfusion related complications and hospital costs.

3.2.2 Decreased Infection Rates

In general, the infection rate after spinal surgery is 2–4 %. Minimally invasive techniques have been associated with a lower infection rate than their open counterparts [13]. In a meta-analysis, the cumulative incidence of infection was 0.6 % for MIS TLIF vs. 4 % for open TLIF [14]. For MIS LIF, the reported infection rate approaches 0 %. In the largest recent series of 600 patients undergoing LIF, none developed an infection [15]. In our most recent published series of MIS correction of scoliosis, there was no case of infection from the lateral approach [16].

3.2.3 Reduced Soft Tissue Disruption

The harmful effects of paraspinal muscle dissection and retraction are well known. It has been shown that the serum markers indicating muscle injury are significantly lower in MIS fusion patients [17, 18]. Imaging studies also demonstrated less muscle edema with MIS fusion compared to open techniques [19]. These imaging findings correlated clinically with less pain and disability in patients undergoing MIS fusion. Additionally, less paraspinal muscle injury can be associated with preservation of the posterior ligamentous tension band. Whether the advantage of preserving posterior tension band can reduce the risks of proximal junctional kyphosis remains to be investigated.

3.2.4 Pain Control and Recovery

Limiting soft tissue dissection is usually associated with less postoperative pain. The diminished postoperative pain can potentially yield other benefits, such as decreased postoperative narcotic use, earlier mobilization, shorter hospital stay, and a faster return to work. For example, in patients with mini-open lateral thoracic corpectomies, the time to mobilization was faster than in open technique. The median discharge was at 4 days postoperatively [6]. This is in contrast to the reported length of hospital stay for the same pathology but with open techniques ranging from 10.75 to 35.53 days. In a prospective nonrandomized study comparing patients undergoing MIS TLIF versus open posterior lumbar fusion, TLIF patients had statistically significant improvements in pain, stress, mood disturbance, and several quality-of-life indicators at 6-week follow-up compared to those from the open fusion group [20]. Immune profiles demonstrated that the TLIF group had a quicker postoperative recovery in CD-8 cells and that IL-6 levels increased substantially, possibly indicating more pronounced neuronal regeneration and healing [20].

Conclusion

Like other surgical specialties, minimally invasive approaches have gained popularity in spine surgery. The past decade has witnessed a rapid expansion of indications and advance in MIS technologies and techniques. The goals of MIS are to achieve or surpass the goals of open surgeries with minimal collateral damage. MIS techniques, however, have their own set of limitations and complications, and the benefits often come at the cost of prolonged surgical time and increased radiation exposure to the patients and surgeons. Careful patient evaluation, judicious selection of procedures, and meticulous surgical techniques are keys to obtaining satisfactory outcomes.

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Costs and Economic Implications

4

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4.1 Introduction

With the evolution of new technologies in spine surgery, there are increasing concerns of both effectiveness and costs. In 2012, US healthcare spending reached $2.8 trillion, or approximately $8,915 per hospitalized patient, up 175 % from a decade ago ($1.6 trillion) [1–4]. With the continued increases in healthcare expenditures, medical and surgical interventions are being increasingly scrutinized for their cost-effectiveness to both the patient and provider. Minimally invasive surgery (MIS) serves to lessen soft tissue injury and hasten postoperative recovery [1, 2]. This leads to less time in the hospital, fewer hospital-associated complications, and less pain medicine requirement, which all serve to lower both patient and provider costs. In addition, with hastened recovery, patients could potentially incur less indirect costs as they would return to work faster. While these results are suggested, there is limited evidence to support that these theoretical advantages are actually occurring. Specifically, high-quality reports have shown that despite the elimination of open procedure-related complications, new complications are associated with MIS [5, 6]. The goals of this chapter are to review the literature on costs and economic implications of the MIS lateral approach to the spine (which include extreme lateral interbody fusion [XLIF; Nuvasive, San Diego, CA], direct lumbar interbody fusion [DLIF], and lateral lumbar interbody fusion [LLIF]).

4.2 The Costs of Spine Surgery

In the value-guided era of healthcare, comprehensive cost analysis is paramount in guiding clinical decision making and patient care. The heterogeneity in costing methodology used in various studies leads to conflicting conclusions on the cost-effectiveness of an intervention for a specific diagnosis [7]. This heterogeneity includes variability between studies on whether both direct and indirect costs are calculated as well as whether the costs are being determined from the perspective of the hospital, the payer, or

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society. Specifically, costs from the hospital perspective include direct costs, costs of staff, supplies, utilities, and rent; however, the costs usually exclude those of the surgeon or anesthesiologist because those costs are covered by insurance companies. Costs from the payer perspective (e.g., insurance companies) include payments to the hospital and physicians (i.e., direct costs). Costs from the societal perspective include indirect costs in addition to the payer perspective direct costs [7]. The other area of heterogeneity that exists in the cost-effectiveness spine surgery literature is regarding the time frame in which costs are measured. High upfront costs associated with surgery may lead to the conclusion that surgery is not cost-effective in a 2–3 month or even 12-month time frame. Extending the follow-up time, however, to 2 years and beyond may allow for different conclusions [7]. MIS lateral fusion, similar to other fusion procedures, is associated with significant costs [8]. Given the recent popularity of this approach, it is important to ask if these costs are justified compared to open fusion procedures.

4.3 Comparative Effectiveness of the MIS Lateral Approach

Barbagallo et al. [8] conducted a systematic review to determine the comparative effectiveness of XLIF/DLIF/LLIF versus posterior lumbar interbody fusion (PLIF) or transforaminal lumbar interbody fusion (TLIF) in patients with degenerative spine conditions. Five studies were included. Patients who underwent LLIF experienced significantly less blood loss (two studies), length of stay (three studies), and mortality risk (one study) than patients who underwent PLIF/TLIF. For each additional level operated on via LLIF, there was a 59 % increase in the complication risk. Upon further analysis, no predictive factors on a worse prognosis after LLIF were identified. Overall, the authors concluded that insufficient evidence exists to compare the procedures. Of the evidence that exists showing that LLIF leads to fewer complications or reoperations than PLIF/TLIF, it is low quality. Given the paucity of evidence on outcomes of XLIF/DLIF/LLIF, assessing the procedure's cost-effectiveness is difficult.

4.4 Cost-Effectiveness of the MIS Lateral Approach

Only two studies have previously been performed specifically evaluating the costs and outcomes associated with XLIF/DLIF/LLIF [5, 6]. Deluzio et al. [5] performed a controlled cost comparison at a single institution between open two-level PLIF ($n=102$) and minimally invasive two-level XLIF ($n=109$) in patients with degenerative spine conditions. Costs included operating room (OR) services and "direct patient costs" and were retrospectively collected as actual hospital costs. These "direct patient costs" included transfusions, reoperations, readmissions, physical therapy, and additional diagnostics. The authors showed cost savings of 9.6 %, or about $2,563 per patient in the perioperative period ($24,208 XLIF, $26,771 PLIF), which was defined as the surgery and first 45 days postoperatively. This cost savings was due to significantly decreased hospital stay (1.2 days XLIF, 3.2 days PLIF) and decreased time in physical therapy. The same authors published a more complete version of their results 2 years later and found a statistically significant cost savings of about $2,800 between the cohorts. The study did not report on quality of life outcomes and, thus, was not a cost-effectiveness analysis.

Smith et al. [6] conducted a similar study ($n=202$) comparing ALIF ($n=87$) and XLIF ($n=115$) with a 2-year follow-up period. Patients who underwent either XLIF or ALIF (one or two levels) for degenerative conditions were identified retrospectively. Bilateral posterior pedicle screw fixation was used. Quality of life (QOL) outcome data included the visual analogue scale (VAS) for low back pain and Oswestry Disability Index (ODI), which were collected preoperatively, and at 12 and 24 months postoperatively. Total costs were estimated via individual hospital charges to patients and included room and board, OR time and services, labs, pharmaceuticals, and

physical therapy. The authors found a 10 % comprehensive cost savings (mean $10,152; $p < 0.05$) for the one-level XLIF cohort (mean $91,995 at 2-year follow-up) compared with the one-level ALIF cohort (mean $102,146 at 2-year follow-up). For two-level operations, the XLIF cohort (mean $124,540 at 2-year follow-up) experienced significant savings (mean $19,644; $p < 0.01$) compared to the ALIF cohort (mean $144,183 at 2-year follow-up). The most significant cost savings came from OR services, which was approximately $5,000 less in the one-level XLIF cohort (versus one-level ALIF cohort) and $10,000 less for the two-level XLIF cohort (versus two-level ALIF cohort). XLIF resulted in 38 % less operating room time, 67 % less blood loss, and 50 % faster hospital discharge compared to ALIF. The frequency of complications was also significantly less in the XLIF cohort (8.2 % XLIF vs. 16.7 % ALIF). Both cohorts showed significant ($p < 0.01$) improvement in all QOL outcomes measures, though there were no significant differences in any QOL outcome measure between cohorts. Patients in the XLIF cohort were significantly younger (mean 12.3 years; $p < 0.01$) and more had underwent prior lumbar surgery (38.2 %; $p < 0.01$) than patients in the ALIF cohort. Comorbidities were similar between groups. The study was limited in several respects. First, the authors used charges rather than true costs or reimbursements to the hospital. Second, indirect costs were not calculated. Finally, an incremental cost-effectiveness analysis was not performed. Nonetheless, it is likely that these additional calculations would not substantially alter the relative differences, and these data support the greater cost-effectiveness for the XLIF.

Cost-effectiveness analyses have been performed comparing various MIS procedures versus the respective open spine surgeries. In 2014, Lubelski et al. [9] conducted a systematic review of studies pertaining to cost-effectiveness of MIS versus conventional open spine surgery for the cervical and lumbar spine. There were only six studies identified (that met inclusion/exclusion criteria) that specifically compared the cost-effectiveness of MIS to open procedures for the lumbar spine [10–15]. Studies that did not include a quality of life component (i.e., costing studies) were excluded. No studies (meeting the inclusion criteria) were identified for the cervical spine approaches. Overall, the studies showed no significant difference between MIS and open surgeries in quality of life outcomes and, in many cases, costs. Follow-up periods were highly variable and cost calculations differed among studies, thereby limiting comparability among studies. The studies included comparisons between tubular discectomy and microdiscectomy, MIS hemilaminectomy and open hemilaminectomy, MIS P/TLIF and open P/TLIF, and MIS TLIF and open posterolateral fusion. The authors also identified studies showing significantly lower costs for MIS P/TLIF than open techniques. However, of studies including long-term outcomes, no differences existed in cost-effectiveness. Despite showing that MIS procedures lead to shorter hospital stays and decreased postoperative pain, the included studies lacked specific details on methodology and, most importantly, cost calculation. In addition, many studies originated from a single institution, which limits generalizability of the results.

Unlike some of the studies included by Lubelski et al., the MIS lateral approach studies (Deluzio et al. and Smith et al.) did show significant differences in costs between the MIS and open approaches. The difference in conclusions lies with the surgery, perspective, follow-up, and, most importantly, cost calculation method, which can vary by what is included in a total cost and the country in which the study was conducted. A lack of transparency in cost calculation methodology compounds the difficulty in reaching a conclusion on cost-effectiveness of one procedure over the other.

4.5 Future Directions

Currently, studies evaluating the costs and cost-effectiveness of lateral MIS approaches are sparse. As such, it is difficult to ascertain the value of XLIF/DLIF/LLIF. For minimally invasive lateral spine surgery to be accepted as a cost-effective alternative to conventional open

fusion procedures, studies specially evaluating cost-effectiveness, rather than costs alone, must be performed. Investigators wishing to conduct a cost-effectiveness analysis should ensure that their analysis is both transparent and comparable to other studies. Based on the Panel on Cost-Effectiveness in Health and Medicine, a societal perspective (inclusion of indirect costs) and explicit definition of direct costs should be used in future cost-effectiveness studies. In addition, given the importance of long-term follow-up in spine care, studies should also try to obtain long-term cost data. Given the potential importance of the results of these cost-effectiveness studies to our healthcare system, it is vital that a standardized cost methodology be adhered to for proper interpretation by policy makers and the public.

Conclusion

There is a paucity of published data examining the cost-effectiveness of MIS lateral approach to the spine. Of those studies examining costs, the MIS lateral approach has been shown to achieve significant cost savings of around $2,500 in the perioperative period and $10,000–20,000 after 2 years (about 10 % savings for both time periods). However, the cost-effectiveness of the MIS lateral approach is unknown. Future studies are necessary to further evaluate the cost-effectiveness of MIS lateral approaches to the spine.

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Workup and Diagnostic Testing

5

William D. Long III, Federico P. Girardi, and Andrew A. Sama

5.1 Introduction

As surgeons have developed familiarity with minimally invasive lateral approaches, a greater variety of spinal pathology is now being addressed. Initial indications for the use of a lateral retroperitoneal corridor traversing the psoas were limited. Only patients with lumbago associated with degenerative disc disease without evidence of severe central stenosis were considered candidates for this technique [1]. Any evidence of central stenosis, moderate spondylolisthesis, or significant rotatory scoliosis eliminated the patient for consideration of this approach. Advancements in instrumentation and expertise in the anatomic nuances of the lateral spine have increased the indications to utilize this approach. In addition to degenerative disc disease, a number of other indications are now accepted with lateral techniques, including moderate spinal stenosis especially foraminal stenosis, degenerative scoliosis, nonunion, trauma, infection, and low-grade spondylolisthesis [2]. Contraindications to performing laterally based surgery on the thoracolumbar spine include severe stenosis, aberrant vascular anatomy, high-grade spondylolisthesis, previous retroperitoneal surgery, and severely collapsed disc spaces and ankylosis of the facet joints at the target levels. The initial evaluation of patients being considered for lateral spine surgery begins with a thorough understanding of the approach itself, which will be discussed in detail in section II of this book. Lateral decubitus positioning, neuromonitoring, fluoroscopy, and soft-tissue management are all essential to a successful outcome using this technique.

5.2 Patient History

Like any patient being considered for spine surgery, the initial workup begins with a thorough history to ensure the appropriateness for surgery and failure of conservative measures. Proper questioning of the patients can yield greater diagnostic value in ascertaining spinal pathology [3]. In addition to ascertaining the patient's pain and neurologic symptoms pertaining to the spinal pathology in question during the history, particular attention must be given to possible characteristics that make them poor candidates for the lateral approach. For example, placement in the lateral decubitus position with the operative table jack-knifed may not be well tolerated by morbidly obese patients or those having

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undergone complicated hip or pelvic surgery. Certain demyelinating diseases, neuropathies, or myopathies may make utilization and interpretation of electromyography (EMG) difficult, thus placing the lumbar plexus more at risk during the dilation through the psoas. Spinal pathology at the L5–S1 level or cephalad to the thoracolumbar junction makes the approach more technically challenging due to the interference from the iliac crest and thoracic cage. Previous retroperitoneal surgery for renal disease or abdominal pathology may produce abundant scar tissue, making safe dissection to access the disc space difficult.

Attention to the details that put the patient at greater risk for nonunion or complications [4] should also be addressed during the history taking, such as tobacco use, uncontrolled diabetes, and osteopenia. Knowledge of patient medication allergies can eliminate the possibility of anaphylaxis, particularly in regards to perioperative antibiotics. Patient medications must be reviewed, with particular attention given to anticoagulants, antihypertensives, and diabetic medications and other medications that may contribute to osteoporosis.

5.3 Physical Examination

The physical examination of the patient should be comprehensive, and address multiple organ systems to ensure the patient can tolerate the rigors of the surgery. Many times medical clearance is obtained from the primary care physician or an internist/cardiologist, ensuring that the patient is medically optimized prior to receiving general anesthesia and surgery [5]. A focus of the exam is again keyed on identifying patients that would be poor candidates for the lateral approach to the spine. A standard neurological examination that tests all levels of the lumbar plexus in order to identify the presence of neural injury (sensory loss, weakness, myelopathy) is critical to establish a baseline preoperatively. As hip flexion and knee extension weakness can be common in the postoperative setting following lateral spine surgery, it is important to grade the myotomes in accordance with the American Spinal Injury Association (ASIA) scale both prior to and after surgery. Reflex testing and checking for upper motor neuron signs provides a thorough look at the neurologic condition of the patient prior to surgery. Noting any preoperative lower extremity muscle atrophy is also important. Inspection and palpation of the abdomen and back will ensure the absence of incisions or hernias. Ranging the lumbar spine through flexion, extension, and rotation may provide the physician some clues as to the flexibility of the thoraco-lumbo-pelvic junctions.

5.4 Adjunctive Tests

Serologic studies are important to obtain prior to surgery. Complete blood count (CBC) and coagulation studies (PT/PTT) are frequently obtained in order to demonstrate adequate red blood cell volume and the absence of coagulopathy. Routine chemistries can uncover electrolyte imbalance and kidney dysfunction as well as the possibility of previously unappreciated type 2 diabetes mellitus. Electrocardiograms (ECG) are commonly obtained to check for the presence of arrhythmias.

5.5 Preoperative Evaluation of the Pain Generator

Once the decision has been made that a patient is a surgical candidate, the clinician can use the nuances of the history and physical exam aspects of the patient encounter to localize the probable source of the patient complaints to a specific dermatome or myotome. This sometimes allows a more focused surgical approach to address the patient's complaints in the context.

5.6 Radiographic Studies

Radiographic evaluation should include x-rays to ascertain the thoracolumbar and pelvic bony anatomy for counting purposes and identify the

presence of sagittal or coronal plane deformities. If a multilevel approach is being considered for the correction of coronal or sagittal deformities, preoperative standing AP and lateral scoliosis x-rays, left and right bending scoliosis films, and lumbar flexion and extension views should be obtained and the appropriate measurements rendered to consider viability of the procedures ability to achieve the desired correction of deformity. The feasibility of approach for any given level and the desired side for the approach can also be planned based on the level of the iliac crest as seen on the AP and lateral standing and scoliosis x-rays. At times the position of the crest or ribs can also be assessed on the left and right bending scoliosis x-rays to estimate whether bending the operating room table will allow easier access.

Since the lateral technique requires a decision on which side to approach the spine from, coronal plane deformities may influence the decision for the position; working on the concavity may allow access to multiple levels through the same incision with adjustment of the retractor in a wand-like fashion. Approaching from the concavity of the lumbar degenerative curve also typically allows access to the L4–5 level if needed. Flexion-extension films of the lumbar spine can demonstrate the presence of a dynamic spondylolisthesis or instability, as well as the presence of vacuum phenomena of the disc spaces with extension that may suggest a better likelihood of correction of disc space height with an interbody approach.

Computed tomography (CT) of the spine can help to better identify the three-dimensional anatomy of the bone and the relationship of adjacent soft-tissue structures such as the major viscera and blood vessels. Anomalous intra-abdominal or retroperitoneal structures such as a horseshoe kidney or duplicated ureter can be identified with contrast CT imaging. CT imaging also allows assessment of the boney architecture of the spinal segment such as an evaluation of facet ankylosis and an analysis of the paucity of bone trabeculae in the vertebral bodies suggesting osteoporosis which may give the surgeon pause in considering an interbody approach to the correction of the disc collapse and sagittal or coronal deformity. Alternatively, the presence of subchondral sclerosis of the endplates seen on CT scan may lend confidence to surgeons plan for intradiscal distraction with lower risk of endplate fracture. The coronal reformat of the CT scan provides yet another planning tool to help decide on side of the approach as well as a better assessment of the presence and location of lateral osteophytes which may come into play when docking a lateral retractor or planning a release of these boney tethers to correct a deformity.

Magnetic resonance imaging (MRI) can clearly delineate the neurologic structures within the spine, identifying nerve roots and their position within the foramen and subsequent trajectory. MRI nicely demonstrates the size and location of the psoas muscle and can be utilized to identify abnormal visceral anatomy within the retroperitoneal space. Magnetic resonance neurography is now being utilized preoperatively to map the location of the plexus in relation to the lateral approach [6, 7]. Axial cuts of the MRI scan through the lumbar spine also allow assessment of the position of the aorta and inferior vena cava as well as the iliac vessels and any possible atypia in their positions that may increase the risk of the anterior or lateral approach to any given segment of the spine.

5.7 Summary

The lateral transpsoas approach to the lumbar spine is becoming more commonplace. Careful patient selection can eliminate some of the technical difficulties one may encounter while using this approach. A thorough history, comprehensive physical exam, and thoughtful radiographic evaluation should provide the spine surgeon with the tools needed to successfully utilize this technique.

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Literature Evidence of the MIS Lateral Approach

6

Jim Youssef, Douglas Orndorff, and Sue Lynn Myhre

Minimally disruptive approaches continue to gain adoption by spine surgeons in the hopes of minimizing soft tissue damage and accelerating postoperative recovery [1]. Lateral techniques such as the extreme lateral interbody fusion (XLIF®, NuVasive, Inc., San Diego, CA, USA) are one of those minimally disruptive approaches. The XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) approach was first introduced in 2001 by Pimenta [2] and since then has gained acceptance and recognition as a spinal treatment.

Previous literature has proposed that XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) is a safe, minimally invasive surrogate to conventional open fusion techniques [3, 4]. Data from long-term, large-series studies have demonstrated fewer morbidities and complications than traditional open approaches [5–10]. However, one of the biggest concerns is neural complications within the psoas muscle due to the anatomical position of the lumbar plexus [11–16].

This chapter presents literature evidence of the MIS (minimally invasive surgery) lateral approach from level 1, 2, and 3 papers that included treatment characteristics, clinical and radiographic outcomes, and reports of complications. The chapter consists of two main sections: (1) patients with adult spinal deformity and (2) patients with degenerative conditions (spondylolisthesis, stenosis, disc disease, adjacent segment disease). Within each main section, four subsections are presented, which consist of (1) treatment characteristics, (2) clinical outcomes, (3) fusion success, and (4) complications.

6.1 Adult Spinal Deformity

A posterior-only or a combined anterior-posterior approach is a customary surgical technique for treating adult spinal deformity in the thoracolumbar spine. Typically, adult deformity patients undergo an anterior column reconstruction with interbody cage placement and bone grafting and subsequent posterior decompression, as well as the option of osteotomy and posterior arthrodesis [17–19]. Despite an accepted and effective surgical approach, these traditional open techniques have generally been affiliated with elevated morbidity and complications (blood loss, prolonged surgical times, infection, inadequate correction of sagittal/coronal balance), which has provided motivation for the evolution of less invasive surgical techniques to manage spinal deformity [17, 20–22]. Recently, XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) has been chosen as a less invasive alternative to fusion and reconstruction of the anterior column [6, 23–29].

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6.1.1 Studies

Three papers met the inclusion criteria for this section, including two level 2 papers and one level 3 paper (Table 6.1). The study and treatment characteristics are summarized in Tables 6.1 and 6.2, respectively. The reported complications and side effects and outcomes are outlined in Tables 6.3 and 6.4, respectively.

Table 6.1 Study characteristics for deformity

Author	Procedure	LOE	Control
Tormenti et al. [36]	X, TLIF	III	PLF
	PLF	III	X, TLIF
Isaacs et al. [32]	XLIF, L5S1	II	–
Phillips et al. [37]	XLIF, L5S1	II	–

LOE level of evidence (I-V)[170]
TLIF minimally invasive transforaminal interbody fusion
PLF posterolateral fusion
XLIF extreme lateral interbody fusion

6.1.2 Treatment Characteristics

Many of the inherent complications affiliated with a conventional anterior or posterior surgery are avoidable with the XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) approach [25, 30–32]. The literature has cited decreased blood loss, quicker recovery, and lower costs as advantages of a lateral surgery [10, 32, 33]. Isaacs et al. [32] reported an operative time of 177.9 min or 57.9 min per level. The length of stay averaged 2.9 days for unstaged surgeries and 8.1 days for staged procedures. Estimated blood loss was minimal (≤100 mL) for the majority of patients (62.5 %), while nine patients did lose up to 300 mL. In comparison, results from traditional procedures have reported a much higher blood loss [34, 35]. Daubs et al. [34] demonstrated a mean blood loss of 2,056 mL (300–5,500). However, the average number of levels was twice that of Isaacs et al. [32] (4.4 levels vs. 9 levels).

6.1.3 Clinical Outcomes

Tormenti et al. [36] reported improved VAS (visual analog scale) scores for both the combined XLIF and posterior and posterior-only groups. The scores improved from 8.8 to 3.5 and 9.5 to 4.0 for the combined and posterior-only groups, respectively. These scores were not statistically significant between groups. The average follow-up period was 10.5 and 11.5 months for the combined and posterior-only groups, respectively. Unfortunately, the sample sizes were very small for each group (8 = combined and 4 = posterior only), and VAS scores for only six of the eight patients in the combined group were available.

Phillips et al. [37] demonstrated significantly better ODI (Oswestry Disability Index), VAS back and leg, SF-36 MCS (36-Item Short Form Health Survey Mental Component Summary), and SF-36 PCS (36-Item Short Form Health Survey Physical Component Summary) scores between presurgery and 2-years postsurgery ($p<0.001$). Additionally, a high percentage of patients (85 %) were very satisfied with their outcomes and 86 % declared they would be willing to do the procedure again. Although the sample size was fairly large, only 77 % of the patients were accessible at the 24-month follow-up.

6.1.4 Fusion

Previous literature has demonstrated a revision rate for pseudarthrosis ranging from 0 to 19 % for anterior plus posterior and posterior-only traditional approaches in deformity patients [38–42]. In contrast, Phillips et al. [37] showed a 2 % revision rate when pseudarthrosis was diagnosed. This small percentage of revision surgeries noticed after XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) agrees with prior studies who have reported high rates of fusion success [25, 28, 43, 44]. The authors believed that the high rate of fusion with XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) procedures most likely indicates the capacity to accomplish a complete discectomy and place a large cage within the disc space packed with more abundant bone graft within the interbody cage on the apophyseal ring of the end plate, as compared to transforaminal lumbar interbody fusion (TLIF) or

Table 6.2 Treatment characteristics for deformity

Author	Indication	Anterior levels	Levels	Internal fixation	# of posterior levels	Total n	Mean follow-up	ORT (mins)	EBL (mL)	LOS (days)
Tormenti et al. [36]	Scoliosis	2–5	L1–L5	BP	6–12	8	10.5 months	–	–	–
	Scoliosis	1–3	L2–S1	BP	4–11	4	11.5 months	–	–	–
Isaacs et al. [32]	Scoliosis	1–6	T8–S1	Mixed	0–9	107	6 weeks	178	50–100	3.8
Phillips et al. [37]	Scoliosis	1–6	T8–S1	Mixed	0–9	82	24 months	–	–	–

ORT operating room time; EBL estimated blood loss; LOS length of hospital stay

Table 6.3 Complications and side effects for deformity

Author	Minor (%)	Major (%)	Transient thigh sensory symptoms (%)	HFW (%)	Motor neural (%)	Reops (%)	Total comps (%)
Tormenti et al. [36]	–	–	75 %	–	–	–	150 %
	–	–	–	–	–	–	–
Isaacs et al. [32]	15.9 %	12.1 %	–	36 %	–	–	24.3 %
Phillips et al. [37]	–	–	–	–	–	–	–

Table 6.4 Outcomes for deformity

Author	Fusion (%)	VAS decrease (%)	ODI decrease (%)	Outcome satisfaction (%)	Redo (%)
Tormenti et al. [36]	–	60.2 %	–	–	–
	–	57.9 %	–	–	–
Isaacs et al. [32]	–	–	–	–	–
Phillips et al. [37]	–3.4 points	–	–	85 %	85 %

ODI Oswestry disability index

posterior lumbar interbody fusion (PLIF) surgeries. However, due to poor radiographic visualization, 10 % of patients were not able to be assessed for fusion, and at the latest follow-up of 12 months (range: 12–36 months), 58 % had a solid fusion, 39 % had a partial fusion, and 3 % showed no consolidation. Additionally, 8 % of patients demonstrated nonfusion at ≥1 level. The length of follow-up for the fused patients as compared to the nonfused patients was not provided in this study. Also, 10.6 % of the patients were documented as smokers. Smoking has been shown to affect outcomes and fusion [45, 46]. The authors did state that fusion status was influenced by fixation method. Thus, solid bridging was greater in those with bilateral pedicle screw supplementation compared to those with either a stand-alone XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA), lateral supplementation, or unilateral pedicle screw fixation.

6.1.5 Complications

Isaacs et al. [32] reported 14 major complications for 13 (12.1 %) of the 107 patients, 2 of which were classified as major medical and 12 were categorized as major surgical. Overall, 21 surgical complications occurred in 16 patients, 9 of which were minor, and 16 medical complications among 11 patients, 14 of which were minor. There were no infections with stand-alone XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) as well as when posterior instrumentation was completed minimally invasively. However, three early reoperations ensued due to deep wound infections, which were related to the open posterior instrumentation approach. Prior minimally invasive studies have demonstrated fewer infections compared to published rates for traditional open techniques [47–49]. Furthermore, it was shown that patients with open posterior fixation had

both a significantly higher incidence of any complication ($p=0.02$) as well as a major complication ($p=0.04$) compared to individuals with percutaneous posterior fixation. In a subsequent publication, Phillips et al. [37] reported that 13 patients needed a supplementary surgical procedure. Reasons for the additional surgeries included pseudarthrosis, treatment at adjacent segments, and posterior-only procedures.

Tormenti et al. [36] demonstrated an unusually high number of complications including bowel perforations, incidental durotomy, pleural effusions, pulmonary embolism, ileus, junctional kyphosis, and a wound infection. By the 11.5-month follow-up, no infections or indications of hardware failure were seen. The authors noted the nature of the scoliotic spine greatly enhances the risk of complications to the intra- and retroperitoneal anatomy. Additionally, the very small sample size should be taken into consideration when interpreting these results. Despite these results [36], traditional approaches do seem to report much higher complication rates than minimally invasive techniques. For instance, Pateder et al. [50] reported a complication rate as high as 45% for deformity patients that underwent traditional surgery, and Fujita et al. [35] demonstrated rates up to 66%.

Compared to traditional procedures, the fewer complications documented for lateral surgeries are likely due to the method of the lateral approach. The lateral technique is able to circumvent several of the related complications seen with open anterior surgeries, since the abdominal vasculature, ureter, and peritoneal cavity are not manipulated [37]. Along those lines, the prevalence of perioperative complications is reduced when walking and mobility occurs early after surgery [51]. Thus, patients who undergo a minimally disruptive lateral surgical procedure are more likely to have a shorter length of hospital stay and therefore ambulate more rapidly following surgery [37].

6.1.6 Neural Deficits

The lateral or XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) approach has both anatomical access advantages and disadvantages [12]. One of those disadvantages is the risk of injuring the lumbar plexus due to the transpsoas exposures [12]. As a result, it makes sense that motor and sensory weaknesses will be seen after an assortment of advances through the psoas muscle [32]. The addition of neural monitoring has helped guard these neural elements [12]. However, unlike motor elements, the lateral femoral cutaneous nerve (LFCN) or sensory elements are not identifiable by electromyogram (EMG) [12].

Isaacs et al. [32] reported that 33.6% (36 patients) of their sample had some amount of lower extremity weakness. The majority (29 patients) of those patients had isolated hip weakness, which as most likely the result of the placement of the retractors in the muscle to allow entry to the spine; and this was significantly associated with length of surgery ($p=0.03$). That is, patients with weakness had a longer surgery time compared to patients without weakness. However, for 86.2% of these patients, the weakness was temporary. Only seven patients had deficits that were categorized as a serious surgical complication either due to the weakness not being resolved within 6 months or the weakness declined more than two grades.

Tormenti et al. [36] reported two motor radiculopathies and six thigh paresthesias/dysesthesias. One patient had sustained motor radiculopathy at the 3-month follow-up, while the other resolved by two months postoperatively. At the latest follow-up, sensory radiculopathies had resolved in five of the six patients.

6.1.7 Conclusion

It appears that the XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) approach is a promising substitute to conventional approaches for treating adult deformity patients. Typically, these individuals are older with multiple medical comorbidities, which make them poor candidates for traditional open fusion procedures. Thus far, the trend in the literature has demonstrated significant improvements in treatment characteristics, clinical and radiographic assessments, as well as the occurrence of fewer complications in individuals

who have undergone a minimally invasive XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) approach in comparison to patients who underwent traditional surgeries [32, 33]. However, high-level evidence-based data is still needed to further clarify the effectiveness of the lateral technique for the adult deformity population.

6.2 Degenerative

The minimally invasive lateral approach has become a steadily popular approach to treating degenerative conditions including spondylolisthesis and fusion of the anterior column and provide indirect foraminal decompression [28, 52, 53]. Due to the increasing number of XLIFs (XLIF®, NuVasive, Inc., San Diego, CA, USA) performed each year, anticipated complications and their predictive determinants, as well as patient and procedural extenuating factors, need to be further identified and distinguished. Although the minimally invasive lateral technique has its benefits over conventional open procedures, there still seems to be some ambiguity about the total risk posed by this approach [54].

6.2.1 Studies

The studies reviewed in this section include one level 1 paper, one level 2 paper, and 13 level 3 papers on the use of XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) in treating a variety of degenerative conditions of the lumbar spine (Table 6.5). The study and treatment characteristics are summarized in Tables 6.5 and 6.6, respectively. The reported complications and side effects and outcomes are presented in Tables 6.7 and 6.8, respectively.

6.2.2 Treatment Characteristics: Estimated Blood Loss

As a result of being minimally invasive as well as the plane of the approach, the XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) technique has the upper hand over traditional open approaches. Minimal blood loss, fewer complications, shortened hospital stays, and faster recuperation and return to one's lifestyle have been documented [5, 7, 9, 28]. Overall, the mean estimated blood loss for an XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) procedure appears to range between 50 and 100 mL per level [12, 55–58].

In 2010, Rodgers et al. [8] showed that those who underwent an open posterior lumbar interbody fusion (PLIF) lost significantly more blood than those in the MIS cohort ($p<0.0001$). In addition, in the open group, 14 patients required a blood transfusion versus zero patients in the MIS group. In agreement with Rodgers et al. [8], others have also reported a significantly greater blood loss for the open groups compared to the MIS groups [1, 59]. Excessive intraoperative blood loss, as well as the need for a transfusion, have been shown to be meaningful risk factors for fostering untimely perioperative complications and increased risk of postoperative infections [8, 60–63].

Youssef et al. [10] also reported less blood loss for the XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA)-only group compared to the XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA)/posterior spinal fusion (PSF) group. However, this was anticipated due to the extra posterior procedure. Regardless, the overall mean blood loss was minimal (155 mL). In regards to special populations, Rodgers and colleagues [7] demonstrated that the estimated blood loss does not significantly differ between an obese and a nonobese patient ($p=0.16$).

6.2.3 Operative Time

The operative time for an XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) approach has been shown to range between 60 and 100 min per level [12, 55–57]. In comparison, the operative time for an open procedure has been demonstrated to last ~35 % longer than similar MIS procedures [1, 59]. However, in studies with patients who undergo multiple levels and combined approaches, it is only logical that higher operative times are reported [10, 58].

Table 6.5 Study characteristics for degenerative

Author	Procedure	LOE	Control
Pumburger (2012)	XLIF/cougar/SD	III	–
Cummock (2012)	X, D, axiaLIF	III	–
Knight et al. [12]	X, DLIF	III	–
Moller et al. [90]	DLIF	III	–
Kepler et al. [66]	XLIF	III	–
Lee et al. [91]	XLIF	III	–
Lucio et al. [1]	X, TLIF	III	PLIF
	Open PLIF	III	XLIF
Malham et al. [55]	XLIF	III	–
Marchi et al. [56]	XLIF	III	–
Pimenta (2013)	XLIF w BMP	I	SiCaP
	XLIF w SiCaP	I	BMP
Rodgers et al. [7, 8]	XLIF	III	BMI > 30
	XLIF	III	BMI < 30
Rodgers et al. [7, 8]	XLIF	III	PLIF
	PLIF	III	XLIF
Smith et al. [33, 85]	XLIF	III	ALIF
	ALIF	III	XLIF
Tohmeh et al. [92]	XLIF	II	–
Youssef et al. [10]	XLIF	III	–

LOE Level of evidence (I-V)[170]
XLIF Extreme lateral interbody fusion
SD Possible shallow docking technique used, Scoli, degenerative scoliosis
LIF Lateral interbody fusion
DLIF Direct lateral interbody fusion
PLIF Open posterior interbody fusion
BMI Body mass index

6.2.4 Length of Stay

Just like estimated blood loss and operative time, the length of stay has been shown to be significantly shorter for MIS patients than open patients [1, 8, 59]. The length of hospital stay primarily has ranged between 1 and 3.5 days for an XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) procedure with and without an additional posterior procedure [1, 7, 8, 10, 58]. Yet, Knight et al. [12] reported an unusually long length of stay of 5 days. It was noted that their data was from four surgeons with different amounts of experience. Additionally, it is the oldest study included in this chapter.

Similar to operative time, the length of stay does significantly increase when an additional posterior procedure is involved compared to XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) alone [10] and when more levels are involved [58]. However, obesity does not seem to influence the length of hospital stay. Rodgers et al. [7] reported that obese patients have a comparable length of stay compared to nonobese patients. However, the length of stay did become significantly longer for patients with a complication versus those without complications [7].

6.2.5 Clinical Outcomes

Published clinical outcomes data from XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) patients has been shown to be comparable or better to traditional surgical techniques. [64, 65] The XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) procedure has shown great improvements in reducing back pain (37–80 %) and disability scores (39–82 %) [10]. For example, Marchi et al. [56] examined two implant sizes (18 mm and 22 m) for stand-alone XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) procedures. Although the biomechanics of the lateral approach and cage subsidence are the focus of other chapters, these authors did provide clinical outcome data. Both groups significantly improved their VAS scores at all time points (postoperative, 6 weeks and 12 months) from preoperative scores. Similarly, Malham et al. [55] reported significant improvements between preoperative scores and the latest follow-up (11.5 months) for VAS back (63 %), VAS leg (56 %), ODI (41 %), SF-36 and PCS (51 %). MCS also improved by 8 %, but it was not significant. Much the same, Kepler et al. [66] and Youssef et al. [10] also demonstrated improved ODI, SF-12 MCS and SF-12 PCS, and VAS scores from preoperatively to postoperatively. Most recently, Pimenta et al. [57] showed substantial as well as maintained clinical improvements for VAS leg/back and ODI measures at all time points (preoperative, 2 and 6 weeks, and 3, 6, 12, 24, and 36 months). Still at 3 years post, the VAS scores were improved 46 % from baseline scores.

Table 6.6 Treatment characteristics for degenerative

Author	Indication	Anterior levels	Levels	Internal fixation	# of posterior levels	Total n	Mean follow- up	ORT (mins)	EBL (mL)	LOS (days)
Pumburger (2012)	Degenerative scoliosis	1.9 pp	T12–L5	NR	–	235	Perioperative	–	–	–
Cummock (2012)	Degenerative scoliosis	1–3	L1–L5	PS	–	59	10 month	255	138	4.0
Knight et al. [12]	Degenerative	1–3	L2–L5	NR	–	58	15 months	161	136	5
Moller et al. [90]	NR	1.9 pp	L	NR	–	53	21.2 months	–	–	–
Kepler et al. [66]	Degenerative scoliosis	2.3 pp	L1–L5	Mixed	–	29	6 months	–	–	–
Lee et al. [91]	Degenerative scoliosis	1–3	L	NR	–	33	6 months	–	–	–
Lucio et al. [1]	Degenerative	2	L1–S1	BP	2	109	45 days	163.2	–	1.2
	Degenerative	2	L1–S1	BP	2	101	45 days	156.5	–	3.2
Malham et al. [55]	Degenerative scoliosis	1–3	L1–5 (T6–7)	Mixed	–	30	11.5 months	–	–	–
Marchi et al. [56]	Degenerative scoliosis	1–2	L	None	–	46	12 months	72.8	50	–
Pimenta (2013)	Degenerative	1	L4–5	None	–	15	36 months	67	<50	–
	Degenerative	1	L4–5	None	–	15	36 months	71	<50	–
Rodgers et al. [7, 8]	Degenerative	1–4	L	Mixed	–	156	3 months	–	–	1.24
	Degenerative	1–4	L	Mixed	–	157	3 months	–	–	1.24
Rodgers et al. [7, 8]	Degenerative	1–3	TL	Mixed	–	40	Perioperative	–	–	1.3
	Degenerative	1–8	TL	PS	–	20	Perioperative	–	–	5.3
Smith et al. [33, 85]	Degenerative	1–2	L	PS	–	115	24 months	93.4	79.1	1.5
	Degenerative	1–2	L	PS	–	87	24 months	150	241.7	3.0
Tohmeh et al. [92]	Degenerative scoliosis	1–2	L3–4 and/ or L4–5	NR	–	102	Perioperative	–	–	–
Youssef et al. [10]	Degenerative scoliosis	1–3	L	Mixed	–	82	15.7 months	199	155	2.6

ORT operating room time; EBL estimated blood loss; LOS length of hospital stay; PS pedicle screws

Table 6.7 Complications and side effects for degenerative

Author	Minor (%)	Major (%)	Transient thigh sensory symptoms (%)	HFW (%)	Motor neural (%)	Reops (%)	Total comps (%)
Pumburger (2012)	–	–	28.7 %	13.1 %	4.9 %	–	–
Cummock (2012)	–	–	42.4 %	23.7 %	6.8 %	–	–
Knight et al. [12]	13.8 %	8.6 %	8.6 %	–	–	1.7 %	22.4 %
Moller et al. [90]	–	–	25 %	36 %	0 %	–	–
Kepler et al. [66]	–	–	–	–	–	–	–
Lee et al. [91]	–	–	–	–	–	–	–
Lucio et al. [1]	–	–	–	–	–	–	6 %
	–	–	–	–	–	–	14 %
Malham et al. [55]	–	–	–	–	–	7 %	13 %
Marchi et al. [56]	38 % (SE)	0 %	15.2 %	23.9 %	–	21.7 %	–
Pimenta (2013)	–	–	–	13 %	–	47 %	27 %
	–	–	–	13 %	–	20 %	27 %
Rodgers et al. [7, 8]	–	–	–	–	–	0.6 %	6.4 %
	–	–	–	–	–	1.9 %	10.8 %
Rodgers et al. [7, 8]	–	–	–	–	–	–	7.5 %
	–	–	–	–	–	–	60 %
Smith et al. [33, 85]	–	–	–	–	–	–	8.2 %
							16.7 %
Tohmeh et al. [92]	2 %	–	17.6 %	27.5 %	2.9 %	–	–
Youssef et al. [10]	–	–	1.2 %	1.2 %	–	2.4 %	9.8 %

Table 6.8 Outcomes for degenerative

Author	Fusion (%)	VAS decrease (%)	ODI decrease (%)	Outcome satisfaction (%)	Redo (%)
Pumburger (2012)	–	–	–	–	–
Cummock (2012)	–	–	–	–	–
	–	–	–	–	–
Knight et al. [12]	–	–	–	–	–
Moller et al. [12]	–	–	–	–	–
Kepler et al. [66]	–	–	39.6 %	–	–
Lee et al. [91]	–	–	–	–	–
Lucio et al. [1]	–	–	–	–	–
Malham et al. [55]	85 %	63 %	41 %	–	–
Marchi et al. [56]	91 %	59.2 %	–	–	–
Pimenta (2013)	100 %	46 %	31 %	–	–
	100 %	46 %	31 %	–	–
Rodgers et al. [7, 8]	–	–	–	–	–
Rodgers et al. [7, 8]	–	–	–	–	–
Smith et al. [33, 85]	–	68 %	60 %	–	–
	–	65 %	59 %	–	–
Tohmeh et al. [92]	–	–	–	–	–
Youssef et al. [10]	100 % (pts wf/u)	77 %	56 %	–	–

Smith and colleagues [59] compared patients with an XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) procedure to those who underwent an ALIF procedure. Up to 24 months post, both groups showed similar as well as significant improvements in leg pain, low back pain, and ODI. Back pain was measured using a 0–10 scale, with 10 being the worst pain possible. At 24 months, low back pain and leg pain decreased 68 % and 65 % and 72 % and 63 % for the XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) and ALIF patients, respectively. ODI also improved approximately 35 % for both groups from preoperatively to postoperatively. Interestingly, outcomes scores were comparable at all follow-up time points between groups, as well as in the difference recorded from preoperative to postoperative.

Significant improvements in clinical outcomes have also been reported in the elderly population who underwent and XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) procedure [8]. VAS scores significantly improved between baseline 8.6/10 points and 12 months 1.4/10 points. Unfortunately, outcomes were not collected for the open group, so no comparisons could be made between surgical approaches. Additionally, Rodgers et al. [7] demonstrated that clinical outcomes after an XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) procedure do not differ between obese and nonobese patients, and complications also do not seem to affect clinical outcome scores between the two groups [7]. However, the average follow-up period was only 3 months long.

6.2.6 Fusion

Thus far, the literature has shown encouraging fusion rates for the XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) procedure ranging from 87 to 100 % [25, 27, 43, 44, 57]. However, longer-term data comparing MIS procedures to traditional open procedures is still needed. Both Pimenta et al. [57] and Malham et al. [55] demonstrated that fusion is a slow but steady progression within the first year after surgery. Pimenta et al. [57] demonstrated a 100 % fusion rate at the 3-year follow-up for both the recombinant human bone morphogenetic protein 2 (rh-BMP2) and synthetic silicate calcium phosphate (SiCap) groups. The authors suggested that the demonstration of a 100 % fusion rate at the final follow-up is most likely due to the advantageous characteristics of the XLIF procedure (XLIF®, NuVasive, Inc., San Diego, CA, USA) [23, 28] such as, the favorable biomechanics and surface area of the cage, and the amount of biologics delivered within the intervertebral space [67].

Lucio et al. [1] reported similar fusion rates at 12 months for both the lateral transpsoas interbody fusion group and the open group. Based on the comparable fusion success between techniques, the authors theorized that both techniques have the capability to handle underlying pathologies. However, the advantages of a minimally invasive approach and the differences in direct and indirect costs will help determine which is most beneficial for a patient.

Additionally, the elderly population appears to fuse well after undergoing an XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) procedure. Rodgers et al. [8]. demonstrated an average 1.1 modified Lenke fusion score [68] at 12 months, where (1) = consolidation, (2) = partially consolidated, and (3) = not yet consolidated. Unfortunately, outcomes were not collected for the open group, so no comparisons could be made between surgical approaches.

6.2.7 Complications

Some of the justifications of minimally invasive procedures are decreased postoperative morbidity, fewer complications, improved treatment characteristics, reduced soft tissue interruption, less blood loss, and shorter operating times and hospital stays [7–9, 69–74]. By comparison, traditional surgeries such as TLIF and PLIF have generally demonstrated higher complication rates compared to the minimally invasive lateral approach [75, 76]. Percutaneous pedicle screw placement has further advanced the minimally invasive approach through decreasing infections and minimizing paraspinal muscle dissection, which are characteristics of traditional posterior

approaches [63, 74, 77–81]. Complications that have been reported include inadequate decompression, interbody graft subsidence, hematoma formation, BMP-induced postoperative seroma, wound infections, and an additional surgery [56–58].

Knight et al. [12] noticed 18 adverse events including but not limited to approach-related complications such as ipsilateral L4 nerve root injury and sensitivity of the lateral femoral cutaneous nerve. Adverse medical events consisted of a myocardial infarction, urinary retention, and acute dementia. The authors indicated that their results were similar to published data [82], and unlike open procedures, they demonstrated zero vascular injuries and no incidences of retrograde ejaculation [83, 84]. It was also remarked by the authors that some of the adverse events happened before the surgeons were highly experienced and thus, most likely the adverse events were representation of the learning curve of these MIS approaches.

Malham et al. [55] observed four complications including a bowel injury, motor deficit, symptomatic subsidence, and cage breakage. Additionally, there were three other asymptomatic subsidence cases noticed without ramifications. Interestingly, three of the four cage subsidence incidences were after stand-alone XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) procedures. Besides the stand-alone variable, smaller cages (18 mm vs. 22 mm), low bone density, BMP-2, and iatrogenic end plate violations have all been implicated as causes of cage subsidence [85, 86]. Also, two reoperations were necessary due to a cage placed posteriorly and symptomatic facet arthropathy.

When comparing MIS and open procedures, Smith et al. [59] noted significantly more perioperative complications in the open group (16.7 %) compared to the XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) group (8.2 %). Fortunately, the most prevalent complications were minor in nature for both groups. However, infections from the posterior instrumentation were also common, mainly in patients who underwent the traditional ALIF procedure (5.7 %) in comparison to the XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) group (0.9 %). Similarly, Lucio and colleagues [1] also demonstrated significantly fewer perioperative complications in the minimally invasive lateral approach group (6 %) versus the open group (14 %). In the open group, three postoperative infections developed compared to zero in the XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) group. Furthermore, only one transfusion was required in the XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) group, whereas 18 transfusions were necessary among the patients who underwent an open procedure. Favorably, reoperations throughout the perioperative stage were infrequent for both groups. However, a number of perioperative residual events did occur in both groups, 37 in the open group and 23 in the XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) group. Statistically speaking, the open group demonstrated significantly more events than the minimally invasive group.

Rodgers and colleagues [8] also observed a significantly higher complication rate in the PLIF group than the XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) group. For instance, infections were noticed in the PLIF group (15 %) compared to none in the XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) group. Much the same, the incidence of postsurgical fatality rate was meaningfully higher in the PLIF group (age = 84.2 years) versus the XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) group (age = 82.6 years). After surgery, six of the PLIF patients were deceased within 18 months compared to one patient in the XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) group who was within 6 months of the operation. However, postoperative mortality rates present the dilemma of separating the aftermath of surgery from the consequence of aging. Additionally, the urgency for subsequent relocation to a rehabilitation service may possibly be the most vital factor to an elderly population undergoing spine surgery [87]. All of the patients in the PLIF group transferred to a nursing facility, whereas 92.5 % of those in the XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) group got well quickly and were able to move back home after surgery. Thus, the authors concluded that a minimally invasive approach is clearly better for an elderly individ-

ual since their XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) patients were able to return to an independent and higher quality of life than those in the PLIF group.

Finally, Rodgers et al. [7] showed no differences in complications for the healthy and obese groups. Overall, the amount of complications reported was quite low. The authors stated that they believe their data is evidence of the potential of an XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) procedure, especially for special populations (i.e., obese patients). Out of 432 patients, there were zero infections, cerebrospinal fluid leaks, and blood transfusions.

6.2.8 Neural Deficits

After a review of the minimally invasive lateral approach literature, the most noticeable patient complaint is postoperative thigh symptoms [5, 6, 43]. In general, the prevalence of neurologic events has been demonstrated to range from 0.6 to 33.6 % following an XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) procedure [9, 10, 32, 36, 88, 89]. Fortunately, for the majority of patients these deficits are transient and resolve within a few months [10, 54, 56, 58, 90, 91]. Yet, in some patients, the sensory or motor weakness does continue for multiple months [53, 58]. To date, the data still remains controversial and incomplete for determining the absolute number of sensory or motor deficits and their natural cause and related factors [54].

Pumberger et al. [54] observed minimal sensory deficits at the 12-month period. Sensory deficits progressively decreased from 28.7, 13.1, 5.7, and 1.6 % of patients at 6-week, 12-week, 6-month, and 12-month follow-ups, respectively. It has been theorized that these sensory deficits are a result of a temporary irritation to the genitofemoral nerve at L2–3 [11, 14] or direct cutaneous nerve neuropraxia or an inflammatory response from the mechanical dissection of the psoas muscle [54].

Regression models for a psoas mechanical deficit revealed that being female and the length of surgery are independent risk factors [54]. The duration of surgery was also a significant risk factor for psoas muscle associated deficits. The authors stated that the precise retraction times were unknown, so operating times were used in the statistical analysis. Although not significant, prior surgery and multilevel fusions may also be potential risk factors. Psoas mechanical flexion deficits followed the same pattern as the sensory deficits. The incidence and degree of deficits diminished over time from 13.1 % of patients at 6 weeks to only 1.6 % at the 12-month postoperative visit.

On the other hand, the lumbar plexus associated motor deficits demonstrated a different pattern than the sensory deficits and psoas mechanical deficits [54]. Overall, the incidence of lumbar plexus deficits was fewer (4.9 %), but the deficits did not resolve as well at 6 months (2.9 %) and 12 months (2.9 %) compared to the sensory and psoas deficits. Regression models for a lumbar plexus associated motor deficit uncovered that the length of surgery is an independent risk factor. Multilevel fusions, prior surgeries, and inclusion of L4–5 demonstrated trends as possible risk factors.

Cummock et al. [58] reported thigh symptoms in 62.7 % of their cases. Overall, numbness was the most prevalent complaint postoperatively, then pain, followed by muscle weakness, and lastly paresthesias. At one year, thigh pain continued in 5.5 % of patients and numbness lingered in 7.0 % of the cases. Favorably, paresthesias were remedied for all by 214 days postoperatively. Sensory deficits were more common than motor deficiencies, which makes sense due to the ability of the EMG monitor to protect motor nerves, but not sensory nerves [12, 13]. Therefore, the genitofemoral nerves and other sensory nerves are at risk, whereas the femoral nerve and lumbar plexus should be protected by the EMG monitoring. However, 23.7 % of patients still experienced motor deficits, despite a lack of significant monitoring changes during surgery. The authors theorized that the likely cause of these motor deficits was either a result of the dissection of the psoas muscle or compressive neuropathy due to dilating the muscle. Blunt stress to the psoas tissue is an understandable source of hip flexor weakness. In fact, all 14 (23.7 %) motor deficit cases demonstrated hip flexor weakness.

Fortunately, all patients' symptoms related to this weakness resolved within 10 months.

Malham and colleagues [55] reported comparable neural adverse event rates to other published data [92]. Interestingly, they noticed less sensory complications with later cases (0 %) compared to earlier surgeries (20 %). The authors suggested that a decreased duration of surgery and retraction of the psoas muscle as well as improved docking position and better adherence to EMG neuromonitoring were likely explanations for the decline in neural events. In addition to logic, these findings further demonstrate the importance of requiring surgeons to be at the high end of the learning curve before performing an XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) procedure on a human patient.

Compared to other fusion procedures, lateral lumbar interbody fusion seems to observe a lower rate of permanent neurologic deficits. For example, after PLIF and TLIF, a 6.1 and 4.1 % permanent motor deficit has been demonstrated [72, 92, 93]. In contrast, ALIF procedures report fewer motor deficits; however, the trade-offs are a higher risk of visceral and vascular complications [92, 94].

The literature demonstrates that with suitable neuromonitoring, the neural elements are safe during the lateral approach. Yet, the rates of neural events widely vary among the published data most likely accredited to diversity in study inclusion criteria and experience as well as the number of treated levels [11, 13, 15, 16]. Prior studies have proposed that the chance of a neural event increases at L4–5 due to the anatomical differences among the lumbar levels [36, 58]. More studies that assess neurologic events prospectively and in greater depth with bigger sample sizes are needed [54].

Conclusions

The exclusive advantages of an XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) procedure over a traditional anterior or posterior approach are well known and documented and include the following: access is minimally invasive, indirect decompression, ability to circumvent prior scar tissue, does not require contending with instrumentation from a prior surgery, corrects deformities, smaller incisions, less blood loss, fewer transfusions, and shorter hospital stays [8, 58].

Based on the literature, the minimally invasive lateral approach has shown to be an overall valuable tool for the treatment of lumbar deformity and degenerative conditions as well as for the elderly and obese populations. The XLIF (XLIF®, NuVasive, Inc., San Diego, CA, USA) approach has reported comparable clinical outcomes and decreased perioperative morbidities [7, 95] compared to traditional techniques. Yet, to achieve a safe and adequate remedy, it is vital that indications, risk factors, and surgical techniques continue to be more thoroughly defined especially for special patient populations. Future work should include prospective, randomized studies with matched cohorts of patient age and size and matched indications for treatment, long-term follow-up, large sample sizes, and high compliance rates. Until then, the conclusions drawn will be limited in nature. All together, it is expected that the minimally invasive lateral lumbar interbody fusion technique will remain to have an influential role in treating various conditions in the spine.

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Part II

Approach and Localization

7 Selecting the Proper Patient for Lumbar Lateral Interbody Fusion and Minimally Invasive Spinal Deformity Surgery

Todd D. Vogel and Praveen V. Mummaneni

7.1 Indications for LLIF

Minimally invasive techniques to access the spine are attractive to surgeons and patients alike as they offer less blood loss, less tissue trauma during surgery, less postoperative pain, shorter hospital stays, and a quicker return to normal activities [4]. Previous techniques for achieving interbody fusion involve open anterior, open retroperitoneal, and posterior approaches. McAfee was among the first to describe the minimally invasive LLIF using a retroperitoneal finger dissection, insufflation of the retroperitoneal space, and endoscopes for viewing and decompressing the spine and using BAK cages for fusion where indicated [3].

Ozgur and Pimenta's original description for the LLIF technique was intended for the patient with axial low-back pain and minimal central canal stenosis [8]. Evolutions in technique have expanded those indications [1]. Indications for the LLIF procedure include degenerative disk disease with axial low-back pain, low-grade (Meyerding grade I or II) spondylolithesis, recurrent disk herniation with mechanical low-back pain, disk collapse following diskectomy causing foraminal narrowing and secondary radiculopathy, treatment of post-laminectomy kyphosis, pseudarthrosis, proximal junctional kyphosis, adjacent level disease above or below a prior fusion, adult degenerative scoliosis with coronal and sagittal deformities, trauma, and tumor. Lateral approaches are being used to treat mid- and lower-thoracic soft disk herniation or calcified thoracic disks causing myelopathy [7].

Contraindications for this procedure include disk herniation causing radiculopathy without mechanical low-back pain or instability, high-grade (Meyerding III or IV) spondylolisthesis, and severe osteoporosis. Relative contraindications include osteoporosis, prior same-side retroperitoneal surgery and active infection in the psoas muscle (Table 7.1).

7.2 The MISDEF Algorithm

The incidence of adult spinal deformity is increasing as the population ages. Spinal deformity patients are typically evaluated with long cassette 36 in. x-rays to assess a variety of radiographic parameters. Relative radiographic indications to consider surgical intervention

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Table 7.1 Indications, contraindications, and relative contraindications for LLIF

Indications	Degenerative disk disease with axial low-back pain
	Low-grade (Meyerding grade I or II) spondylolithesis
	Recurrent disk herniation with low-back pain
	Disk collapse following diskectomy causing foraminal narrowing and secondary radiculopathy
	Treatment of post-laminectomy kyphosis
	Pseudoarthrosis
	Proximal junctional kyphosis
	Adjacent level disease above or below a prior fusion
	Adult degenerative scoliosis with coronal and sagittal deformities
	Trauma
	Tumor
Contraindications	Disk herniation causing radiculopathy without mechanical low-back pain or instability
	High-grade (Meyerding III or IV) spondylolithesis
	Severe osteoporosis
Relative contraindications	Osteoporosis
	Prior same-side retroperitoneal surgery
	Active infection in the psoas

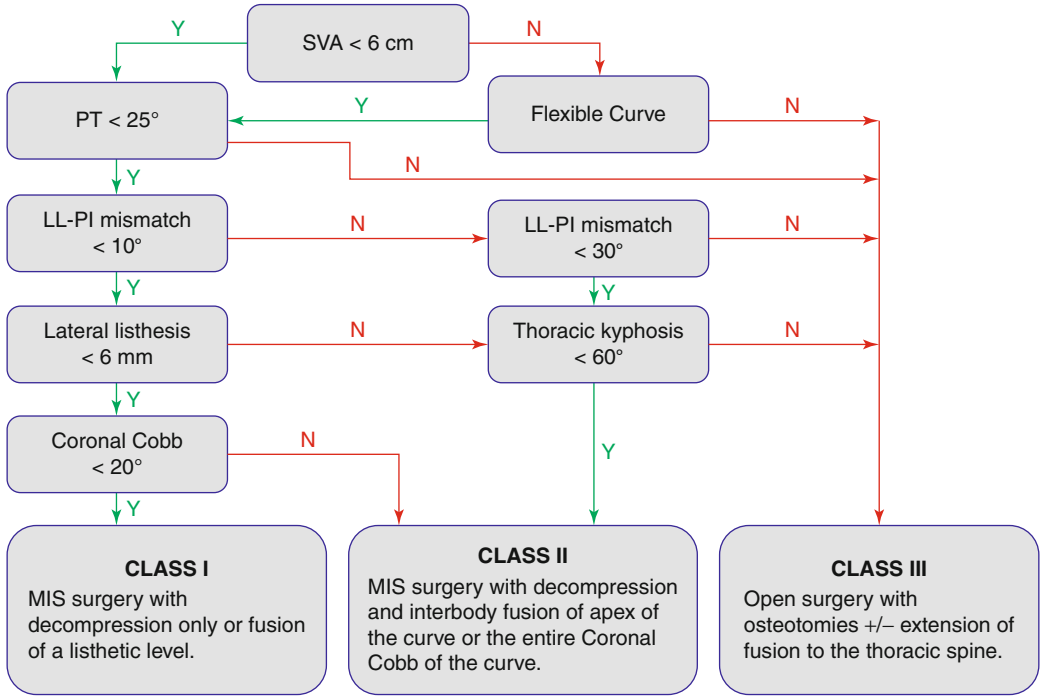
include a sagittal vertebral axis (SVA) greater than 5 cm, a coronal Cobb measurement greater than 20°, lumbar lordosis-pelvic incidence (LL-PI) mismatch greater than 10°, pelvic tilt (PT) greater than 25°, or a lateral listhesis affecting coronal balance to name a few [2, 9, 10]. These radiographic parameters must be accompanied by correlative clinical symptomatology of back and/or leg pain before surgery is recommended. The main goals for treatment of adult spinal deformity include decompression of the neural elements, establishing or maintaining sagittal and coronal balance, and achieving arthrodesis.

Traditionally, the adult deformity population has been treated with open surgical techniques. The morbidity associated with open techniques includes excessive blood loss and deep wound infection. Minimally invasive surgery (MIS) techniques have gained popularity with the goal of decreasing morbidity associated with open surgical techniques. However, initial MIS deformity correction efforts have often demonstrated under-corrected sagittal balance and pseudarthrosis at levels fused posterolaterally but not treated with an interbody fusion [11, 12]. Appropriate patient selection may have also contributed to early failures.

Early classification and treatment recommendation systems include the Silva and Lenke guide for adult degenerative spinal deformity scheme [10]. This scheme used six treatment levels to describe open techniques for the correction of adult degenerative scoliosis. Subsequent advances in minimally invasive techniques and adoption of their practice led to the creation of a modified scheme by Mummaneni et al. that included a combination of open and MIS techniques. This scheme was refined to a second algorithm presented here [5].

The minimally invasive spinal deformity surgery (MISDEF) algorithm was created to provide the framework for rational decision making when considering open versus minimally invasive techniques (Table 7.2). The MISDEF algorithm considers the strengths and weaknesses of a variety of minimally invasive techniques when compared to open techniques. Additionally, it attempted to address the complexity and poor interobserver reliability of previous algorithms. The MISDEF algorithm organizes three groups to simplify the algorithm (Figs. 7.1, 7.2, and 7.3). Progressively worse deformity leads to more aggressive correction approaches. Class I deformities in the MISDEF algorithm may be approached with

Table 7.2 MISDEF algorithm



MIS or mini-open muscle-sparing decompression alone or MIS fusion of a single listhetic level. Instrumentation, if placed, may be placed through an expandable port tube or through a percutaneous method. A Class II approach utilizes MIS or mini-open decompression and interbody fusion of the curve apex or the entire coronal Cobb angle of the major curve. This class of patients may benefit from a lateral interbody fusion in combination with a posterior MIS fixation strategy. A Class III approach entails a traditional open surgical approach involving osteotomies and/or extensive fusion including extension up to the thoracic spine.

Class I patients present with symptoms of neurogenic claudication or radiculopathy due to central, lateral recess, or foraminal stenosis and have relatively mild spinal deformity. They typically have a flexible curve on dynamic films. Radiographic parameters include a LL-PI mismatch less than 10°, SVA less than 6 cm, a PT less than 25°, minimal, if any, lateral listhesis (<6 mm), coronal Cobb angle of less than 20°, and no thoracic kyphotic deformity. Patient characteristics include minimal back pain. These patients may have a grade 1 spondylolisthesis at a single level that may not be at the apex of their coronal curve. A grade I subluxation may be treated with a single interbody fusion (either lateral MIS fusion or TLIF) as needed. Ideally, the fusion at this level would result in direct (TLIF) or indirect (lateral MIS fusion) foramenal distraction to alleviate stenosis. The primary goal for this group of patients is the decompression of neural elements rather than the correction of a mild spinal deformity (Fig. 7.1).

Class II patients typically have a more dominant back pain component as their chief complaint in addition to radiculopathy or claudication. Patients are typified by their LL-PI mismatch of 10–30°, a lateral listhesis greater than 6 mm, and/or a coronal Cobb angle of the major curve greater than 20°.

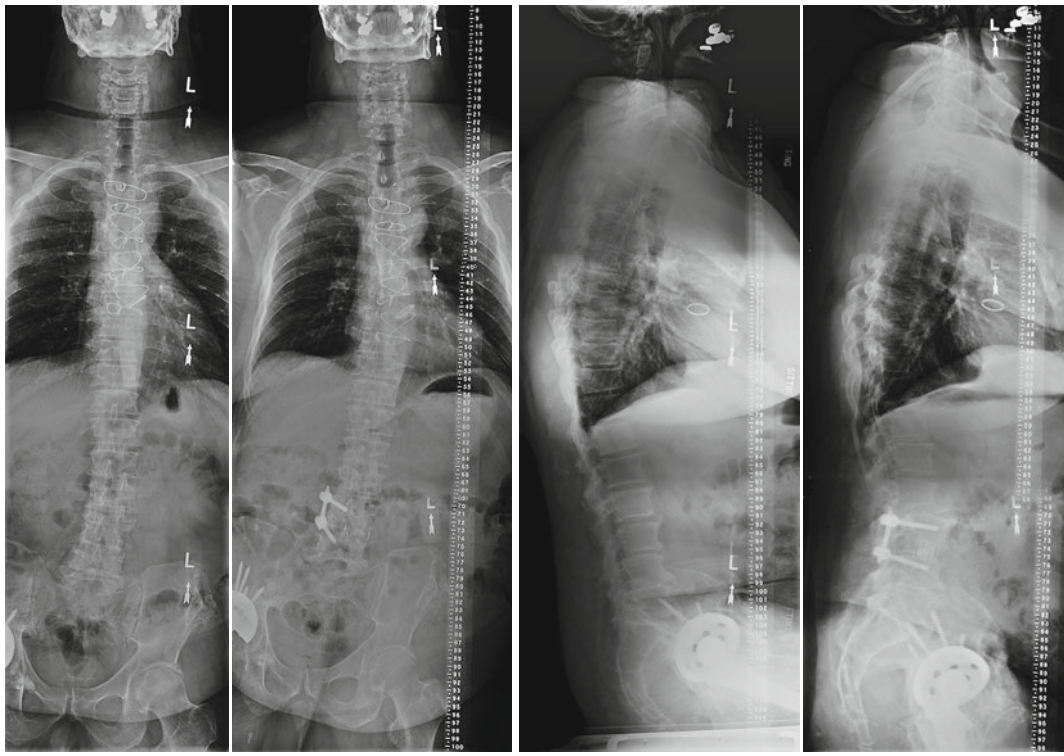


Fig. 7.1 Class I patient. A 64-year-old M presents with neurogenic claudication. He had severe central canal stenosis at L3/4. Preoperative long cassette x-rays demonstrated PI 55°, PT 19°, LL 22°, TK 16°, SVA 5.2 cm, and coronal imbalance 3 cm. Note he was unable to stand preoperatively for his x-rays. He underwent a LLIF at L3/4 with unilateral screw fixation and central canal decompression. Postoperative long cassette x-rays demonstrated PI 54°, PT 20°, LL 26°, TK 23°, SVA 6 cm, and coronal imbalance 4.4 cm

A lack of bridging anterior osteophytes and SVA less than 6 cm is important to note within this group. Patients with flexible deformities that reduce to an SVA of less than 6 cm when they are supine may be considered within this group. Instrumentation can be performed via a percutaneous or mini-open method. Interbody techniques include lateral and posterior options through a muscle splitting technique. Multiple levels of lumbar fusion are typically required within this technique (Fig. 7.2).

Class III patients have significant sagittal or coronal imbalance in addition to back and leg pain. Patients in this group typically have an SVA of 7 cm or greater, LL-PI mismatch greater than 30° with PT great than 25°. Multilevel osteotomies or a three-column osteotomy for realignment should probably be considered. MIS techniques are typically not a viable option to globally balance the spine in Class III patients. The exception to this includes use of a lateral approach with release of the anterior longitudinal ligament (so-called anterior column release, or ACR). Another exception is the patient who has a flexible curve that reduces the SVA to under 7 cm with positioning (Fig. 7.3).

The reliability of the MISDEF algorithm was tested with a team of 11 fellowship-trained spine surgeons who were presented with 20 representative cases from the literature. Images included posterior/anterior and lateral 36 in. long cassette radiographs along with select MRI views. A short history of symptoms and measured radiographic parameters (SVA, coronal Cobb angle, pelvic tilt

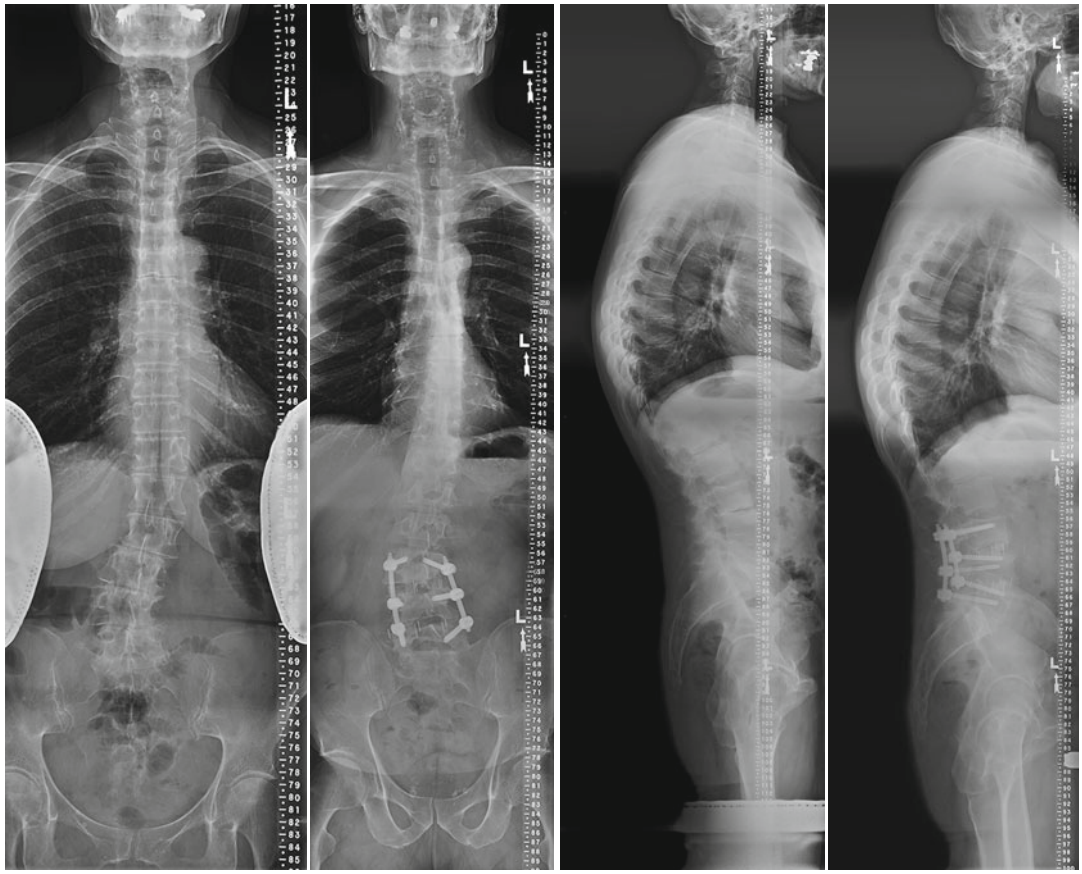


Fig. 7.2 Class 2 patient. A 66-year-old F presents with back and leg pain. She had minimal central canal stenosis with foraminal stenosis at multiple levels. Preoperative x-rays demonstrated PI 43°, PT 20°, LL 22°, TK 24°, SVA 5 cm, and coronal imbalance 2.4 cm. She underwent a L2/3, L3/4, L4/5 LLIF with L2-sacroiliac fixation through a minimally invasive posterior approach. Postoperative scoliosis films demonstrated PI 43°, PT 15°, LL 34°, TK 31°, SVA 2 cm, and coronal imbalance 1 cm

(PT), and LL-PI mismatch) were presented to the surgeons. Three cases were consistent with MISDEF Class I, ten cases were consistent with MISDEF Class II, and seven cases were consistent with MISDEF Class III. The results were tabulated and the cases were re-presented 2 months later in a new order and the results again tabulated. Fleiss kappa coefficient analysis was used to determine both intraobserver and interobserver reliability. There was an interobserver kappa of 0.58 for the first round of surveys and an interobserver kappa of 0.69 for the second round of surveys consistent with substantial agreement. The mean intraobserver kappa for the two surveys was 0.86 ± 0.15 (±SD) and ranged from 0.62 to 1.

Strengths of this algorithm include its simplicity, moderate intraobserver and interobserver reliability. Limitations include that it has not been validated in relation to radiographic and health-related quality-of-life outcomes. Additionally, not all deformities can be appropriately treated with a minimally invasive technique. This system accounts for this with the class III deformities being recommended for treatment with open techniques.

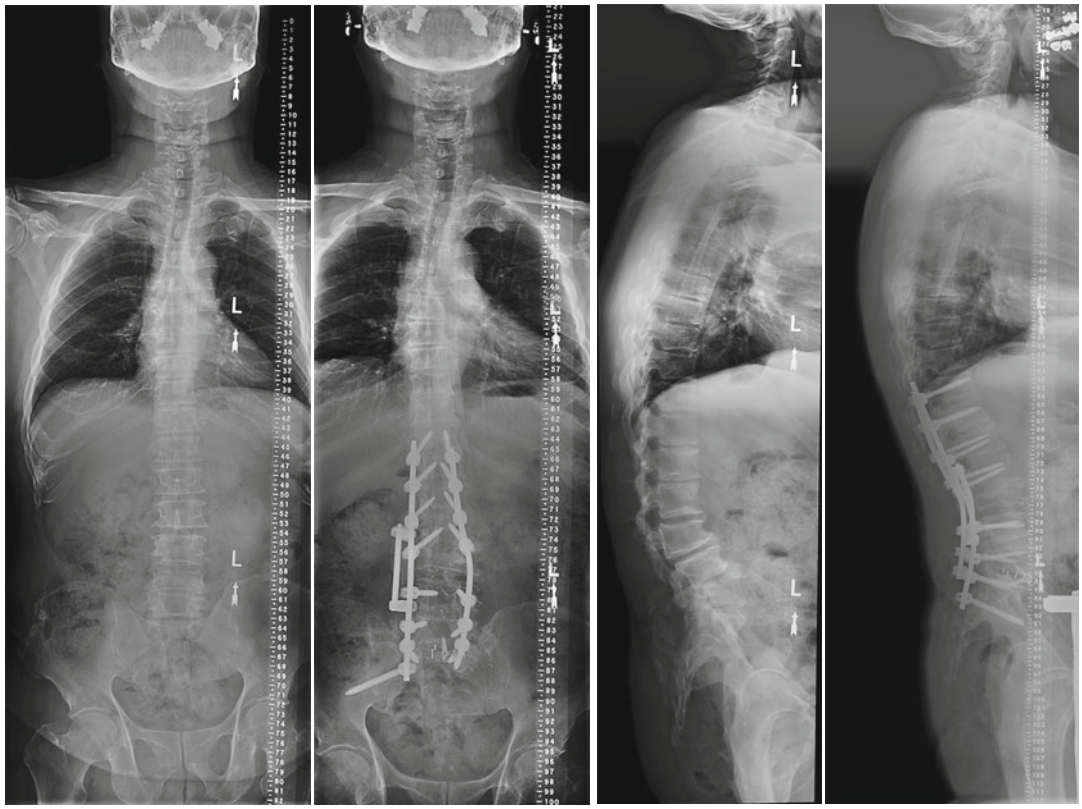


Fig. 7.3 Class 3 patient. **A** 60-year-old M presents with back and leg pain. MRI demonstrated spinal stenosis compounded by adult spinal deformity with a PI-LL mismatch. Preoperative x-rays demonstrated PI 38°, LL -4°, PT 29°, TK 10°, SVA 8.5 cm, and coronal imbalance −3.9 cm. He underwent a posterior T9 to sacrum fusion with L3 PSO, T9−11 and L1−L5 laminectomy, and iliac fixation. Postoperative x-rays demonstrated PI 39°, LL 32°, PT 14°, TK 9°, SVA 4.3 cm, and coronal imbalance 3.5 cm

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Positioning and Safety

8

Viren S. Vasudeva, Muhammad M. Abd-El-Barr, Yi Lu, and Michael W. Groff

8.1 Introduction

The lateral decubitus position has classically been used in spine surgery to gain lateral access to the vertebral column via thoracotomy and retroperitoneal approaches [1, 2]. In some cases – particularly those requiring corpectomy – a lateral approach is preferred to gain sufficient access with decreased risk to the neural elements compared to posterior approach. Currently, with the rising popularity of the minimally invasive lateral lumbar interbody fusion which was developed in the 2000s, it is more important than ever for spine surgeons to understand proper lateral decubitus positioning in order to optimize exposure and minimize the risk of iatrogenic injury to the patient [3–5].

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8.2 Positioning the Patient

Although patient positioning for surgery may become a routine process, it is crucial that it is performed properly before every case. Optimizing the exposure of the operative site will enable the surgeon to carry out the operation more smoothly. Additionally, with the patient immobilized under anesthesia, the combined factors of time and mechanical pressure can result in skin breakdown, pressure ulcers, or peripheral nerve injury. These types of iatrogenic injuries must be avoided in order to ensure a good outcome for the patient and to prevent potential litigation [6–8].

Prior to positioning, the patient is anesthetized and intubated while supine on a stretcher. With the help of other team members, the patient is then transferred to the OR table and turned to the lateral position with the dependent arm outstretched. Before moving the patient, the OR table should be prepared either with a draw sheet (to support chest rolls), or a vacuum bean-bag positioning device, or a lateral positioner. At this point, it is important to ensure that the patient is centered on the OR bed and that the iliac crest is in line with a break in the bed so that when the bed is flexed, the distance between the twelfth rib and the ilium is enlarged thereby increasing the operative window (Fig. 8.1).

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Fig. 8.1 Patient in the lateral decubitus position

Pillows, blankets, or a gel donut are then placed beneath the patient's head to support it in a neutral position. The patient's eyes, especially the dependent eye, should be checked to ensure that they are free of pressure which could lead to postoperative blindness. The downward facing ear should be checked to ensure that it is not bent. The patient's chest is then lifted, and a small axillary roll is placed beneath the patient's upper ribs. The axillary roll functions to raise the patient's chest off of the OR bed and remove mechanical compression of the neurovascular structures in the patient's axilla. This will allow room for expansion of the chest wall during respiration, adequate blood flow to the dependent arm, and will prevent brachial plexus traction. If the axillary roll is placed too high, the roll itself could cause compression of the structures in the axilla which it is designed to protect. By palpating the radial artery pulse on the patient's dependent arm, the surgeon can ensure that the axillary role is not impeding the blood flow through the axillary or brachial artery (Figs. 8.2 and 8.3).

Next, the patient's chest and abdomen are supported in the lateral position by tightening the draw sheet around chest rolls placed on either side of the patient. If a vacuum bean-bag positioning device is used, it should be molded around the patient's body, and negative pressure should be applied to create a rigid structure. If the patient is female, care should be taken to ensure that her breasts are free and particularly that there is no pressure on the nipples.

The patient's dependent arm, which is outstretched, is then supported by an armrest and padded with a foam or gel pad. By keeping this arm in supination, the ulnar nerve is protected as it passes through the cubital tunnel [5]. The upper arm is secured to an arm board with shoulder flexion $\leq 90°$ [6].

A foam or gel pad is placed under the dependent knee. This provides some protection to the common peroneal nerve as it crosses over the head of the fibula. A pillow is placed in between the patient's legs and feet. Both legs are placed in slight flexion which provides stability to the patient's pelvis and reduces tension on the psoas muscle and the nerves of the lumbar plexus. Another pad is placed under the patient's feet. When positioning has been completed, Velcro safety straps are passed over the patient's hip and shoulder to provide further stability. Three-inch silk tape may be used as well to increase stability, and some surgeons prefer to cross the tape over the patient's legs as seen in Fig. 8.1. If the shoulder tape lays over the patient's upper arm, the elbow and radial groove of the humerus should be avoided in order to prevent injury to the ulnar or radial nerves respectively [10, 11]. Padding may be placed under the tape to protect the patient's skin.



Fig. 8.2 Image illustrating the proper placement of the patient's arms and head in the lateral decubitus position. Note that the head is elevated so that the cervical spine remains in neutral alignment and that the eyes are free from external pressure

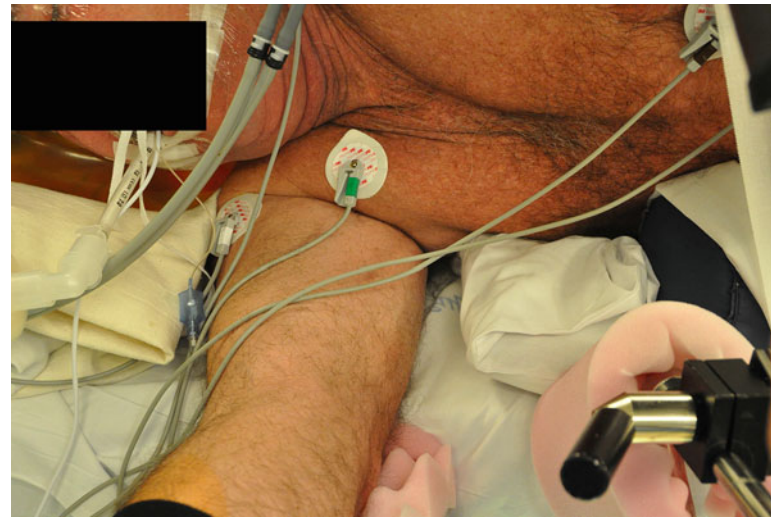


Fig. 8.3 Placement of the axillary roll in the lateral decubitus position. The roll is placed underneath the upper ribs and not within the axilla itself where it would cause direct compression of the axillary artery and brachial plexus

Finally, the bed may be placed into slight flexion as described above based on the surgeon's preference. If this maneuver is performed with the bed already in the reverse Trendelenburg position, the surgeon can ensure that the patient's upper body remains parallel to the ground [10]. It has been suggested that increasing the amount of flexion of the bed results in higher skin-to-surface interface pressures and this may increase the likelihood of pressure ulcer formation or rhabdomyolysis [12]. Before beginning the case, fluoroscopy should be used to ensure that there will be proper visualization of the surgical target. For minimally invasive surgeries, it is critical to obtain good fluoroscopic images. To obtain a true lateral image, the C-arm is brought in perpendicular to the floor (90°). The table is then placed in Trendelenburg or reverse Trendelenburg until a true lateral image with linear endplates and superimposed pedicles is achieved. Following this, the C-arm is rotated so that it is parallel to the floor in order to obtain a cross-table AP image (0°). The left-right tilt of the table is adjusted until a true AP image with midline spinous processes and symmetric pedicles is achieved. This process may be especially complicated in patients with scoliosis where there is often axial rotation of the spinal segments; however, ensuring that



Fig. 8.4 Patient in the lateral decubitus position with the bed flexed. Note that the point of flexion is underneath the iliac crests which allows for an improved retroperitoneal exposure

the patient is in the true lateral position with good fluoroscopic images will help the surgeon to avoid inadvertently damaging the endplates, neural structures, and visceral or vascular structures anterior to the spine during lateral surgery (Fig. 8.4).

8.3 Complications Associated with Patient Positioning

8.3.1 Pressure Ulcers

Pressure ulcers have been reported to occur in anywhere from 8.5 to 66 % of patients in the immediate postoperative period [6, 13–17]. Schultz et al. found that 89 out of 413 (21.5 %) surgical patients developed pressure ulcers over six postoperative days. These ulcers were primarily stage I and were more likely to occur in patients who were older, had diabetes, and who had smaller body mass [16]. The development of these ulcers is also related to the length of the surgery [5, 13].

Pressure ulcers occur when external pressure is so great that subcutaneous blood flow is compromised to the point where the skin and subcutaneous tissue hypoperfusion results in tissue ischemia and eventually necrosis. More specifically, ulcers occur when the external pressure exceeds the capillary filling pressure of ~32 mmHg. Longer operative times mean longer periods of hypoperfusion to pressure points and increase the likelihood of ulcer formation [6]. The most common sites of pressure ulcer formation are the sacrum, heels, ischium, and trochanter, and special attention should be paid to ensure that these areas are appropriately positioned and padded for surgery [5].

To prevent the formation of pressure ulcers during surgery in the lateral decubitus position, it is important for the surgeon to make sure that all dependent areas and boney prominences are properly padded after positioning. Ideally, the circulating nurse should also be vigilant during the procedure to ensure that the patient does not slip out of position underneath the drapes. Despite these precautions, if a patient develops pressure ulcers as a result of surgery, this should be disclosed to the patient and the wound should be cared for appropriately. Severe ulcers may require evaluation by a plastic surgeon.

8.3.2 Peripheral Nerve Injury

Perioperative peripheral nerve injury is reported to occur after 0.03–0.1 % of surgeries [9, 18, 19]. Possible mechanisms of peripheral nerve injury during spine surgery include direct compression, trauma, ischemia, stretch, or inflammatory processes [18]. Peripheral

nerve injury may occur when the nerve is stretched beyond 5–15 % of its resting length [18, 20–22]. This in turn increases the intraneural pressure and leads to compression of the vasa nervosum resulting in decreased tissue perfusion and nerve fiber ischemia [20]. Similarly direct nerve compression may also lead to a reduction in perfusion pressure and subsequent nerve ischemia thereby slowing nerve fiber conduction [18, 23]. The most common site of perioperative peripheral nerve injury is the ulnar nerve which occurs in 0.5 % of patients undergoing noncardiac surgery [9, 24]. The ulnar nerve may be more prone to injury if there is a preexisting subclinical neuropathy. Abnormal nerve conduction has been observed in the contralateral ulnar nerve in patients who developed perioperative ulnar nerve injury [25]. Furthermore, ulnar nerve injury is more common in males. This may occur because men have a statistically larger coronoid process of the ulna, while women have increased fat over the medial aspect of the elbow [26]. Another common site of peripheral nerve injury during surgery is the brachial plexus. Brachial plexus injury more commonly involves the upper nerve roots [18]. In the lateral decubitus position, brachial plexus injury may occur if the axillary roll is place too high within the axilla itself causing injury due to direct compression. On the nondependent side brachial plexus injury may occur if the nondependent arm is hyper-abducted or if the head is tilted downward. Extreme elbow flexion or extension should also be avoided [18].

8.3.3 Rhabdomyolysis

There are reports of rhabdomyolysis following surgery in the lateral decubitus position [10, 27–29]. This rare complication is associated with longer operative time, male sex, and increased body mass index [10, 27]. To identify this complication early, the anesthesia provider should closely monitor urine output and renal function in obese patients who are undergoing long surgeries.

8.3.4 Postoperative Visual Loss

Although postoperative visual loss is generally associated with patients undergoing spine surgery in the prone position, this exceedingly rare but devastating complication has been reported in patients who are positioned in the lateral decubitus position as well [18, 30]. The most common causes of postoperative visual loss are ischemic optic neuropathy and central retinal artery occlusion. More specifically, posterior ischemic optic neuropathy is the most likely cause after spine surgery. The etiology of this condition is unknown; however, to minimize the risk of this complication, the patient's eyes should be closed and free from external pressure during positioning, and the head should be positioned above the heart in neutral forward position when possible [31].

Conclusion

Understanding how to properly position a patient in the lateral decubitus position is crucial for spine surgeons, especially given the increasing popularity of minimally invasive surgeries performed in this position. Although patient positioning is a team effort involving the surgeon, nursing, and anesthesia, it remains the surgeon's responsibility to ensure that the patient is positioned in a way such that optimizes surgical exposure while minimizing risk to the patient. Complications including pressure ulcers, peripheral nerve injury, rhabdomyolysis, and perioperative visual loss may occur rarely despite preventative measures [9]. In these situations, it is important to identify and treat these complications early, and patients should be aware of these potential complications prior to surgery.

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Intraoperative Electrophysiologic Monitoring

9

Reid R. Hoshide and William R. Taylor

9.1 Introduction

The lateral approach to minimally invasive lumbar spine surgery has been around since the 1980s [1–6]. However, this approach had been fraught with resultant nerve injuries which were appreciated postoperatively. In its beginnings, the rate of intraoperative nerve injury during lateral approaches to lumbar spine surgery was approximately 30 %, making this approach unappealing compared to alternative approaches to the lumbar spine [1]. The addition and advances of intraoperative neuromonitoring (IONM) have made this technique safer with lesser rates of postsurgical paresis. Advances in IONM made this previously morbid approach less morbid by means of awareness to the surrounding neural structures that can be compromised with the lateral access approach to the spine. In this chapter, we describe the considerations, benefits, and utility of IONM in lateral access lumbar spine surgery.

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9.2 Anatomic Considerations

The lumbar plexus is a network of motor and sensory nerves that start from the L1 nerve root and end at the L5 nerve root. The lumbar plexus traditionally runs lateral to the dorsal half of the vertebral body. The one exception of this dorsal-half travel of the lumbar plexus is the genitofemoral nerve. The genitofemoral nerve emerges from L1 and L2 and runs obliquely within the psoas muscle, running anterior relative to the vertebral bodies. A small cadaveric study revealed that if the lateral disc space was divided into four zones from anterior to posterior, zones I, II, and III were free of major motor nerves in the L3–4 disc space. The L4–5 disc space was free of major motor nerves in zones I to II. The genitofemoral nerve, the nerve most prone to injury, was observed coursing through the psoas muscle at zone II at L2–L3, emerging from the psoas at zone I at L3–4, and superficial to the psoas at L4–5 in zone I [7–9]. This serpentinous course of the genitofemoral nerve makes it vulnerable to collateral injury when accessing the lateral lumbar spine (Fig. 9.1).

Sensory nerves can also be at risk for injury. A small cadaveric study has shown that the iliohypogastric, ilioinguinal, and the lateral femoral cutaneous nerves run obliquely during blunt retroperitoneal dissection [10]. Unfortunately, it is difficult to measure injury to these sensory nerves during lateral access spine surgery.

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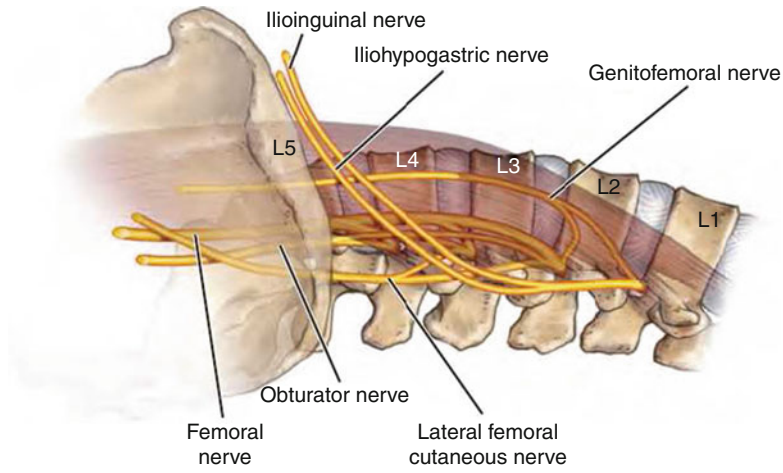


Fig. 9.1 The position of the major neural structures of the lumbar plexus within and around the psoas muscle (Reprinted from *eXtreme Lateral Interbody Fusion* (p46), by JA. Goodrich, 2013, St Louis, MO: Quality Medical Publishing, Inc. Copyright 2008 by NuVasive, Inc. Reprinted with permission)

While not every patient's anatomy will be the same, the importance of IONM can significantly reduce nerve injury and can allow the surgeon to adapt intraoperatively and to identify injuries to nerves early during the approach to the lateral lumbar disc space.

9.3 Types of Intraoperative Electrophysiologic Monitoring for Lateral Access Surgery

9.3.1 Motor Evoked Potentials (MEP)

Motor neurons of the spinal cord travel in the anterolateral spinal cord. Injuries to motor neurons can be detected by MEPs, which run at specific moments during the procedure at the request of the surgeon. MEPs are very sensitive to anesthetic choice and require anesthetics that lack any paralytic or muscle relaxant properties. If paralytics or muscle relaxants are required for the induction of anesthesia, they must be rapidly cleared and muscle twitches must be confirmed to have returned in order to establish a reliable preincisional baseline. MEPs are carried out by electrical stimulation of electrodes placed in the scalp above the motor cortex of the brain. Stimulation of these electrodes will then trigger a response from the associated motor group within the homunculus. A response of the associated muscle group is then recorded distally and compared to a reliable preincisional baseline. A disruption in the signaling of a specific muscle group with the MEPs should alert the surgeon that there is a lack of transmission somewhere within the neural pathway that would be inhibiting transmission of the signal. Aside from surgical misadventures causing a nerve injury, the anesthesiologist should check their anesthetic choice, blood pressure, and any point of external compression-related positioning. An assistant can also check to see if the recording electrode is still intact. Any of these variables can confound MEP recordings and result in the appearance of a nerve injury.

9.3.2 Somatosensory Evoked Potentials (SSEP)

Sensory fibers of the spinal cord travel within the dorsal columns. Measurements of injuries to sensory nerves can be recorded by SSEP monitoring [11, 12]. Stimulation is managed by electrodes in different sensory distributions of the legs. They are recorded through scalp electrodes over the sensory cortex of the brain and are compared to a reliable preincisional baseline. SSEPs are less confounded by anesthetics and therefore can be a more reliable of a measurement of nerve injury. Because SSEPs measure the sensory component

of neural function, anesthetics with paralytic properties do not confound their readings. However, inhalational agents given as part of anesthesia induction can attenuate results and hamper SSEP readings. SSEPs are averaged over a 15 min timeframe and therefore are not an accurate indicator of the injury at the time of its exact instance. Additionally, multiple nerve roots can contribute to a sensory deficit in a specific sensory distribution. The multiple nerve root contributions to a sensory domain would make it difficult to isolate exactly which nerve root was injured. Proposed alarm criteria are variable and preoperative injuries must be considered. A proposed 50% reduction in amplitude and 10% decrease in latency are generally considered to be significant events and a trigger for alarm from the neurophysiologist to the surgeon and anesthesiologist. This should be correlated with intraoperative events including correction maneuvers of the spine, hardware insertion, compression from retractors, and hypotension.

9.3.3 Spontaneous Electromyography (spEMG)

Spontaneous electromyography (EMG) allows for the passive evaluation of muscle group firing that might undergo mechanical stimulation by their associated nerve root. This type of EMG can also be referred to as "free-run" EMG due to its continuous, passive means of monitoring. spEMGs function by way of recording muscle groups in each nerve root category. A single electrode is placed distally in the muscle group of interest, and recordings are performed throughout the procedure without any need for proximal stimulus, hence the term "free run." The role of spEMGs is to monitor the degree of distal responses to proximal surgical manipulation. Spontaneous EMG has also been used to document adequacy of decompression, showing a decrease in spontaneous firing of decompressed nerve roots intraoperatively. Such changes however may or may not occur during the time of surgery and are usual only in the minority of cases where there is an absence of chronic nerve root injury [13]. spEMG recordings are important for identifying nerve or muscle irritation [14]. For example, if there is evidence of the tibialis anterior firing on spEMG, this could be an indicator of mechanical stimulation of the L5 nerve root or downstream nerves, either from the retractors or the surgeon's instrument. Cold irrigation in the operative site can also cause increased activity of spEMG. Increased activity seen on spEMG warns the surgeon that the nerve or nerve root is being stimulated. Stimulation of the nerve seen on spEMGs are an indicator for a nerve at risk for potential injury. It is important to point out that spEMGs that have returned to normal activity following a recorded stimulus could indicate that not only was the stimulus removed and the nerve returned to a normal resting state but could direly also indicate that the nerve injury has been completed and is no longer able to depolarize and transmit a signal to the recorded muscle group. In this case, it would be important to investigate this further through an MEP run.

9.3.4 Triggered Electromyography (trEMG)

Triggered electromyography (trEMG) has been demonstrated to be particularly useful for lateral access spine surgery [15]. Triggered EMG is the intentional stimulation of a nerve by a proximal source, which is recorded distally at an associated muscle group. This carries a high utility in measuring the proximity of nerve or nerves to the trigger source. An intentional electrical stimulus, measured in milliamps, is deployed through the queried point of contact (a trochar, retractor, etc.). The electrical stimulus starts at a low ampere and then moves up to the point of which there is an appreciable distal response from a muscle group. This is known as a threshold stimulus. The higher the recorded threshold stimulus, the higher amount of safe distance (or protective tissue) exists between the trigger source and the nerve. This function of IONM is particularly useful in investigating the surrounding structures upon entry and access through the psoas major muscle as the surgeon approaches the lateral lumbar spine. For example,

a trEMG firing can be performed at the placement of the Jamshidi trocars, the retractor setup, or as a handheld probe that can investigate tissue within the operative corridor if there is a concern for a nearby nerve. Low-threshold firing of any downstream nerves would indicate that there is a nerve or nerve root within the proximity of the stimulus that is prone to injury. This technique carries high utility in "neural mapping," which will be described later in this chapter.

9.4 Patient Preparation and Anesthesia Requirements

Electrodes for lateral access lumbar spine surgery must encompass the basic muscle groups that are referable to their associated nerve root at risk. The NuVasive (San Diego, CA) system requires four muscle groups to be tested: vastus medialis (L2, L3, L4), biceps femoris (L5, S1, S2), medial gastrocnemius (S1, S2), and tibialis anterior (L4, L5). An anode is placed at the level of the surgical site in the paraspinal muscles, with a reference electrode at the patient's hip contralateral to the electrocautery pad. To facilitate the neuromuscular junction twitch test, an electrode is placed on the peroneal nerve.

Collaboration with the anesthesia team is essential to ensuring that there are adequate, unencumbered recordings for IONM [16, 17]. It is essential that all twitches on a train-of-fours return on a twitch test prior to establishing an electrophysiologic, preincisional baseline. To achieve this, the anesthesiologist must either refrain from using paralytics or use short-acting paralytics during induction of anesthesia if MEPs are desired. Some surgeons may even request total intravenous anesthesia (TIVA), which excludes the use of inhaled agents that could attenuate the responses of SSEPs. In procedures where MEPs are used, it is highly recommended that the anesthesiologists place a bite-block to prevent induced injury to the tongue, oral mucosa, or the endotracheal tube with MEP stimulation. If monopolar cautery is to be used, it is essential to keep monitoring needles away from the monopolar cautery grounding pad, as the needles can intercept the transmitted current and cause burn injury. Moreover, electrode readings can be especially susceptible to monopolar artifact if placed too close to the monopolar grounding pad.

Patient positioning is also an important aspect in ensuring that IONM is used to its maximal benefit. Inappropriate patient positioning could compress or stretch nerves, restrict blood flow, or place monitoring electrodes at risk for slipping out. The result of poor patient positioning can be problematic and cumbersome to rectify once the procedure has started. It is important to ensure that all pressure points are padded, there is adequate freedom of the legs from any compressive or stretch sources, and there is adequate stabilization of the monitoring needles subcutaneously. The knees should be bent and the hips flexed to prevent stretch injury of the nerves and musculature of the lower extremities. Aside from the benefits of IONM, these maneuvers also reduce postoperative pain, paresis, and pressure sores related to poor positioning.

9.5 Neural Mapping During the Approach

Because minimally invasive spine surgery relies on percutaneous techniques, the surgeon will increasingly rely on radiographic visualization of the spine and electrographic understanding of the neural anatomy. Direct visualization of the neural anatomy is difficult and, at times, impossible. Thus, it is essential to understand the patient's neural spatial anatomy through IONM. "Neural mapping" is the technique that utilizes triggered EMG for the discovery of nerves within the vicinity of the surgical corridor. As mentioned previously, a surgical corridor through the psoas muscle carries the dangers of significant neural injury, especially to the genitofemoral nerve. When traversing the psoas muscle in the lateral approach, myotome threshold values of 1–5 mA indicate very close proximity or direct contact with motor nerves, recordings of 5–10 mA during passage through the psoas indicate proximity without direct contact, and current thresholds

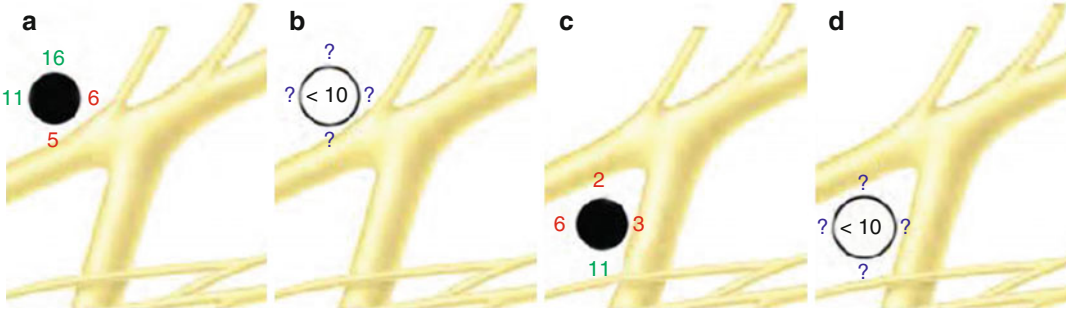


Fig. 9.2 The position of the insulated dilator relative to the motor nerves demonstrates the importance of discrete, directional feedback to the surgeon. Favorable positioning of dilator: (**a**) NuVasive, Inc.'s discrete threshold neuromonitoring versus (**b**) traditional neuromonitoring using a searching threshold. Unfavorable positioning: (**c**) NuVasive's discrete threshold neuromonitoring and (**d**) traditional neuromonitoring using a searching threshold (Reprinted from *eXtreme Lateral Interbody Fusion* (p50), by JA. Goodrich, 2013, St Louis, MO: Quality Medical Publishing, Inc. Copyright 2013 by NuVasive, Inc. Reprinted with permission)

greater than 10 mA are typically considered a safe distance from the nerve provided that there are no anesthetically induced neuromuscular blockades confirmed with the twitch test previously described [15]. The importance of understanding the spatial relationship of the neural elements by IONM is important in avoiding injury to the lumbar plexus and reducing postoperative morbidity of lower extremity paresis. The sequential dilators that are used for the initial access to the lateral lumbar spine are insulated and have an electrode on the distal end of the dilator. This electrode faces a single direction, which aids in the directionality of nerve identification. This permits trEMG stimuli through the dilator recordings as thresholds and are recorded for circumferential identification of neural structures during the approach. Once docked onto the lateral lumbar spine, the dilators can then be rotated to understand the circumferential spatial orientation of the nerves in the vicinity of the surgical corridor. This "mapping" of the neural elements is essential to preventing injury of the nerves (Fig. 9.2).

9.6 Ongoing Monitoring

Once the surgical corridor is achieved, the risk of neural injury is likely related to retraction injury rather than direct injury from a trespassing dilator. Retraction injury of the nerve can be a result of nerve ischemia, stretch injury, or compression. Once the retractor system is opened maximally, focus on the spEMG is important for monitoring the ongoing health of the muscle group, which serves as a proxy for the ongoing health of their associated nerve. Frequent trEMGs should be taken from the electrode within the retractor system to spot-check the nerve responses. An increase in the threshold response can be an indicator of nerve injury. This type of response should indicate to the surgeon to reduce or remove the retraction and allow the nerve to recover. It would also be important for the surgeon to note that timeliness is important for the remaining part of procedure to avoid long-term nerve injury.

Conclusion

The lateral access to the lumbar spine is a strategic approach for minimally invasive spine surgery. The morbidity of nerve injury associated with this technique has been reduced with the aid of IONM. These tools empower the surgeon to identify and conceptually map the neural architecture of the surgical corridor, identify nerve injuries early, and therefore act timely in preventing ongoing nerve injury that would have otherwise gone unrecognized. Preventing neural injury is incumbent on the surgeon to be able to test and identify impending neural insults by utilizing the various tech-

niques of IONM as described above. With appropriate IONM, significant injury and morbidity is reduced during minimally invasive lateral access lumbar surgery.

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Motor-Based Monitoring During Minimally Invasive Lateral Spine Surgery

10

Hesham M. Zakaria and Muwaffak Abdulhak

10.1 Introduction

The lateral approach to the spine was first described in the early 1990s [1, 2], but due to potential harm to the lumbar plexus, this approach was not pursued until technology had advanced enough to minimize its morbidity. The current model for the minimally invasive lateral transpsoas approach to the lumbar spine for interbody fusion (MI-LIF) was developed from the late 1990s to early 2000s [3–6]. The first commercially available access device was marketed as an extreme lateral interbody fusion (XLIF®, NuVasive, Inc., San Diego, CA) with electromyography (EMG) incorporated into the system [6]. In subsequent years, other lateral approach devices entered the market, including the direct lateral interbody fusion (DLIF®, Medtronic Sofamor Danek, Memphis, TN), the lateral lumbar interbody fusion (LLIF, Globus Medical, Inc., Audubon, PA), the VEO System (Baxano Surgical, Inc., Raleigh, NC), the MIS Lateral System (DePuy Synthes, Inc., Raynham, MA), and the nonretracted transpsoas approaches.

Although the devices differ, the approach to the lateral spine and disk space is similar. In the lateral position and under direct fluoroscopy, an incision is made on the lateral flank, with a retroperitoneal dissection performed to approach the psoas muscle. The initial probe is passed through the psoas to reach the lateral aspect of the spine. Serial dilators are then used to create a working space in which to perform the surgery. There are many potential hazards during this approach, one being damage to the neurological bundles as they exit from the foramen to course laterally, ventrally, and caudally to their target sites. Specific nerves at risk during surgery include the ilioinguinal nerve, the genitofemoral nerve, the lateral cutaneous femoral nerve, the femoral nerve, the lumbosacral trunk, and the lumbar plexus generally. Injury of these nerves can cause debilitating pain, numbness, or weakness. Safe anatomical approaches and techniques for avoiding the psoas muscle and lumbosacral plexus during the lateral approach are discussed elsewhere in this book [7–14]. Here we will discuss motor-based monitoring, with the goal being protection of the motor nerves during surgery.

10.2 Motor Monitoring and the Lateral Approach

Iatrogenic nerve injuries during lateral transpsoas approach to the lumbar spine occur from compression, laceration, stretching, or ischemia, which induce structural, microvascular, and electrophysiological changes that diminish nerve function and

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are tantamount to nerve damage [15–21]. The purpose of nerve monitoring is twofold: to localize areas that may contain sensitive nerve bundles and to identify early signs of nerve injury, so the surgeon can discontinue or remove the offending agent and prevent further damage [22–25].

The recommended use of neurophysiologic monitoring for the lateral approach differs for each system. Some devices have automated monitoring incorporated into their function [6], while other devices and techniques market themselves as not requiring any monitoring at all [26–29]. The standards for motor monitoring for any spine surgery include motor-evoked potentials (MEPs) and spontaneous versus evoked EMG [30–34]. A new technique for motor monitoring during spine surgery is that of mechanomyography (MMG). To truly integrate these systems into one's practice, the capabilities and limitations of each test must be understood. Ideally, intraoperative monitoring provides accurate and real-time feedback about the integrity of the nervous system. Plans for monitoring should always be discussed with the anesthesiologist and electrophysiologist. Baseline recordings should be obtained before surgery, to be used to compare with intraoperative recordings. The surgeon should be alerted to any changes or fluctuations from baseline values and will then correlate these findings with intraoperative proceedings. However, it is important to note that some changes from baseline values may be due to physiologic changes, anesthetic parameters, or technical problems. It is crucial to realize that motor monitoring requires only intravenous anesthesia without neuromuscular blockade; induction is typically with a short-acting muscle relaxant (succinylcholine, rocuronium), followed by short-acting anesthetics (propofol, fentanyl, ketamine) for anesthesia [32, 34]. A train of four stimulations should be used to ensure that all muscle relaxants have worn off at the time of stimulation.

10.3 Motor-Evoked Potentials

MEPs can potentially evaluate the entire motor pathway from the cortex to the motor end plate, including the spinal cord. Proximal stimulation of the motor pathway via transcranial electrodes on the motor cortex elicits a distal motor signal, which may be monitored at the spinal cord (not relevant during MI-LIF), or at the distal limb muscles as myogenic responses. MEPs have been traditionally used to detect motor deficits along the corticospinal tract during spinal cord surgery. Significant changes to MEPs, which indicate likely neurological injury, are defined by an increase in the threshold transcranial voltage more than 50–100 V or complete loss in myogenic response (Fig. 10.1). For peripheral monitoring, the ideal muscle group to observe has rich corticospinal tract innervation; in the lower extremities, the abductor hallucis brevis (S1) or tibialis anterior (L5) is usually monitored [34].

MEPs have a theoretical application to MI-LIF, but thus far have not been used for a number of reasons. First, usually only a single muscle group within the L5 or S1 distribution is monitored, creating a potential for false-negative readings at other spinal levels unless all myotomes are monitored. Second, due to deep positioning of the lower extremity motor areas within the interhemispheric fissure, a greater current is needed to obtain MEPs; it is often that the current is so high that the bilateral upper extremities are concurrently activated. A high-current intensity also creates nonspecific activation of the corticospinal tracts, including the internal capsule and brain stem/foramen magnum, whereas selectivity is only possible with small amounts of currents to specify discrete cortical locations. Normally the anode is the only stimulating electrode, but as the current increases, the cathode also becomes stimulating, creating bilateral activation [34]. Ultimately, the utility, ease, and accuracy of EMG make MEPs inefficient for use during MI-LIF.

10.4 Electromyography

EMG is being successfully used for other MIS procedures [35] and is the most commonly used method for motor monitoring during MI-LIF [6, 35–45]. EMG is advantageous for its ease of use and interpretation, especially during MI-LIF

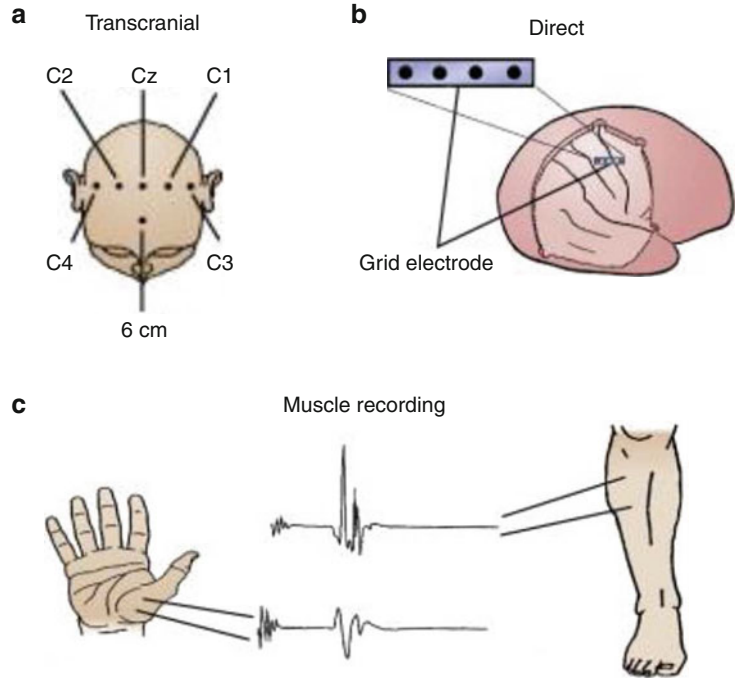


Fig. 10.1 This image shows the setup for MEPs and how the myogenic responses appear (Adapted with permission from Fig. 6, *Schmidek and Sweet's Neurosurgical Operative Techniques*, 6th ed. Chap. 4. *Intraoperative neurophysiology*, pp 30–45. Elsevier, 2012. Original source: Deletis et al. [73]. This figure also adapted with permission from *Pediatric Neurosurgery: Surgery of the Developing Nervous System*. McLone D, ed. 4th ed. Chapter titled *Intraoperative neurophysiological monitoring*, pp 1204–1213. Elsevier 1999). (**a**) Schematic of electrode positions for transcranial electrical stimulation of the motor cortex. (**b**) Illustration of grid electrode overlying the motor cortex. (**c**) Recording of muscle motor-evoked potentials from the thenar and tibial anterior muscles

where nerves lie near the field of view and manipulation. As a test for the proximity of a nerve, it has a high sensitivity and low specificity, making it ideal for screening for nearby nerves [25]. Selecting the appropriate muscles for monitoring depends on the surgeon's ability to access a specific myotome with a percutaneous needle, knowledge of anatomical safe zones during MI-LIF, and which specific nerves are at risk based on surgical anatomy [7–9].

For approaches to the lumbar spine, the nerve roots and distal nerves from T12 to L5 are at risk; it is important to note that even though EMG is normally used for monitoring motor nerves, spontaneous EMG can also be used with triggered EMG to detect antidromic stimulation of sensory nerves [45]. With these two thoughts in mind, Table 10.1 lists the specific nerves, the nerve roots at risk, and the recommended muscles or dermatomes for distal monitoring [43, 45–47].

Free-running EMGs are active whenever a nerve root is compressed, irritated, or injured, which causes spontaneous firing of the nerve and activation of the corresponding myotome. Each morphologic EMG activity reading corresponds to a specific neurotonic discharge: spikes repre-

Table 10.1 At risk nerves, their specific nerve root, and distal innervation

Nerve	Primary nerve root	Muscle
Subcostal	T12	Rectus abdominis
		External oblique
Iliohypogastric	T12–L1	Transversus abdominis
Ilioinguinal		Internal oblique
Genitofemoral (mainly sensory)	L1–L2	Cremaster
		Scrotum (sensation)
		Labia majorum (sensation)
Obturator	L2–L4	Adductor longus/ brevis
		Gracilis
		Adductor magnus
		Obturator externus
Lateral cutaneous (only sensory)	L2–L3	Thigh sensation
Femoral	L2–L4	Iliopsoas
		Quadriceps femoris
		Sartorius
		Vastus lateralis
		Pectineus
Sciatic/deep fibular	L5	Tibialis anterior

sent individual discharges, bursts represent brief bundles of discharges, train activity represents persistent regularly repeated discharge patterns, and neurotonic discharges represent persistent prolonged bursting. A single burst of activity that occurs during surgical manipulations identifies and localizes a specific nerve and does not usually cause any deficit. However, activity that is sustained over 2 s is alarming and should prompt the surgeon to stop whatever specific procedure is causing the sustained activity.

Triggered EMG allows the surgeon to probe specific tissues that are suspicious for containing a nerve. The stimulator tip is a bipolar probe, which sends current into the area being probed to potentially activate any local nerves. EMG thresholds less than 5 mA indicate direct contact, and 5–10 mA indicates close proximity [43, 45, 48]. If there is a myogenic response, the surgeon knows to avoid that specific area.

Both free-running and stimulated EMGs should be used in tandem during the dissection of an MI-LIF. Great care should be taken during dissection through the psoas muscle as well as during dilation, as these procedures involve blind manipulation of surrounding structures that may cause nerve injury. Particularly during these times, free-running EMG should be activated and triggered EMG used frequently to localize potential nerves. EMGs with discrete thresholds and directional orientations are the most ideal, as they provide proximity and location of the nerve to the surgeon's working space [45, 47, 48].

10.4.1 EMG Limitations

While EMG is sensitive in localizing nerves, it is not perfect in preventing nerve injuries for many reasons. Sharp immediate transection through a nerve will produce an immediate permanent injury without any EMG readout [45]. Additionally, the stimulated nerve may still shift within the soft tissue and change its location, requiring frequent sampling to ensure safety [45]. Recent studies have shown that chronic nerve stretching during retraction may not only injure the nerve [49, 50] but also decrease the ability of EMG to detect the nerve as it will become less responsive with greater time of retraction [50]. The incidence of motor neurological deficit ranges from 0.7 to 33.6 % [36, 37, 41, 45, 46, 50–61], with reports of false negatives during EMG use [55]. Ultimately, a transient neuropraxia may just be a consequence of nerve manipulation, especially those nerves that are smaller in caliber [45]. A dexamethasone bolus may help decrease nerve injury during these routine retractions [47, 52]. EMG is unable to identify nerve fibers of the sympathetic nervous system [62].

10.5 Mechanomyography

Mechanomyography (MMG) is a relatively new intraoperative monitoring technology. The basis for MMG monitoring is the detection of the mechanical oscillations on the muscle surface, which occur during muscle contraction, and it is the complementary mechanical signal to the electrical activity detected during EMG [63, 64]. It is primarily used for the identification of muscle fiber typing, assessment of muscle force, evaluation of muscle fatigue, characterization of the muscle resonance frequency, and assessment of muscle contractile properties [63, 65]. Its application to MI-LIF surgery is similar to that of triggered EMG, where the surgeon uses a probe to stimulate areas of interest; if a nearby nerve is stimulated, the MMG sensor will detect the mechanical signal of muscle contraction, alerting the surgeon of a potentially dangerous area. MMG has a few advantages over EMG. First, MMG sensors are noninvasive stickers, and their placement for detection of signal does not need to be precise nor specific [66]. Second, MMG is a mechanical signal, and so it is not affected by changes in skin impedance, which may occur when the skin is wet (sweat, normal saline, etc.) [67].

Conclusions

The use of EMG monitoring has contributed to the substantial decrease in nerve injury after MI-LIF [52, 68–70], and its routine use is strongly recommended [43, 46, 71]. A recent systematic review and meta-analysis of

MI-LIF show strong evidence for the use of nerve monitoring and low-strength evidence that approaches without neuromonitoring have an increased neural complication rate [72]. While knowledge of anatomical safe zones should assist in the approach during MI-LIF [7–9], it should not exclude the use of EMG monitoring which has potential safety benefits with little additional cost. It is important to note that even after diligent monitoring, some patients may awaken with mild and temporary hip flexion weakness; this weakness may not be due to direct nerve injury, but from splitting of the psoas muscle during the approach [13, 43, 45, 47, 52, 53, 56, 71].

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Frameless Navigation

11

Elyne Kahn, Kevin S. Chen, and Paul Park

11.1 Introduction

In spine procedures, radiographic imaging is necessary for localization and is often used to guide instrumentation placement. Fluoroscopy is commonly used; however, its frequent use can be associated with significant intraoperative radiation exposure [3, 4]. More so than in traditional open procedures, minimally invasive procedures typically result in greater radiation exposure, as fluoroscopy is used in place of visual cues due to the decreased spine exposure. In minimally invasive LLIFs, significant fluoroscopy is used to accurately localize the disc space and ensure appropriate placement of the interbody cage. As LLIF continues to gain popularity, spine surgeons must find ways to reduce associated radiation exposure.

CaSN is one validated method that can minimize the use of intraoperative fluoroscopy, thereby reducing the radiation burden to the surgeon and other operating room personnel [1]. Most commonly used for posterior instrumentation, CaSN can also be applied to LLIF.

In this chapter, we describe the surgical technique associated with successful use of the O-arm Surgical Imaging System combined with the StealthStation CaSN (Medtronic, Minneapolis, MN) for LLIF.

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11.2 Technique

11.2.1 Positioning

After induction of general anesthesia, neuro-monitoring leads are placed. Somatosensory evoked potentials and electromyography are monitored. The patient is turned to the lateral position on a Jackson flat table (Fig. 11.1). Typically, a left-sided approach is performed unless there is a significant deformity present, in which case the approach is dictated by the concavity of the curve. Positioning includes placement of an axillary roll and a large roll underneath the flank to open the space between the lower rib cage and iliac crest. The legs are flexed. This maneuver, along with keeping the bed flat rather than "breaking" or "jackknifing" the table, avoids potential stretch injury to the femoral nerve [2]. The use of the flat table also allows easier positioning of the O-arm unit. The patient's position is secured with tape at multiple points, so that tilting of the table can be performed safely.

The skin is prepped and draped in the standard manner. When draping, the anterior superior iliac spine (ASIS) is included in the field. The ASIS will serve as the fixation point for the stereotactic

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Fig. 11.1 Patient is positioned on a Jackson flat table, secured at multiple points with taping, with a large roll underlying the flank

frame. The screen and camera for CaSN are placed at the foot of the bed.

11.2.2 Image Acquisition and Registration to CaSN

An initial stab incision is made over the ASIS, followed by impaction of an iliac pin into the bone. The StealthStation reference arc is then fixated to the iliac pin (Fig. 11.2). Additional sterile drapes are placed to cover the field, leaving the reference arc exposed. The O-arm fluoroscopy unit is then positioned to acquire a 3D image of the targeted spinal levels, which is auto-registered to the StealthStation CaSN system (Fig. 11.3). After registration, the O-arm unit is removed from the surgical field.

11.2.3 Surgical Approach and Cage Placement with CaSN

The initial dilator serves multiple purposes. It is used as a nerve stimulator via a clip electrode as well as for navigation when a tracking arc is attached (Fig. 11.4). This navigated dilator is used to determine the incision site on the flank. Typically, for a one-level procedure, a one-to-one and a half-inch incision is made. After dissection through the subcutaneous tissues, the fascia over the abdominal muscles is opened. The abdominal wall muscles (external oblique, internal oblique, and transversus abdominis) are split, and blunt dissection is used to enter the retroperitoneal space (Fig. 11.5). The psoas muscle can be palpated. A clip electrode for nerve stimulation is attached to the navigated dilator, which is guided

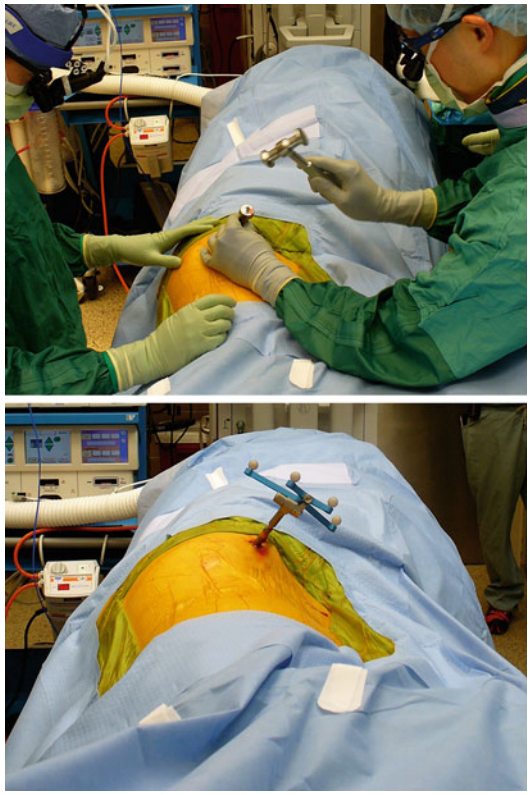


Fig. 11.2 An iliac pin is impacted into the ASIS, with subsequent attachment of reference frame



Fig. 11.3 Positioning of O-arm fluoroscopic unit in preparation for acquisition of a 3D image

into the retroperitoneal space by CaSN (Fig. 11.6). The dilator is navigated through the psoas muscle while being stimulated to prevent nerve injury and advanced into the disc space. The clip electrode and tracking frame are then

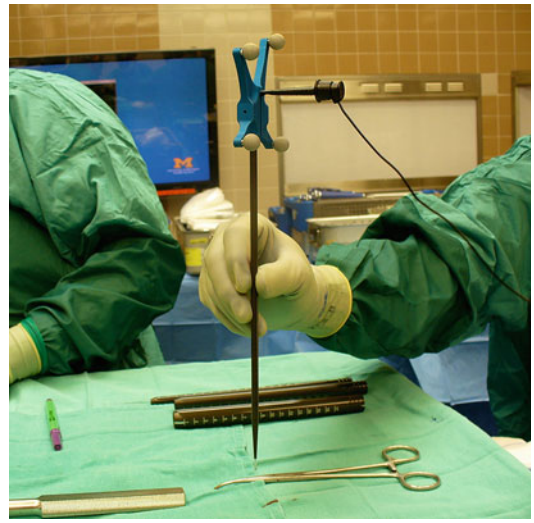


Fig. 11.4 Dilator with nerve stimulation clip and tracking frame attached

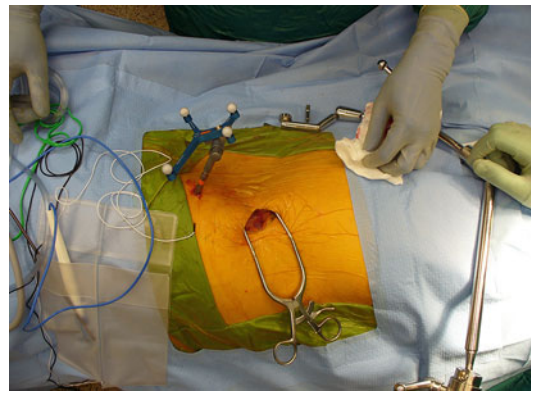


Fig. 11.5 Split abdominal musculature

removed, at which point sequential dilation is performed and an appropriate length expandable retractor is placed (Figs. 11.7 and 11.8). Note that fluoroscopy has not been used.

The retractor is expanded and the light source positioned to optimize visualization. Typically, there is residual psoas muscle present, which is carefully split and retracted. The disc space is visualized, and the navigated dilator is used to confirm adequate positioning of the retractor over the disc space. A knife is used to incise the annulus and discectomy is performed. At this stage, the fluoroscopy unit is positioned in the surgical field to obtain anterior-posterior spot images as

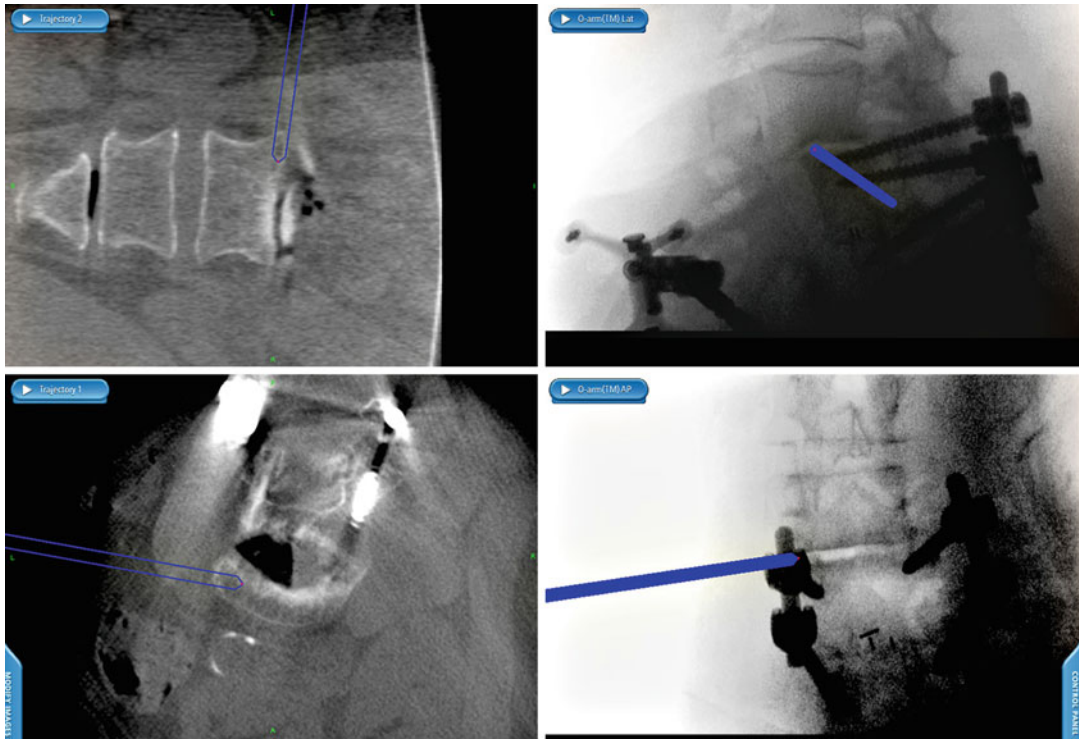


Fig. 11.6 CaSN screenshot showing path of the navigated dilator with clip electrode attached

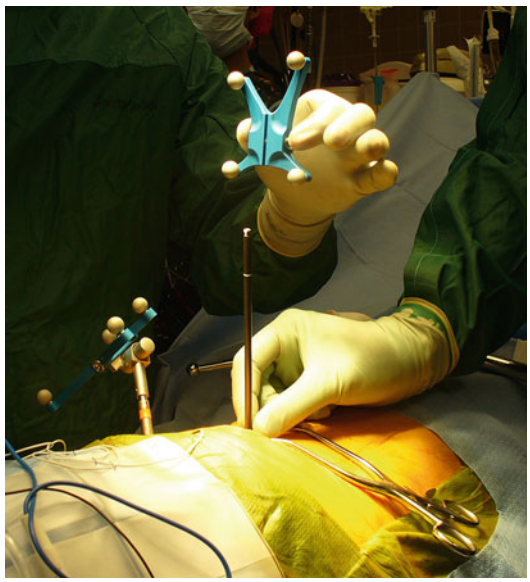


Fig. 11.7 Removal of tracking frame after dilator has been advanced into the disc space using CaSN

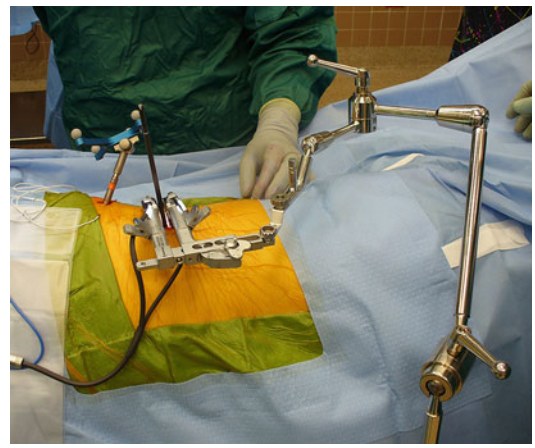


Fig. 11.8 Placement of expandable tubular retractor

needed. Frequently a Cobb elevator, which is not navigated, is used to release the contralateral annulus. Spot fluoroscopy is used to confirm insertion of the Cobb elevator completely through the contralateral side. The endplates are prepared for grafting (Fig. 11.9).

At this point, a trial spacer is navigated into the disc space under CaSN (Fig. 11.10). Allograft bone is packed into the disc space and interbody cage. Cage selection is based on the size of trial spacer used. The cage is attached to a navigated

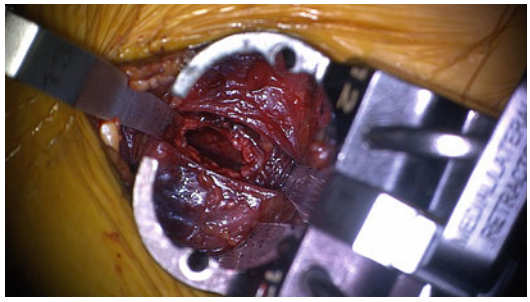


Fig. 11.9 Disc space after discectomy

holder, which allows placement of the cage under CaSN (Fig. 11.11). Spot fluoroscopy is used to confirm appropriate placement (Fig. 11.12).

After cage placement, hemostasis is obtained. The fascia overlying the abdominal musculature is re-approximated, and the remaining incision is closed in layers, with the skin closed with tissue glue. The iliac pin is removed, and this incision is closed with absorbable deep dermal stitches and tissue glue (Fig. 11.13).

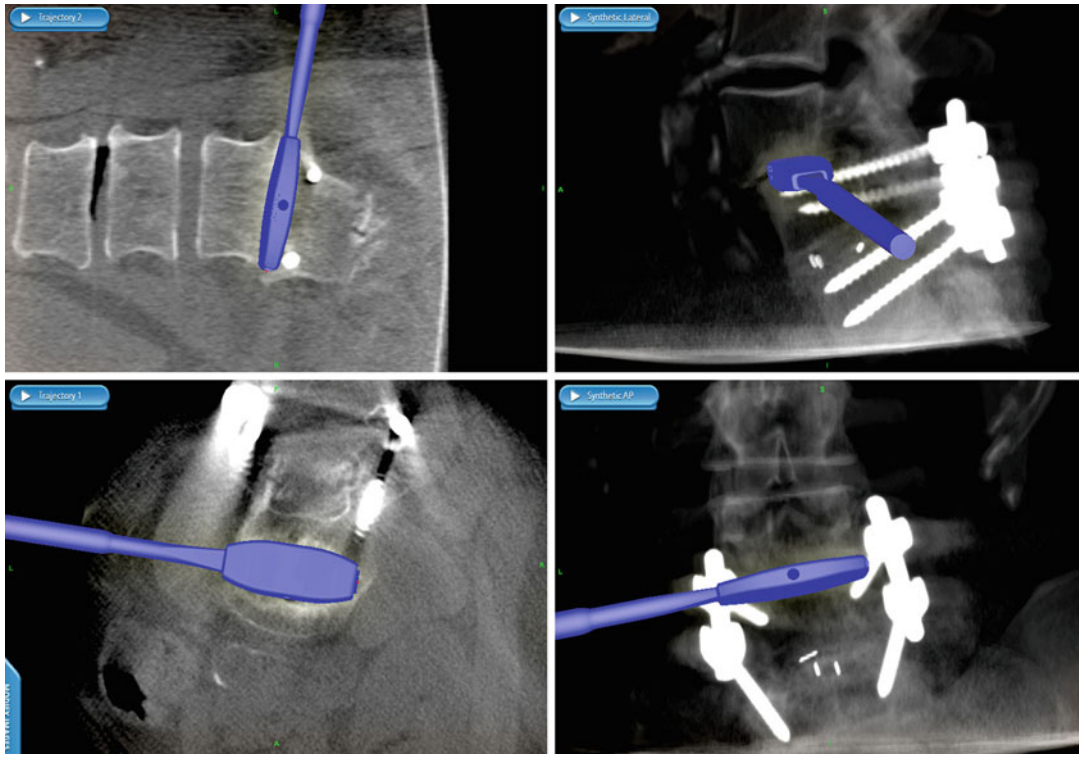


Fig. 11.10 CaSN screenshot as interbody trial spacer is navigated into the disc space

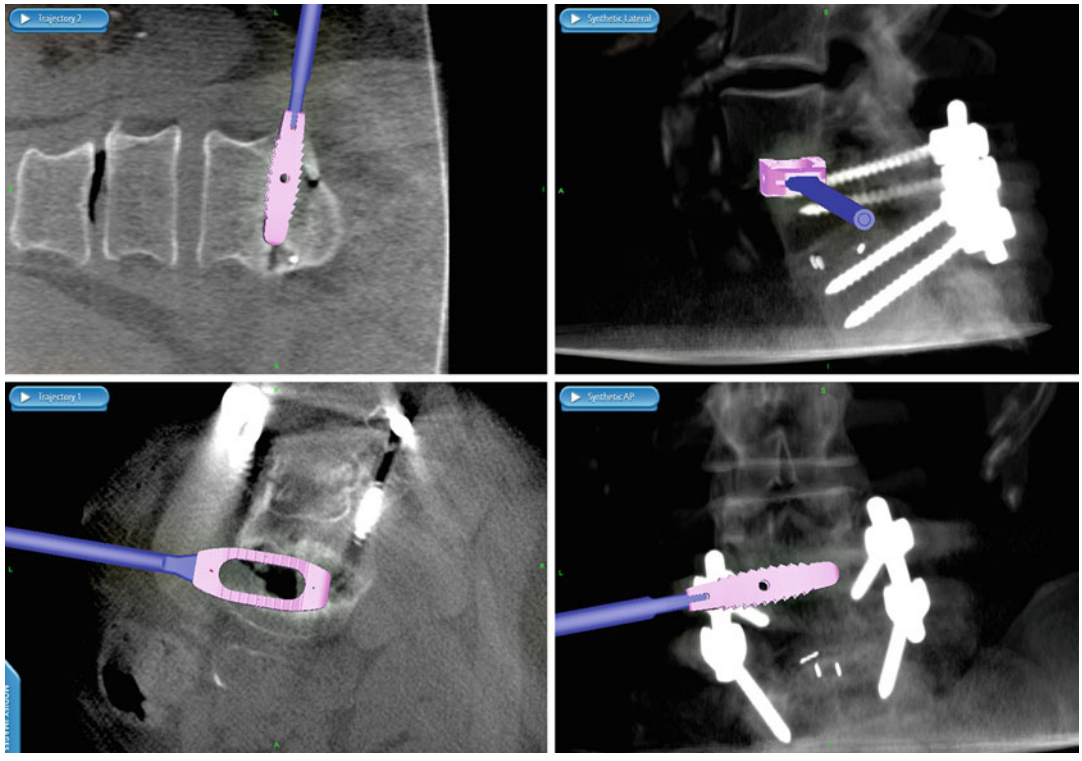


Fig. 11.11 CaSN screenshot as interbody implant is navigated into the disc space

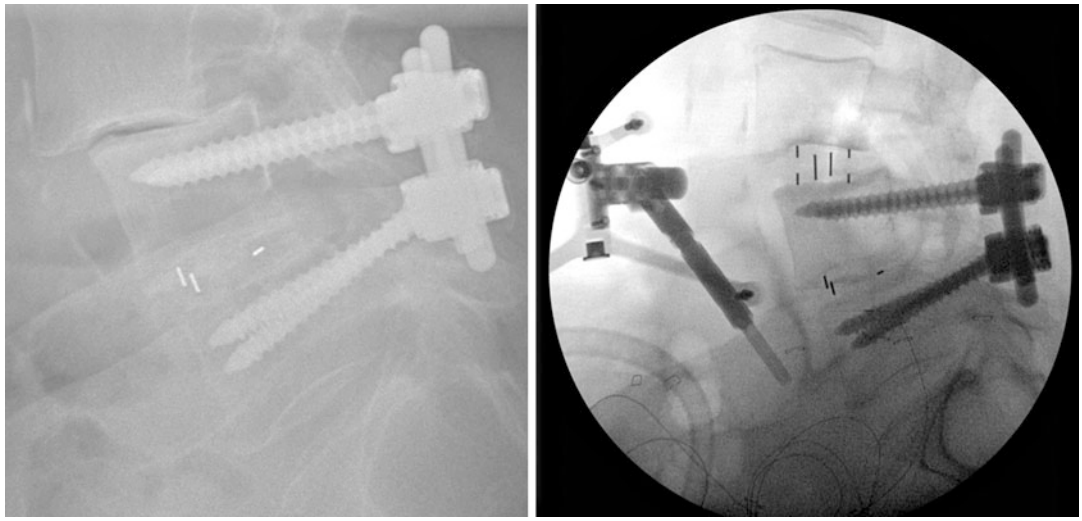


Fig. 11.12 Preoperative lateral x-ray (*left*) and intraoperative fluoroscopic lateral x-ray (*right*) illustrating appropriate placement of interbody cage by CaSN

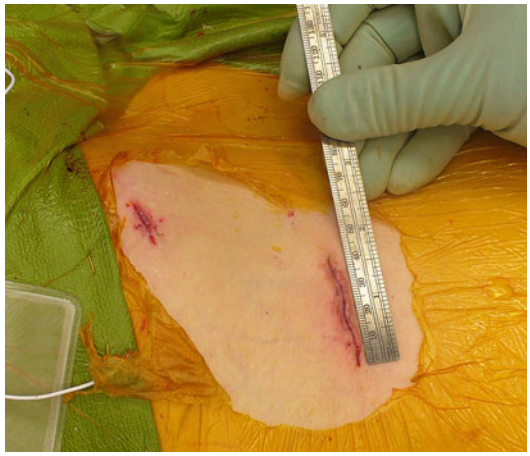


Fig. 11.13 Postoperative closed incisions

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Techniques for Avoiding Psoas Muscle and Lumbosacral Plexus Injury

12

Matthew F. Gary and Michael Y. Wang

12.1 Introduction

Minimally invasive surgical (MIS) approaches to the lumbar spine have been touted for their shorter length of hospital stay, reduced healthcare costs, lower postoperative pain, and lower blood loss when compared to open surgery [1–3]. The minimally invasive lateral lumbar interbody fusion (LLIF) has been praised for its improved preservation of posterior ligamentous structures, large cage footplate, high fusion rates, and enhanced ability to correct coronal malalignment when compared to traditional posterior approaches [4–7].

However, this approach also has its own unique set of complications which are rarely seen with a posterior-only approach, including lumbosacral plexus and psoas muscle injury [8–24]. The ultimate goal of degenerative spine surgery is to improve quality of life by decreasing pain and deformity. These elective procedures must minimize potential complications lest the treatment become worse than the disease itself. A patient who presents with radicular pain and leaves postoperatively with severe quadriceps weakness would likely question the utility of the procedure in improving quality of life, especially since a posterior-only approach does not typically carry a high risk of this complication.

As new approaches and techniques evolve, ultimately the goals of spine surgery remain the same: maximize patient quality of life while minimizing the risks associated with the treatment. Since surgery for degenerative disease is typically elective, even low rates of a particular complication can be problematic if the complication causes significant pain or loss of function. To this end much research has been conducted to understand the complications associated with the lateral approach and the best methods for avoiding them.

Because one of the most common and devastating complications from LLIF is related to the lumbosacral plexus, a thorough knowledge of the regional neuroanatomy in relation to the psoas muscle and disc spaces is essential for surgery to be performed with maximal safety. Proper preoperative planning, careful abdominal dissection, electrophysiologic monitoring, limited retraction, shallow docking, and an oblique approach are just a few of the tools discussed below to help the practitioner avoid plexus injury.

12.2 Anatomy

Unlike the brachial plexus, which has been thoroughly studied and dissected by neurosurgical and orthopedic residents, the lumbosacral plexus

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anatomy remains foreign to many spine surgeons. The first step in avoiding an injury to the lumbar plexus is to understand the anatomical relationships between the lumbar plexus, psoas muscle, and intervertebral disc spaces. A number of cadaveric studies have examined these anatomical relationships with particular attention to the LLIF approach [25–31]. The plexus is a retroperitoneal structure that is situated mostly within and around the psoas major muscle.

The ventral divisions of the T12–L4 nerve roots form the lumbar plexus. The iliohypogastric nerve is formed from T12 to L1. It innervates the transversus abdominis and internal oblique muscles, and it subserves sensation to lateral gluteus and the abdominal below the umbilicus. It emerges from the lateral boarder of the psoas and travels obliquely anterior to the quadratus lumborum muscle to the iliac crest.

The ilioinguinal nerve is formed from L1. It supplies sensation to the scrotum and labia and has a similar retroperitoneal course to the iliohypogastric nerve. The genitofemoral nerve arises from L1 to L2. It innervates the cremaster muscle in males and has genital branches (sensation to the groin) and femoral branches (sensation to the upper anterior thigh). It is unique as when it travels inferiorly from its origin, it emerges from the psoas muscle and travels along the anterior surface of the psoas muscle. The lateral femoral cutaneous nerve arises from L2 to L3. It supplies sensation to the lateral aspect of the thigh, and it emerges from the lateral aspect of the psoas muscle at these levels.

The femoral nerve arises from L2 to L4 and descends through the fibers of the psoas muscle before emerging from the lateral border of its lower aspect. Its motor division supplies multiple muscles (iliopsoas, pectineus, sartorius, and quadriceps femoris). Thus, weakness of leg extension is the most notable deficit related to femoral nerve injury. Also, its sensory branches supply the anterior and medial aspect of the thigh and leg. A severe femoral nerve injury prevents normal ambulation, and in severe cases, it prevents standing. Thus, a femoral nerve injury is a serious complication 5.

The obturator nerve arises from L2 to L4 and supplies the adductor muscles of the thigh (obturator externus, adductor longus, gracilis, pectineus, and adductor magnus). The sensory branch innervates a small portion of the upper medial thigh. Like the femoral nerve, the obturator descends within the fibers of the psoas muscle to its lower aspect where, unlike the femoral nerve, it exits along its medial border.

12.3 Symptoms and Relevance to LLIF

Thigh symptoms following a lateral approach include pain, paresthesias, numbness, and weakness in hip flexion and knee extension. These complications are secondary to either direct injury to the nerves traversing the psoas muscle or indirect compressive injury to these nerves from retractors (Fig. 12.1). The reported incidence of postoperative thigh pain following a lateral lumbar approach remains high. Bergey et al. reported a 30 % incidence of postoperative thigh and groin pain following LLIF [32], while Cummock et al. noted 39 % of patients had postoperative thigh pain and 24 % had weakness [33]. Gu et al. determined that the safe zone for performing a discectomy lies between the plexus posteriorly and the sympathetic trunk anteriorly [34].

The anatomical position of the lumbar plexus relative to the intervertebral disc spaces was studied by Uribe et al. in an attempt to find safe "working zones" [31]. They divided the lateral vertebral body from anterior to posterior into four equal zones with Zone I, the anterior quarter; Zone II, the anterior middle quarter; Zone III, the posterior middle quarter; and Zone IV, the posterior quarter. Zone III was the safest approach for L1–4 disk spaces (Figs. 12.2 and 12.3). At these levels, all the major elements of the lumbar plexus were posterior to Zone III with the exception of the genitofemoral nerve. The genitofemoral nerve was at risk for injury in Zone II of the L2/L3 disc space and Zone I of the L3/L4 and L4/L5 disc space. They also found that the L4–5 disc

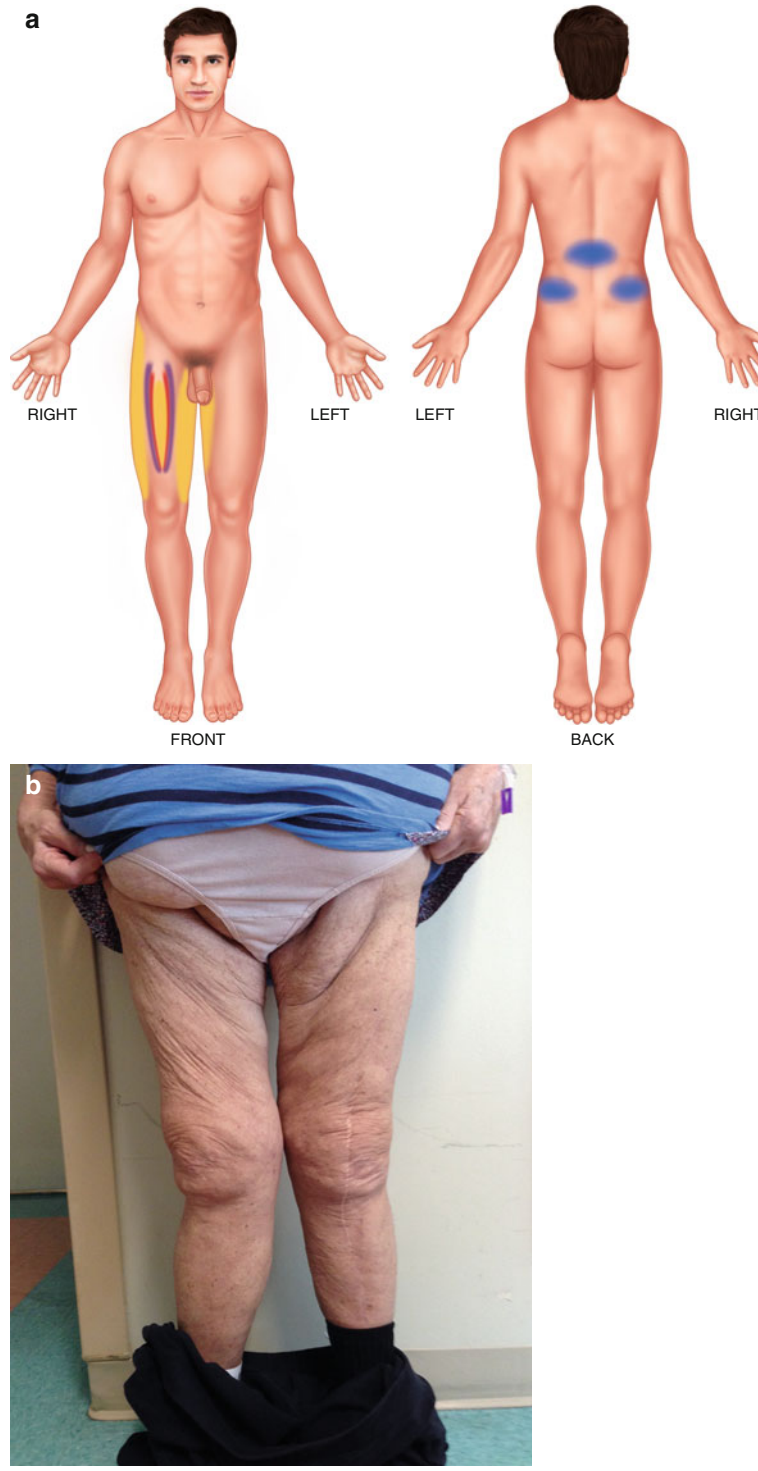


Fig. 12.1 (**a**) Pain drawing of a patient with thigh pain and numbness following a lumbosacral plexus stretch injury with an LLIF surgery; (**b**) thigh atrophy from an upper lumbar plexus injury causing quadriceps weakness and wasting

space was more safely approached from a more anterior trajectory, namely, at the midpoint of the vertebral body. Benglis et al., Banagan et al., and Guerin et al. likewise noted a ventral progression of the lumbar plexus with lower disk levels [25, 26, 29].

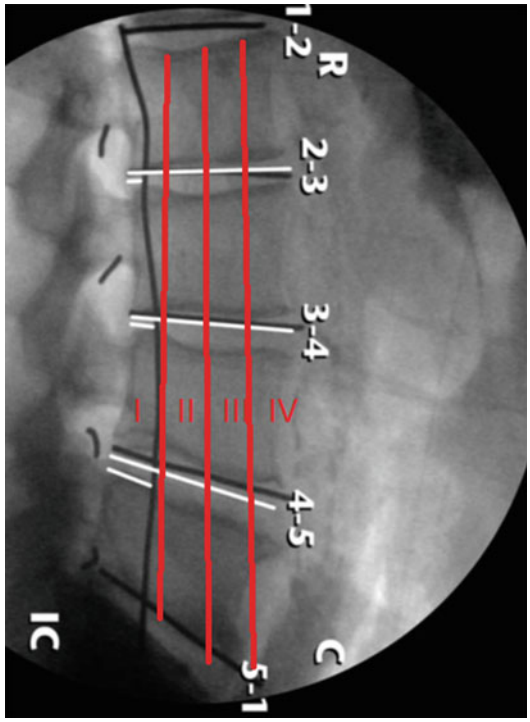


Fig. 12.2 Working zones of the psoas muscle as described by Uribe [31]

12.4 Preoperative Planning and Setup

Given the narrow safe working zones described above, adequate patient and fluoroscopic positioning are critical to ensuring the proper placement of retractors during the lateral approach. Poor patient positioning and a lack of understanding how to find the true lateral or anterior/posterior (AP) imaging will lead to the placement of instrumentation through critical structures. The patient is placed in the lateral decubitus position with an axillary roll. The arms are well padded with the top arm supported by either a pillow or arm sling. The head is supported with padding and the leg on top is placed on a pillow and flexed. Flexing the top leg allows relaxation of the ipsilateral iliopsoas and plexus thus reducing traction on them during the procedure. The iliac crest is placed just below the break in the table, and the torso is lowered to open the space between the ribs and iliac crest on the approach side. The bed is then placed in reverse Trendelenburg to bring the spine parallel to the floor. Finally, the patient is secured in this position with tape across the chest and hips.

AP fluoroscopic imaging is obtained to ensure a true lateral position. On AP the spinous processes at the levels of interest should be perfectly centered between their respective pedicles. If there is a large discrepancy, the patient is repositioned accordingly. If there is a minor discrepancy, the bed can be rotated to obtain a true AP

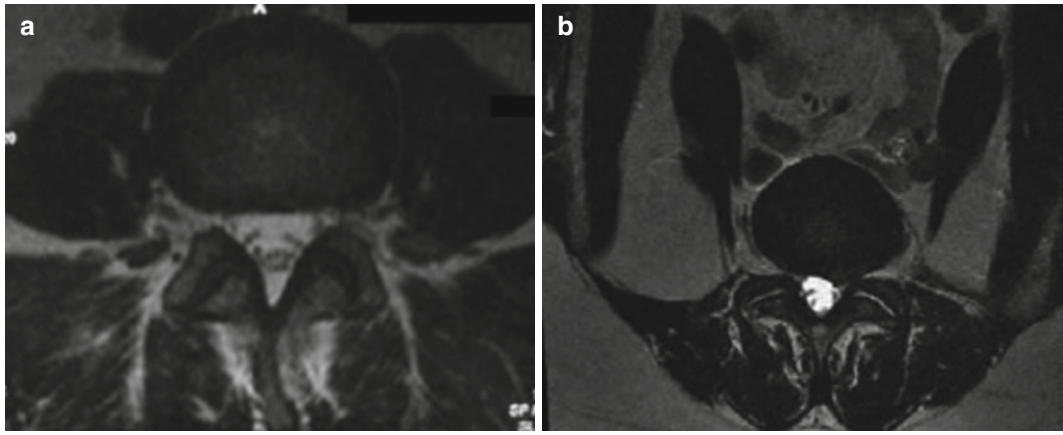


Fig. 12.3 (**a**) Psoas anatomy at a level conducive to an LLIF approach; (**b**) the "rising psoas" sign showing the muscle moving anteriorly and taking the plexus with it, rendering the nerve anatomy unpredictable

image. Having the patient in a perfectly lateral position allows for proper placement of the instrumentation in the safe working zones described above. It also ensures that the discectomy and cage placement are performed safely. A lateral image is obtained, the borders of the disc space are marked on the skin, and the incision is planned (single- or two-incision technique). The flank incision should always be in a horizontal direction to avoid injury to the plexus branches traversing the lateral abdominal musculature and to respect the Langer lines.

When performing LLIF through an MIS approach, the surgeon must also be aware of the anatomy of the psoas muscle.

12.5 Retroperitoneal Dissection

Though injury to the plexus is most frequently encountered while dissecting through the psoas muscle, the nerves traveling outside of the psoas in the retroperitoneal space are also at risk of injury during the abdominal dissection. Dakwar et al. performed cadaveric studies looking at the trajectories of the major motor and sensory branches of the lumbar plexus outside of the psoas muscle and within the retroperitoneum and abdominal wall [28]. They found that four plexus branches were at risk of injury during dissection through the abdominal wall and retroperitoneal space: subcostal, iliohypogastric, ilioinguinal, and lateral femoral cutaneous nerves. Injury to these nerves can occur during the flank or lateral incision and can lead to abdominal wall paresis and sensory deficits in the corresponding dermatome.

In order to avoid injury to these nerves, once the external oblique muscle fascia is sharply opened, blunt muscle dissection should be performed until the retroperitoneal cavity is identified. Bovie cauterization and bipolar must be limited, and any electrocautery should be limited to bipolar electrocoagulation. If a nerve is discovered during dissection, it can be carefully dissected and mobilized. Once the retroperitoneal space is encountered, blunt dissection of the peritoneal contents from posterior to anterior is performed until the transverse process and psoas muscle are encountered [28]. If using finger dissection, one must be careful not to avulse any presumed fibrous bands as they could be nerves.

12.6 Electromyography

Triggered electromyography (t-EMG) has been described to detect motor branches of the plexus during dissection through the psoas muscle [6, 35]. Using threshold stimulation, one can potentially determine the proximity of the dilators to adjacent nerves. Clinically normal nerves elicit an EMG response with stimulation ranging from 1 to 5 mA, with a mean of about 2 MA [36, 37]. The closer the stimulator is to the nerve, the lower the current needed for stimulation. Thus, thresholds of 5 mA or less indicate that the stimulator is possibly in direct contact with the nerve. Thresholds between 5 and 10 mA are generally considered to be a gray zone where caution must be elicited, while thresholds greater than 10 mA are considered safe.

Some dilators have directional stimulation that allows the operator to test where the lowest threshold (and thus the nerve) is located relative to the dilators. If a threshold less than 10 mA is encountered, the dilators can be repositioned away from the stimulated nerves. Tohmeh et al. prospectively studied the EMG threshold values of 102 consecutive patients undergoing LLIF. They found that 55.7 % of the cases had alert-level EMG feedback (thresholds less than 10 mA) with initial dilator placement, which lead to repositioning. Transient motor deficits occurred in three patients (2.3 %) with all resolving by 6 months. Of note, two of the three patients had spontaneous EMG (S-EMG) activity in the affected myotome during the surgery while trial spacers were being inserted. Despite these promising findings, t-EMG is limited to motor nerves only leaving the sensory nerves vulnerable. Thus, Tohmeh et al. found that 17.6 % of their patients experienced thigh sensory deficits immediately postoperatively. However, t-EMG does not warn of stretch injury, and false negatives may occur from shunting of the stimulation through the blades [38].

12.7 Retraction

When further visualization of the disc space after inserting the working retractor into the psoas muscle, it is important to only open the anterior blade. Opening the posterior blade can lead to stretch injury of the plexus and/or can crush the plexus between the blades of the retractor and the transverse processes. Also the length of surgery has been found to correlate with increased extremity symptoms, presumably from longer periods of psoas and plexus retraction [8]. Thus, once the retractor is opened, the disc space must be prepared in a timely fashion.

12.8 Shallow Docking

As illustrated above, good t-EMG may significantly lower the risk of injury to the motor nerves but it does not limit sensory nerve injury. To this end a different technique is described whereby instead of serially dilating through the psoas muscle, the working retractor is guided onto the surface of the psoas muscle without entering it [38]. Once the working retractor is in proper position as determined by fluoroscopy, the psoas muscle is bluntly dissected in a longitudinal fashion exposing the disc space (Fig. 12.4). Any nerves will likely be clearly visualized or at least amenable to "mapping" of the surface of the psoas muscle to detect the proximity of any lumbosacral plexus nerves.

During dissection, t-EMG can be used to distinguish motor from sensory nerves. These exposed nerves are then dissected away from the exposed disc space so that the interbody work can safely be performed. Of note, the retractor is not advanced through the psoas muscle limiting retraction injury on both the muscle and nerves. Acosta et al. described their experience utilizing this technique on 15 consecutive patients. No patients were noted to have postoperative weakness, numbness, or pain immediately or at last follow-up; however, the study was admittedly of small sample size [38].

12.9 Oblique Approach

The oblique approach is a variant of the lateral approach discussed in great detail in the following chapter. It is mentioned here since its

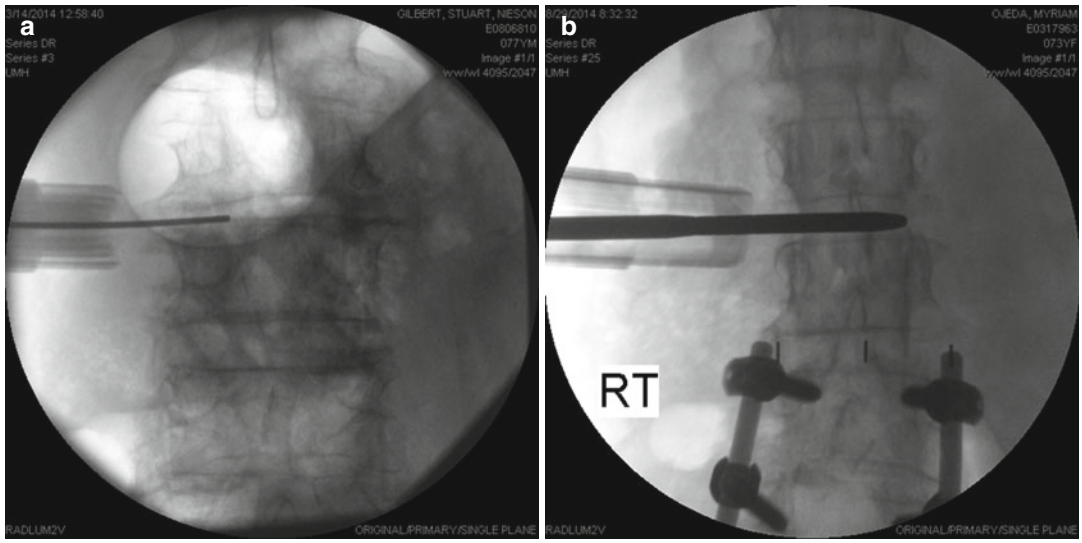


Fig. 12.4 Shallow docking technique showing (**a**) retractor placement on the surface of the psoas muscle followed by (**b**) dilation below the disc pace

main function is limiting psoas muscle and plexus injury. During this approach, the anterior aspect of the psoas muscle is exposed, dissection is performed between the anterior border of the psoas muscle and the sympathetic trunk, and the entire psoas muscle is retracted posteriorly while the sympathetic trunk is retracted anteriorly [39, 40]. This has the advantages of being further away from the plexus than the standard lateral approach. Also, no dissection through the psoas muscle is needed limiting any injury to it. However, this approach has its own set of challenges including: manipulations of the sympathetic trunk, rocking of the inserter posteriorly to obtain correct positioning of the cage, and closer proximity to the great vessels.

Conclusion

Understanding of the potential complications associated with the MIS lateral approach has increased tremendously since becoming popularized. The rate of permanent postoperative weakness is low if performed correctly, but can still be unpredictable. The rate of transient thigh and leg symptoms remains elevated, which has motivated surgeons to focus on techniques for avoiding them: (1) anatomical knowledge, (2) proper positioning, (3) blunt abdominal dissection, (4) t-EMG, (5) limited retraction, (6) shallow docking, and (7) oblique approach.

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Part III

Soft Tissue Management

13 Single Versus Dual Incisions for Lateral Retroperitoneal Approach

Gisela Murray, Chun-Po Yen, and Juan S. Uribe

13.1 Single Incision

13.1.1 Surgical Technique

The patient is properly positioned and taped. With the help of a fluoroscope, the incision is centered transversely following the disk space at the posterior third of the targeted disk. The exception is at L4/5, where the center of the incision is made at the middle of the disk space. A 3 cm skin incision is made. The subcutaneous fat is dissected until the fascia is encountered. This fascia should be opened with the monopolar cautery in a transverse incision aligned with the disk space. The underlying muscles are gently dissected with the use of two tonsil hemostats through each muscle layer: external oblique, internal oblique, and transversus abdominis muscles. Lastly, the transversalis fascia is opened and the retroperitoneal space is encountered. This step should be cautiously directed straight down. If the dissection is carried too anteriorly, it may cause bowel injury, or if carried too posteriorly, it may lead to nerve injury. The index finger is introduced to dissect the retroperitoneum and mobilize the peritoneum and its contents anteriorly. The surgeons can palpate and follow the transverse process to the psoas muscle. The index finger then pushes the peritoneal contents anteriorly and guides the initial dilator to the lateral surface of the psoas muscle. The larger dilators and retractor are subsequently introduced in a similar fashion (Fig. 13.1).

13.2 Dual Incisions

13.2.1 Surgical Technique [1]

When performing a dual-incision technique, the lateral incision is marked at the same location as above. A second incision is made posterior to this first mark at the lateral border the erector spinae muscles. Alternative blunt scissor and finger dissections are used to open the corridor through the abdominal muscles and fascia. This step should be made with caution to avoid inadvertent violation of the peritoneum. Once in the retroperitoneum, the index finger is used to sweep the peritoneum anteriorly and then to palpate the transverse process and the psoas muscle. Then, the finger dissection is continued upward and toward the lateral mark. A skin and fascial incision is made at this location, and the initial dilator is introduced. The index finger, which is in the retroperitoneal space through the posterior

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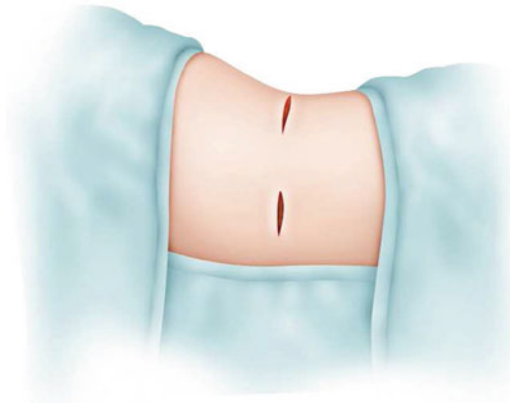


Fig. 13.1 Dual incisions allowing for dissection of the retroperitoneal space blindly with a finger

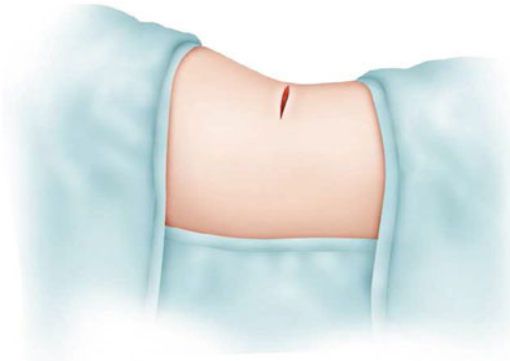


Fig. 13.2 Use of a single incision with a mini-open approach where retroperitoneal dissection is accomplished under direct vision

incision, is used to escort the initial dilator down to the psoas muscle (Fig. 13.2).

13.2.2 Advantages and Disadvantages

Both of the approaches for the lateral interbody fusion are well-accepted options. Each has their own set of advantages and disadvantages. The dual incision was the initial procedure described by Pimenta [1]. The advantage of this procedure is effective displacement of peritoneal structures anteriorly and provides easier maneuver of the dilators toward the psoas muscle. However, there are few disadvantages, including the risk of injury of the iliohypogastric and ilioinguinal nerves [2, 3]. Both of these nerves run within the retroperitoneal space anterior to the quadratus lumborum and iliopsoas toward the iliac crest and can be injured while performing the posterior incision. It is more time-consuming to perform two separate incisions.

On the other hand, the single-incision procedure has the benefit of providing a shorter procedure and less postoperative incisional pain. This approach is generally faster and also potentially avoids the injury to nerves that run adjacent to the quadratus lumborum. The theoretical disadvantage of the single incision is that the peritoneum was not displaced sufficiently anterior; thus the risk of injuring the peritoneal structures might be greater. However, by introducing the index finger through the lateral incision to protect the peritoneum and guide the initial dilator through the same incision, we have not experienced any bowel injuries.

Conclusions

Both techniques can be performed safely with minimal risk of complications. The surgeons should perform whichever technique they feel comfortable. Meticulous dissection following the tissue planes is the key to avoid any complications.

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Lateral Transpsoas Retractor Technology

14

E. Jyles Rodgers and W.B. Rodgers

14.1 Introduction

The lateral or anterolateral transpsoas approach to the lumbar spine was developed in the early 1990s [1, 2] but was largely abandoned due to a challenging access corridor and high incidence of neural complications [2]. In the late 1990s and early 2000s, Luiz Pimenta, MD, PhD, developed a 90° lateral, retroperitoneal, transpsoas approach to the lateral aspect of the anterior lumbar spine called extreme lateral interbody fusion (XLIF®, NuVasive, Inc., San Diego, CA) [3]. What contributed to the success of the XLIF approach was the integration of approach (sequential dilators) and procedural instrumentation with evoked electromyography (EMG) that stimulated directionally and provided discrete threshold responses (NVM5®, NuVasive, Inc.) to *map* neural structures (e.g., lumbar plexus) in the vicinity of the access corridor [4, 5] and a specialized retractor designed for the lateral transpsoas approach (MaXcess®, NuVasive, Inc.). The purpose of this chapter is to describe some of the commercially available retractors and procedures available for accessing the lateral lumbar spine. The authors note that they have no experience with retractor systems other than the MaXcess and, as such, much of this chapter will be focused and descriptive.

14.2 MaXcess® (NuVasive, Inc.)

The retractor used in the XLIF approach, MaXcess, was the first specialized retractor to be developed for the lateral transpsoas approach (Fig. 14.1). The MaXcess retractor is currently in its fourth iteration since release in 2003 and is defined by a series of features designed to streamline lateral approach surgery. It would be impossible to discuss the retractors of lateral transpsoas surgery without first discussing placement of the retractors, as traversing the iliopsoas muscle with regard to the lumbar plexus is the cornerstone and differentiating factor among the various lateral procedures. In XLIF, sequential dilators are passed through the retroperitoneal space, with digital guidance, and bluntly through the psoas muscle while rotating and under evoked EMG. Using this technique with three sequential dilators, mapping of neural structures is made possible by discrete threshold EMG responses in directional orientations [4]. Over the third dilator, the MaXcess retractor is placed. As the lumbar plexus should be posterior to the access corridor,

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Fig. 14.1 Photograph showing the MaXcess® (NuVasive, Inc.) retractor with detachable handle, table mount, and anterior retractor

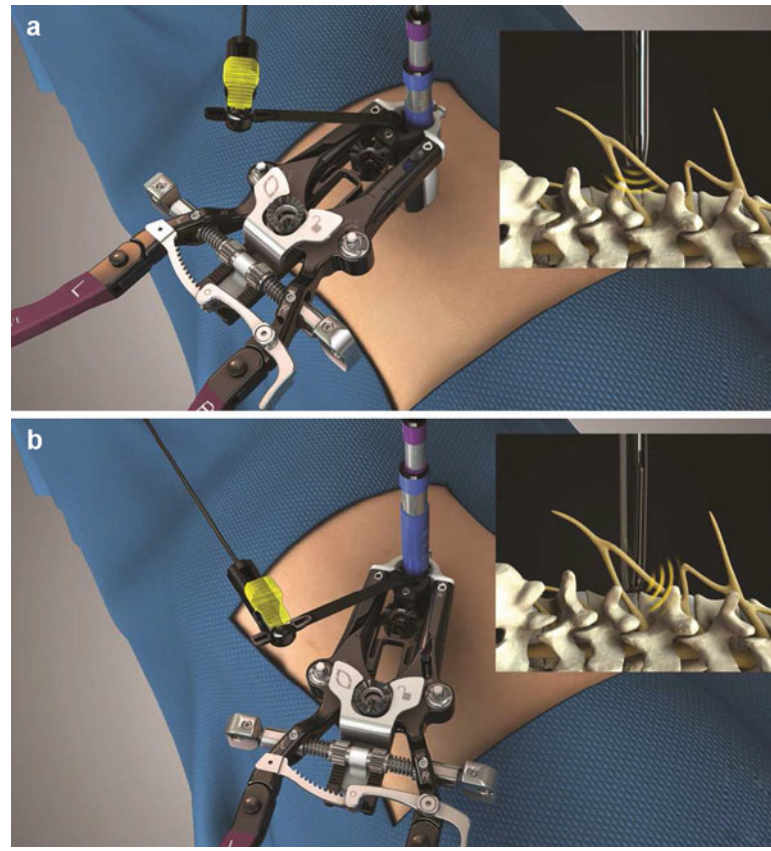


Fig. 14.2 Intraoperative illustrations showing evoked-EMG stimulation in MaXcess off the posterior (*center*) blade electrode over the sequential dilators while rotating (**a**, **b**) the retractor to provide directional and distance EMG information about motor nerves posterior to the retractor

evoked EMG is embedded into the posterior blade of the retractor for continuous mapping while docking the retractor around the border between the middle and posterior third of the lateral disk space (Fig. 14.2) [5]. It should be noted that it is the senior author's (WBR) preference to dock the retractor as far posteriorly as safely possible to allow better disk space preparation, partial central vertebrectomies (preserving the cortical ring of the endplate) as needed for decompression, the use of larger interbody implants, and more complete grafting.

The MaXcess retractor's primary feature is a split-blade design, with three main blades, one in the posterior orientation to the surgical approach and one each in cranial and caudal orientations

(Fig. 14.3). The diameter of the closed blades is approximately 12 mm. Each of these blades can be manipulated independently of each other both to retract separately in cranial, caudal, and/or anterior orientations (by the cranial-caudal blades) simultaneously and posteriorly, if needed, by the posterior blade (Fig. 14.4). Each of the cranial and caudal blades can also be splayed either inwardly or outwardly to allow for additional or less cranial or caudal surgical site exposure without extension of the surgical incision (Fig. 14.5). Light sources are placed into each of the cranial and caudal blades for visualization of the lateral disk and working space (Fig. 14.6). A shim is placed down the posterior blade and into the disk space to hold the retractor in the chosen

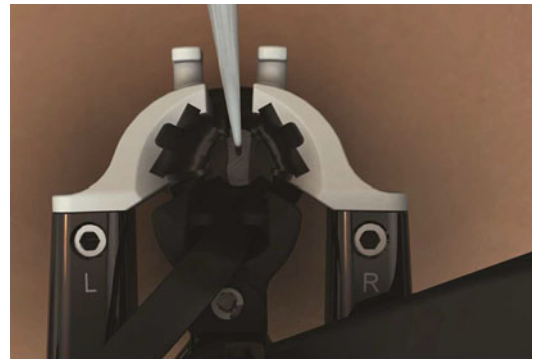


Fig. 14.3 Illustration of the surgeon's point of view in XLIF® (NuVasive, Inc.), with the three unretracted blades of the MaXcess retractor (posterior, cranial, and caudal) with a K-wire in the disk space and the NVM5® (NuVasive, Inc.) stimulating electrode shown in the posterior blade

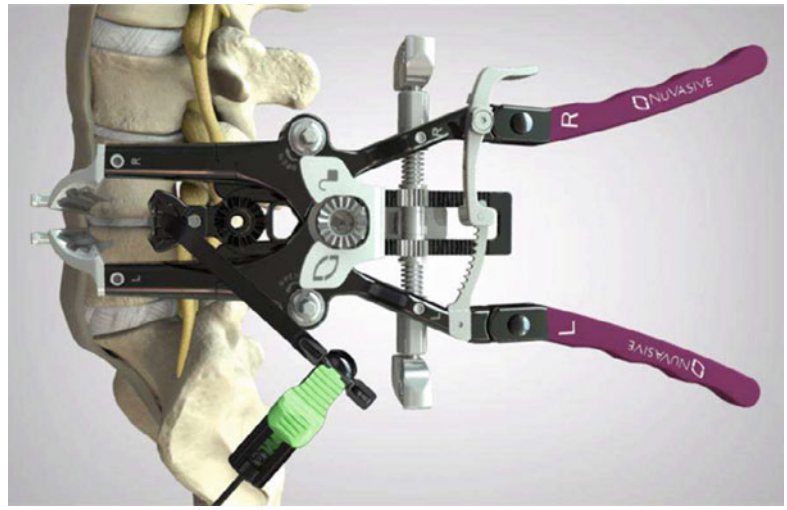


Fig. 14.4 Lateral illustration showing the MaXcess retractor with anterior-only retraction by the cranial and caudal retractor blades with the posterior blade NVM5 EMG electrode and visual discrete threshold feedback clip (*green clip* on electrode)

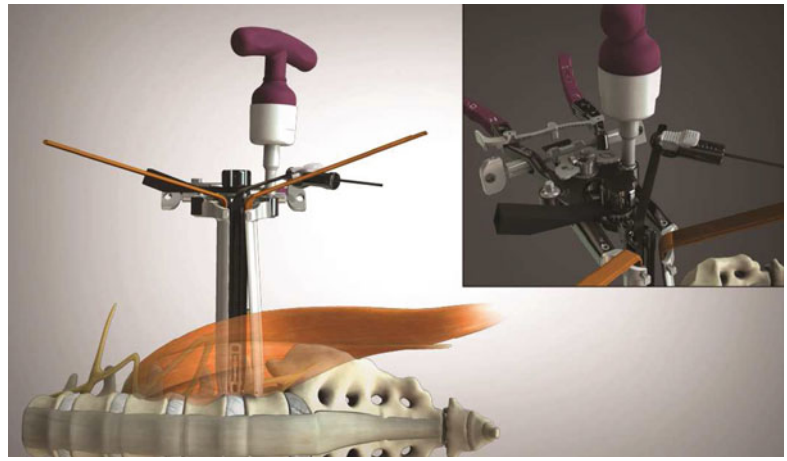


Fig. 14.5 Anterior illustration of XLIF with MaXcess showing individual blade splay for surgical site expansion or retraction without change in incision size

position. A fourth retractor blade can be placed anterior to the cranial and caudal blades, primarily to realize the potential space anterior to the anterior longitudinal ligament (ALL) or to provide a barrier between those structures and the working space (Fig. 14.1). Intraoperatively, the MaXcess retractor allows for broad visibility of the working corridor and disk space (Fig. 14.7).

Categorically, the features of the MaXcess retractor include:

Access: Sequential dilation under real-time, surgeon-directed, evoked EMG with discrete threshold responses in directional orientations.

Mounting: Table mounted.

Blades: Split, with three blades, with each retractable separately and with inward and outward splay capabilities for the cranial and caudal blades. Optional fourth blades include ALL retractor or spatula accessories, the latter for tumor, trauma, and thoracic applications (Fig. 14.8). The closed retractor diameter is 12 mm.

Neuromonitoring: Evoked EMG (NVM5) integrated into approach (dilator) and procedural instrumentation, including the posterior blade of the retractor (Fig. 14.9).

Other retractor systems for lateral transpsoas access have similar features and somewhat similar applications, so will be categorically described

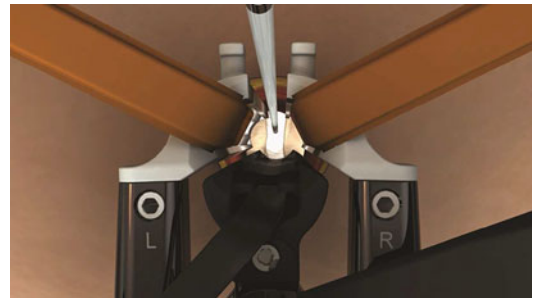


Fig. 14.6 Surgeon's point of view illustration in XLIF showing the MaXcess retractor with lighting elements in place in each of the cranial and caudal blades

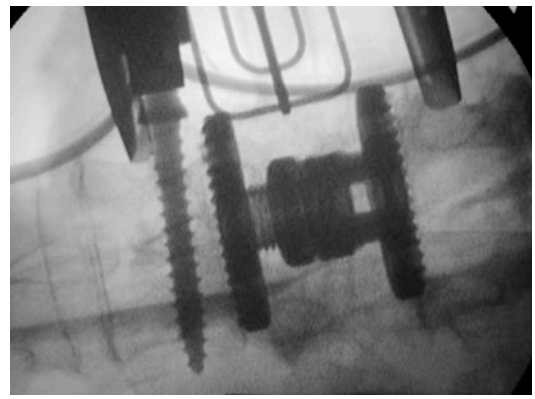


Fig. 14.7 Anterior intraoperative fluororadiography showing and XLIF corpectomy using the MaXcess retractor and the anterior (*fourth blade*) spatula attachment for lung deflection

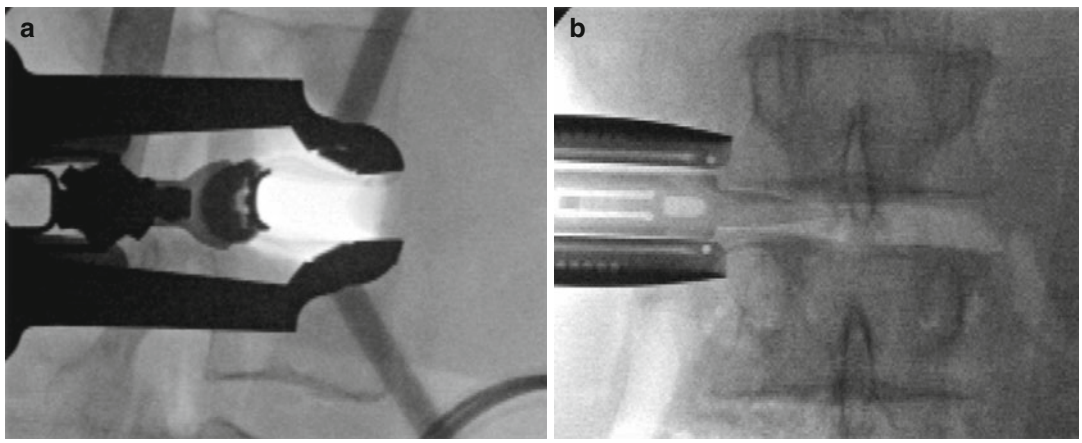


Fig. 14.8 (**a**) Lateral intraoperative fluororadiograph showing exposure and imaging view capability with the MaXcess retractor in XLIF. (**b**) Anterior intraoperative fluororadiograph showing the posterior blade shim in place in the disk with limited retraction to expose only the disk

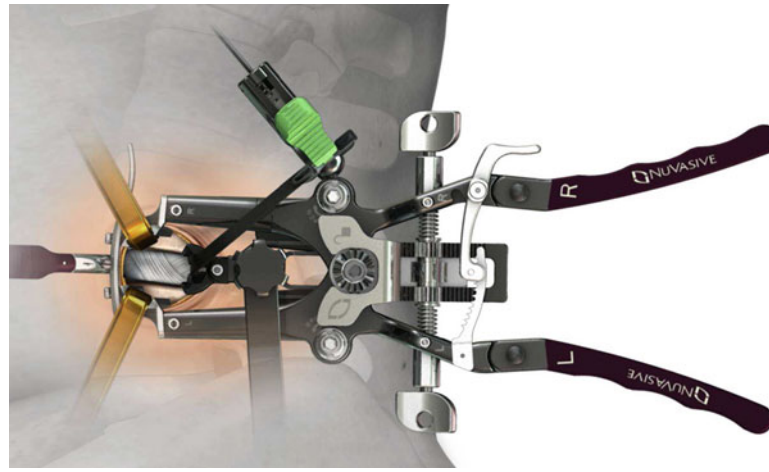


Fig. 14.9 Lateral illustration showing the MaXcess retractor in XLIF with the table mount, posterior blade NVM5 stimulating electrode, light cables, and anterior (*fourth*) blade in place

as MaXcess was, based on how *access* is gained, how they are *mounted*, their *blade* structure and capabilities, and their use of *neuromonitoring* (Fig. 14.10).

14.3 Mars® 3V (Globus, Inc.)

Access: A series of sequential dilators without incorporated neuromonitoring.
Mounting: Table mounted.
Blades: Three aluminum blades, one posterior and one each in cranial and caudal orientations (as with MaXcess). Each blade can be splayed outward, including the posterior blade, which is able to be splayed posteriorly. Closed, the retractor has an exposure diameter of 23 mm.
Neuromonitoring: No integrated neuromonitoring. Relies on third-party neuromonitoring.

14.4 Quadrant® (Medtronic Sofamor Danek, Inc.)

Access: A series of five sequential dilators, several with directional stimulation using evoked EMG.
Mounting: Table mounted with the use of stability pins.
Blades: Two blades, one each in cranial and caudal positions, with retraction possible in cranial and caudal directions only. No integrated neuromonitoring components. Closed retractor diameter of 22 mm.
Neuromonitoring: NIM-Eclipse® neuromonitoring platform.

14.5 Pipeline® (Depuy Synthes, Inc.)

Access: A series of sequential dilators without incorporated neuromonitoring.
Mounting: Table mounted.
Blades: Telescoping blades, retractable only in the cranial-caudal orientation.
Neuromonitoring: No integrated neuromonitoring. Relies on third-party neuromonitoring.

14.6 Oracle® (Depuy Synthes, Inc.)

Access: A series of sequential dilators without incorporated neuromonitoring.
Mounting: Table mounted.
Blades: Three blade system, but with retraction only possible posteriorly from the posterior blade. Blades can splay but only outward.
Neuromonitoring: No integrated neuromonitoring. Relies on third-party neuromonitoring.

14.7 Aira® 3 (Stryker, Inc.)

Access: A series of sequential dilators without incorporated neuromonitoring.
Mounting: Table mounted with the use of stability pins.

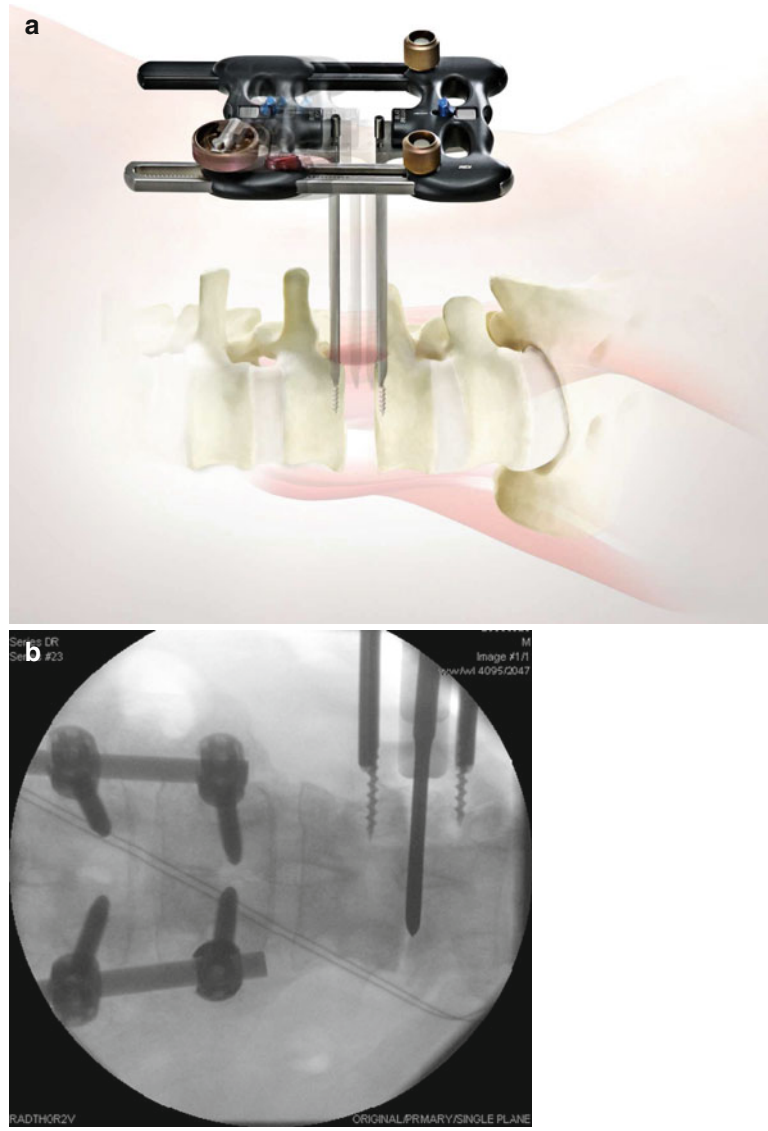


Fig. 14.10 (**a**) The RAVINE retractor which anchors on the vertebral bodies and does not require attachment to the table. (**b**) Intraoperative X-ray showing the pins holding the retractor to vertebral bodies

Blades: Two blade retractor, with cranial and caudal blades that can retract only in the cranial-caudal direction and which have a closed diameter of 22.5 mm.

Neuromonitoring: No integrated neuromonitoring. Relies on third-party neuromonitoring.

14.8 Ravine® 3 (K2M, Inc.)

Access: A series of sequential dilators without incorporated neuromonitoring.

Mounting: Directly to the vertebral bodies using stability pins.

Blades: Two blades, one each in cranial and caudal positions on two tracks that allow for cranial-caudal retraction without splay functionality. The retractor is positioned 90° from the more common handles posterior orientation. Closed retractor diameter is 24 mm.

Neuromonitoring: No integrated neuromonitoring. Relies on third-party neuromonitoring.

14.9 Veo® (Baxano, Inc.) [6]

Access: A series of sequential dilators without incorporated neuromonitoring.

Mounting: Table mounted.

Blades: Radiolucent tubular (no blades/retraction ability) exposure. The retractor is delivered to the superficial border of the psoas muscle followed by blunt dissection of the psoas muscle under direct visualization.

Neuromonitoring: No integrated neuromonitoring. The Veo approach is promoted as a lateral transpsoas approach able to be carried out without the use of neuromonitoring, since direct visualization of nerves is recommended.

14.10 Supra-psoas (Shallow) Docking [7]

Access: Blunt digital development of the retroperitoneal space without dilators.

Mounting: Table mounted or handheld.

Blades: A variety of retractors can be used, but are docked, as in the Veo system, on the superficial surface of the psoas muscle, and dissection through the psoas muscle is performed bluntly with visual inspection of neural structures.

Neuromonitoring: No integrated neuromonitoring. Relies on either visual inspection of neural structures or third-party neuromonitoring.

Conclusion

The MaXcess retractor in XLIF was the original lateral transpsoas retractor and, in the authors' opinion, has the most comprehensive set of key features available, including specialized access using sequential dilation under evoked EMG in directional orientations; a split-blade design that allows for retraction individually in cranial, caudal, or posterior directions with inward and outward splay capabilities; evoked-EMG neuromonitoring incorporated into the posterior blade of the retractor; and a series of optional fourth blade (anterior) retractors for deformity and tumor/trauma pathology. Other available retractors have combinations of these features along with several other derivations (nonuse of monitoring, tubular retractor design, supra-psoas docking, etc.).

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Anterior to Psoas (ATP) Fusion of the Lumbar Spine

15

Cristian Gragnaniello and Kevin Seex

15.1 Introduction

When fusing a lumbar spinal segment, certain facts are well established: the disc should be removed, the end plates prepared carefully, and then graft material placed against the end plates, contained or supported by a lordotic cage. The cage will help correct any deformity, resist subsidence, and improve stability. In an "ideal cage" competition, the large lateral cages are the obvious winners when compared to PLIF, TLIF, or ALIF cages. Spanning both lateral cortical rims while sparing the anterior longitudinal ligament, they provide the best support, most graft volume, and most stability for the anterior column even without supplemental fixation. The standard approach for their insertion and placement is also the most logical going through both lateral annuli without disrupting normal stabilizing structures. None of the above is in dispute. The question raised in this chapter is whether the best access to the lateral annulus is really *transpsoas* (i.e., through the psoas muscle).

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The psoas muscle can be very large and is always full of nerves which means its safe navigation requires expensive and highly technical equipment [6]. The amount of transpsoas lateral surgery now performed is the most obvious testament to its clinical usefulness, but what if we can achieve the same (or better) clinical goals without the complexity created by going transpsoas? Arguments in favor of the transpsoas approach are its reproducibility and relative safety [7–9, 12, 13, 15, 16]. These are important, but the unquestionable success of transpsoas may reflect more on the impressive educational achievements of NuVasive rather than the technique itself.

This chapter describes an alternative surgical approach, ATP, to insert the same lateral cages through the lateral annulus at right angles to the spine without going through the psoas, thus without neuromonitoring and without hesitation when approaching L4/5 [10].

Q: Is this the same as OLIF25™?
Ans: OLIF25™ is a Medtronic trademark, for their technique that shares the same anatomical corridor as ATP but uses different instrumentations, techniques, and arguably philosophies. We suggest the collective noun for ATP, OLIF25™, and OLIF51™ should be oblique or oblique lateral approaches.

As ATP is most valuable at L4/5 and above, this chapter will cover surgery in detail on those

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levels. L5/S1 requires special instrumentation and techniques that are only briefly covered later in the chapter.

15.2 Indications

- As per lateral transpsoas approaches
- Interbody fusion for degenerative disc disease, segmental instability, and spondylolisthesis from L1 to S1
- Tumors affecting the vertebral body
- Vertebrectomies

15.3 Contraindications

- Prior retroperitoneal pathology/surgery on the side of proposed approach

15.4 Equipment

- Operating table must be radiolucent. Unlike transpsoas where a break in the table is required, as ATP passes obliquely anterior to the iliac crest, this is only occasionally helpful.
- C-arm from start to finish. Time efficient use of the C-arm makes the operation much smoother. One should reimage and adjust the spine to true AP and lateral position before each separate level.
- One key element to efficient and safe retroperitoneal surgery is rapid identification of anatomical structures. Extra light and magnification make this miniopen procedure much easier and is strongly recommended.
- Loupes for magnification is routine, but we have used the intraoperative microscope to decompress a contralateral foraminal disc protrusion. In this case, the patient is placed with the side of the foraminal disc protrusion on the far side (i.e., for a right-sided foraminal disc protrusion, the patient is placed in right lateral decubitus).
- Intraoperative neuromonitoring is not required so the muscles can be kept relaxed for easier retraction.

15.5 Surgical Technique

15.5.1 Patient Positioning

Positioning and taping do not differ from those used in a transpsoas approach. The patient is placed in lateral decubitus. The hip is gently flexed to relax the psoas muscle and the femoral nerve both of which will be retracted. All areas that are at risk of pressure injury are protected, including a pillow that is placed in between the knees. Taping of the lower pelvis and uppermost hip and femur stabilizes the pelvis and spine. Breaking the table while not routine can be helpful to tighten the skin, elevate the ribs, or open a scoliosis if approaching from the concavity (Fig. 15.1). AP fluoroscopy is essential to ensure

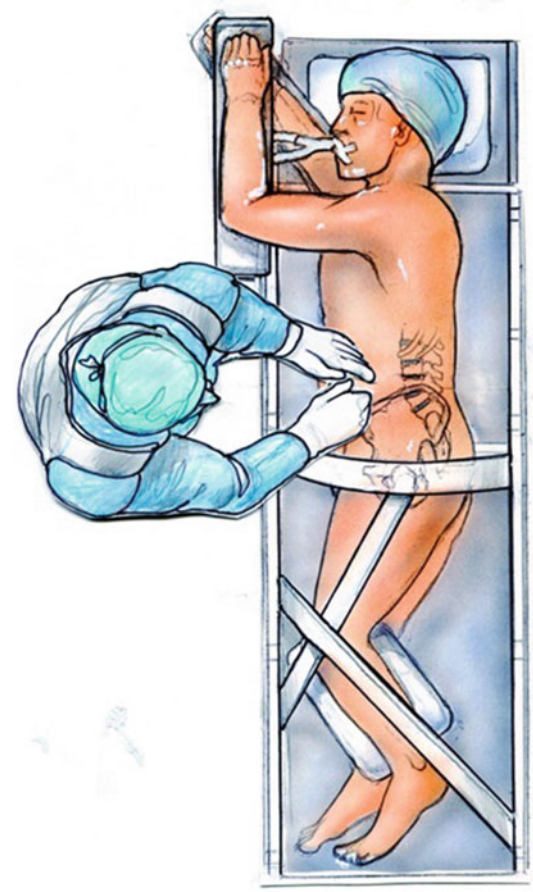


Fig. 15.1 Artist's depiction of the positioning of the patient in lateral decubitus, taping, and padding of contact surfaces NB: the chest is only taped after AP flouroscopy

that the level being approached is not rotated usually before taping the chest. Following this lateral fluoroscopy is used to adjust the target disc space perpendicular to the floor by adjusting the table head up or head down. The projection of the discs on the flank and abdomen is marked including the anterior projection of the disc space. Posteriorly this line helps the radiographer to align the C-arm parallel with the disc space (Fig. 15.2). Anteriorly this projection can be considered the "runway" for all the instruments entering the disc space to avoid endplate injury (Dr Paul Taylor personal communication).

Q: Left or right side up?

Ans: The approach is generally performed in right lateral decubitus (left side up) as this avoids the need for any vascular retraction, but a scoliotic spine concave on the right may benefit from a right-side-up approach for multilevel surgery. It is useful to be able to approach the spine from either side, e.g., for revisions or adjacent levels. An advantage of learning this miniopen technique is that it is the same for a left- or right-sided approach, which is an advantage over the Medtronic's OLIF25™ as this uses wires and tubes that would be unsuitable on the right. This miniopen technique requires identifying structures in the path to ensure safe passage; on the left, this is simple but on the right, the inferior vena cava (IVC) requires identification and a healthy respect although it is not difficult to mobilize..

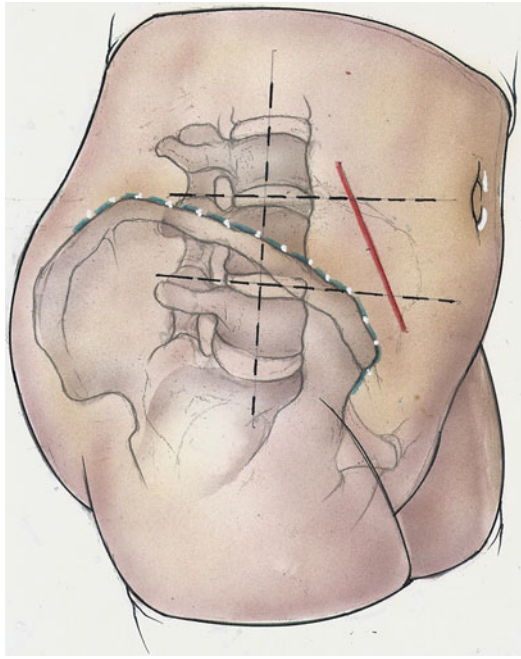


Fig. 15.2 Schematic demonstrating the marking of the projections of the discs, posterior and anterior margins of the vertebral bodies and discs. Also an example of skin incision is demonstrated

15.5.2 Incision

At L4/5, the surgical corridor approaches the disc space through the natural space between psoas and the left common iliac vessels. If the disc space is oblique, the skin incision should be one-third below and two-thirds above the anterior projection of the disc onto the abdominal skin. For L4/5, this is usually 20 mm in front of the anterior superior iliac spine toward the umbilicus (Fig. 15.2). A single- or double-level operation can comfortably be done within a 60 mm skin incision utilizing the so-called sliding window in the relaxed abdominal wall [14]. For horizontal lying discs, center the incision on the disc. Three or four levels may require a longer skin incision although in scoliosis cases, access on the concave side can often be done with a surprisingly small incision. For more than two levels, we use the same skin incision but usually split the deeper two muscles twice having extended the external oblique split.

15.5.3 Exposure of the Disc

All muscles are incised following the line of their fibers and bluntly dissected.

Iliohypogastric or ilioinguinal nerves may be encountered and mobilized typically beneath the internal oblique muscle. The transversalis fascia is opened as laterally as possible to avoid the peritoneum, be particularly careful in the thin. If one removes the self-retainer retractors at this point, one can usually just feel psoas through the fat

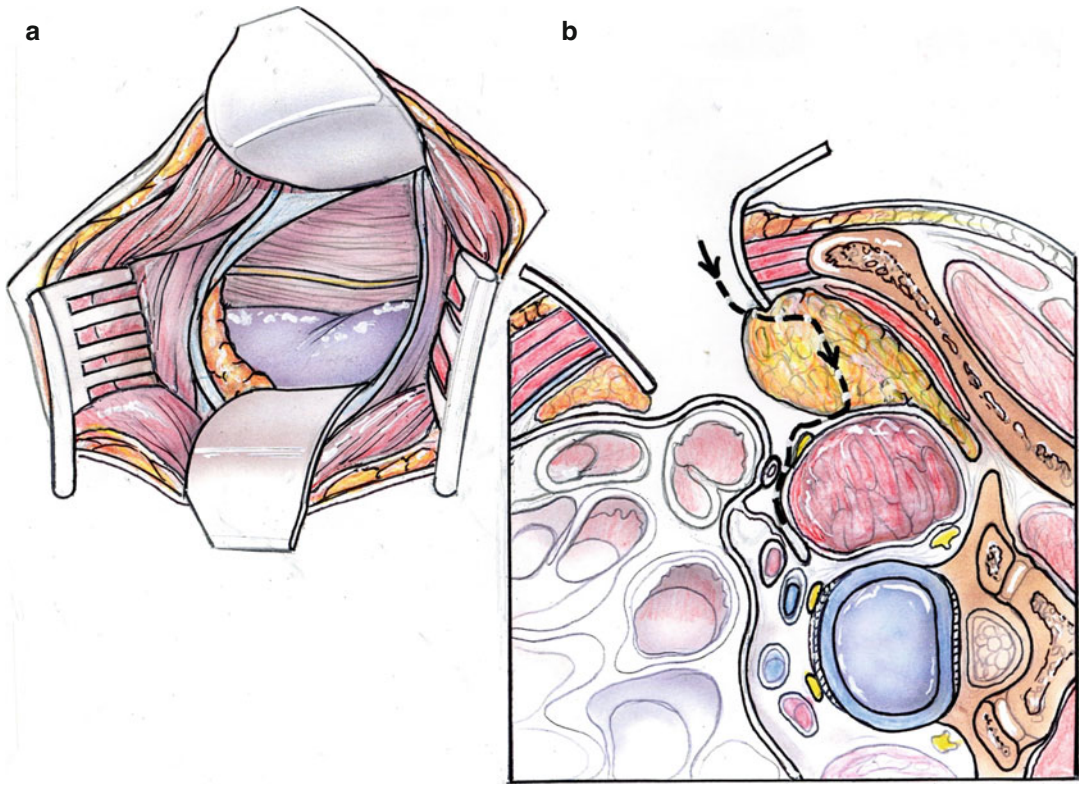


Fig. 15.3 Artist's depict after initial dissection into the retroperitoneum showing psoas with genitofemoral nerve on its antero medial surface (**a**) and axial view of the retroperitoneal fat in situ demonstrating the mobilization necessary to expose psoas major (**b**)

with the tip of a finger. This provides an immediate indication of correct direction. The retroperitoneal fat is "paddled" backward using a pair of swabs on sticks. Initial dissection is posterolateral and then vertical to push the retroperitoneal fat (with peritoneum and ureter) anteromedially, until psoas muscle comes into view (Fig. 15.3a, b).

The muscles of the lateral abdominal and pelvic walls should not be stripped clean because of the risk of injuries to the cutaneous nerves traveling in the retroperitoneal space on the abdominal wall [4]. Similarly the psoas fascia should be kept intact as this protects and retains the genitofemoral nerve (GFN) on its anterior surface. The GFN is usually seen and retracted with psoas.

At this stage, psoas (and GFN) is gently retracted posteriorly with a handheld retractor and psoas followed carefully around its anterior surface to reach the spine. Be aware that the psoas may overhang the spine in the lateral position, so follow it closely back to the spine.

In order to expose the spine, gentle dissection is required on the medial aspect of psoas through retroperitoneal fat and fascia, retracting peritoneum with ureter on its surface and passing laterally to the great vessels.

A single L-shaped blade Curvy™ retractor (Relax Retractors, Sydney, Australia) is applied medially with its back retracting the retroperitoneal fat while protecting the vessels and its orthogonal blade pushing psoas posteriorly. A separate straight handheld retractor is used to retract psoas (Fig. 15.4a, b).

A long smooth-ended dissector and a Yankauer suction tip are useful to dissect the loose fatty connective tissue between psoas and the fat over the vessels, to reveal the spine, the disc space, the sympathetic chain, and the segmental vessels. Occasionally the fascia needs to be torn. At this stage, other anatomy on display may include lymphatics, lymph nodes, small bridging vessels, and occasionally tiny nerve branches of unclear

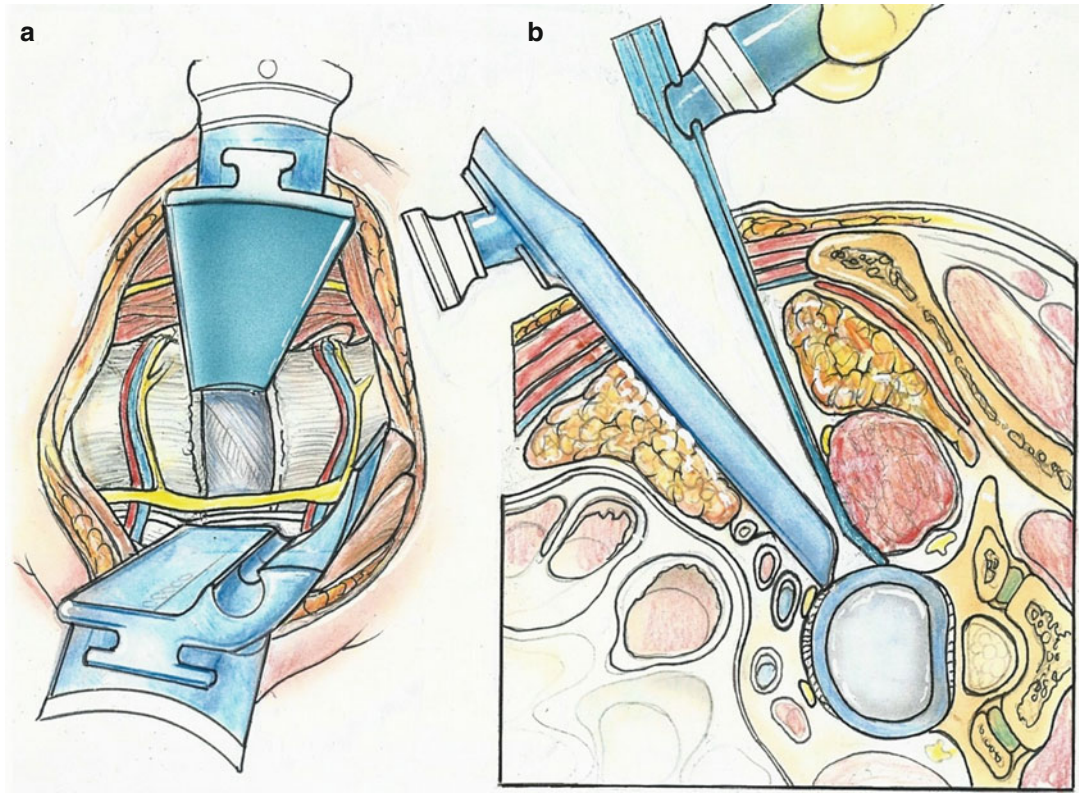


Fig. 15.4 Surgeon's view of the single L-shaped Curvy™ retractor applied medially with its back retracting the retroperitoneal fat while protecting the vessels and its orthogonal blade pushing psoas posteriorly and a separate straight retractor to retract psoas. (**a**) The same seen on an axial diagram (**b**)

origin. Below the L4/5 disc, the iliolumbar vein may be seen. On the spine, one can see the vertical fibers of the anterior longitudinal ligament (ALL). It saves time to identify the disc space early by feel (it's the ridge) or x-ray. One then concentrates solely on this area as diverging from this path may lead to unpleasant encounters with segmental vessels (in the valleys). The Curvy™ retractor is positioned medially over the disc space with the "leg" over the disc and the "foot" lying in a medial-lateral direction protecting the iliolumbar vein inferiorly. The Curvy™ fixation screw can be inserted into the target disc for temporary fixation, freeing up a hand (Fig. 15.5).

The most medial psoas attachments to the disc margin are separated with a dissector or Cobb elevator to allow more psoas retraction. The disc is then incised with a knife to about 20–25 mm behind the ALL. A limited discectomy is performed, and the reverse tooth of the selected G clamp blade is placed beneath the lateral uncut annulus. This blade is attached to rest of the G clamp which is then compressed to retract psoas. The extent of the cut in the annulus limits the posterior extent of psoas retraction, which provides an end point for retraction to avoid compression of the lumbar plexus.

The sympathetic chain can be mobilized usually medially by dividing its tiny branches, the rami communicantes (Fig. 15.6).

At this stage, with psoas retracted and the end plates identified, the initial retraction with Curvy™ blade on the disc is improved with repositioning of the blade lateral to the sympathetic trunk with its screw inserted into the L5 body to secure the blade. The medial blade usually lies close to the posterior edge of the ALL (Fig. 15.7).

A lateral x-ray is then taken to verify the limit of the posterior retraction, as retraction to about mid body is sufficient and adequate for disc preparation; this can be adjusted if required. Only a

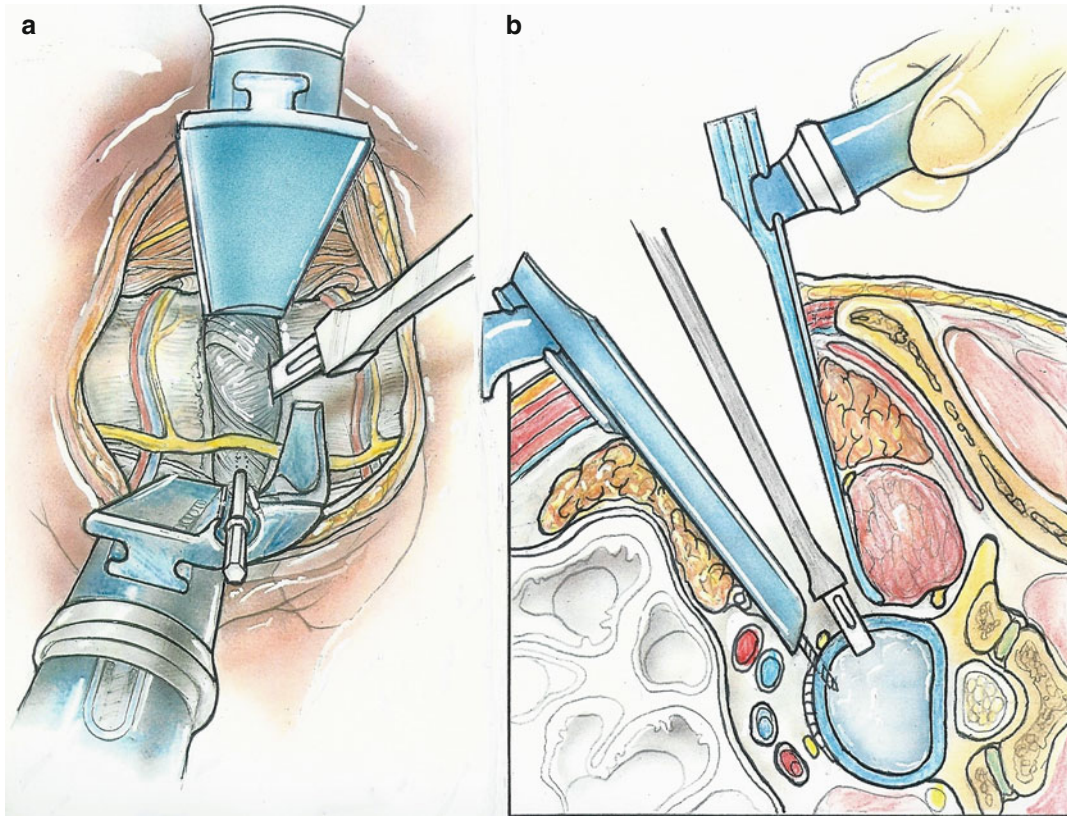


Fig. 15.5 The Curvy™ retractor is positioned medially over the disc space with the "leg" over the disc and the "foot" lying in a medial-lateral direction protecting the iliolumbar vein inferiorly. A fixation screw can be inserted into the target disc for temporary fixation, freeing up a hand. Disc incision with a knife to about 20–25 mm behind the ALL will allow the insertion of the G clamp with the foot inside the annulus limiting its retraction of psoas (surgeon's view (**a**) and axial diagram (**b**))

limited amount of psoas retraction is needed for thorough disc preparation and contralateral release. Both retractors, the Curvy and G clamp are now stable without requiring table mounting.

The iliac vessels, if seen are protected under the medial retractor blade.

The iliolumbar vein at L5 usually sits in the middle of the body; rarely it may overlie the disc space in which case it can be ligated between vessel clips. The vessel is always divided prior to retracting the common iliac vein to expose the L5/1 disc or a transitional L4/5 level. It is noteworthy that the lateral position and oblique approach reveal a greater length of the iliolumbar vein making ligation much easier than during supine L4/5 ALIF surgery.

15.5.4 Discectomy and Endplate Preparation

This phase of the operation is the same as per transpsoas except that surgeons need to be constantly aware that the tools are oblique and over insertion through the annulus can enter the foramen or even the spinal canal. Osteophytes can be removed by means of heavy rongeurs.

Initial discectomy with large pituitary rongeurs and disc curettes is performed.

"Dingo" instruments are shaped so that the surgeon is still working orthogonally to the spine as the handle and the terminal end of the instrument are in the same line. The offset (dog-leg) serves to avoid the iliac crest.

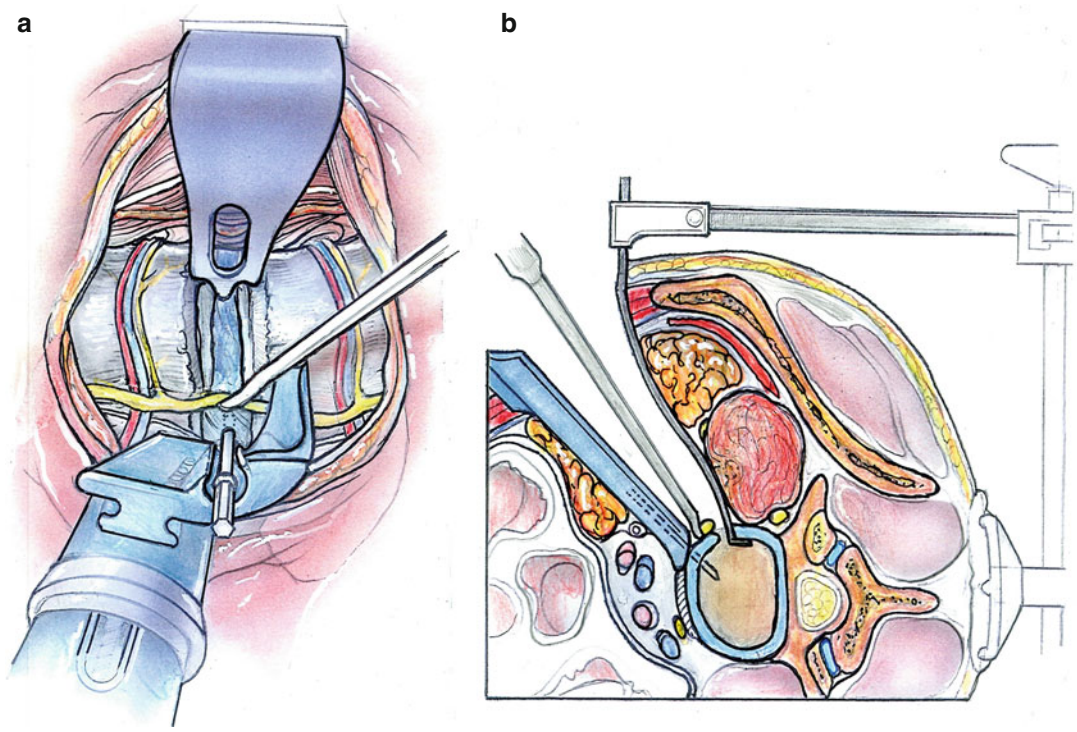


Fig. 15.6 The reverse tooth of the G clamp blade is seen beneath the lateral uncut annulus. The blade and the clamp retracting psoas have been compressed to retract psoas. The sympathetic chain has been mobilized by dividing the rami communicantes (surgeon's view (**a**) and axial diagram (**b**))

A Cobb elevator is placed in the disc space and under AP x-ray control, impacted through the contralateral annulus and any bridging osteophytes (Fig. 15.8).

After completion of the discectomy and with disc distraction, the oblique trajectory also allows for potential direct visualization of the thecal sac and contralateral foramen to allow decompression under direct vision. Pituitaries at these depths are best used slowly.

Disc removal and Endplate preparation are done with great care to ensure complete disc removal (avoids pushing disc out on the contralateral side) and to preserve the end plates.

15.5.4.1 ALL Release

In selected cases at this stage the ALL that has been previously visualized can be fully exposed with a narrow retractor blade passed carefully and slowly across the front of the spine beneath the IVC, immediately anterior to the ALL.

A long blade can be used to divide the ALL with the blade directed toward the disc space and always under constant vision. This is not a technique for the inexperienced or faint of heart. It is easier at 34 than 45.

15.5.5 Cage and Plate Insertion

Dingo design implant inserters allow for a standard lateral cage or hyperlordotic implant to be inserted across the disc space gaining bilateral cortical endplate coverage (Figs. 15.9, 15.10, and 15.11).

As with conventional transpsoas, lateral cages in this position are a highly effective method for correction of coronal deformity, lateral listhesis, restoration of foraminal height, and some correction of spondylolisthesis (Fig. 15.12a–c).

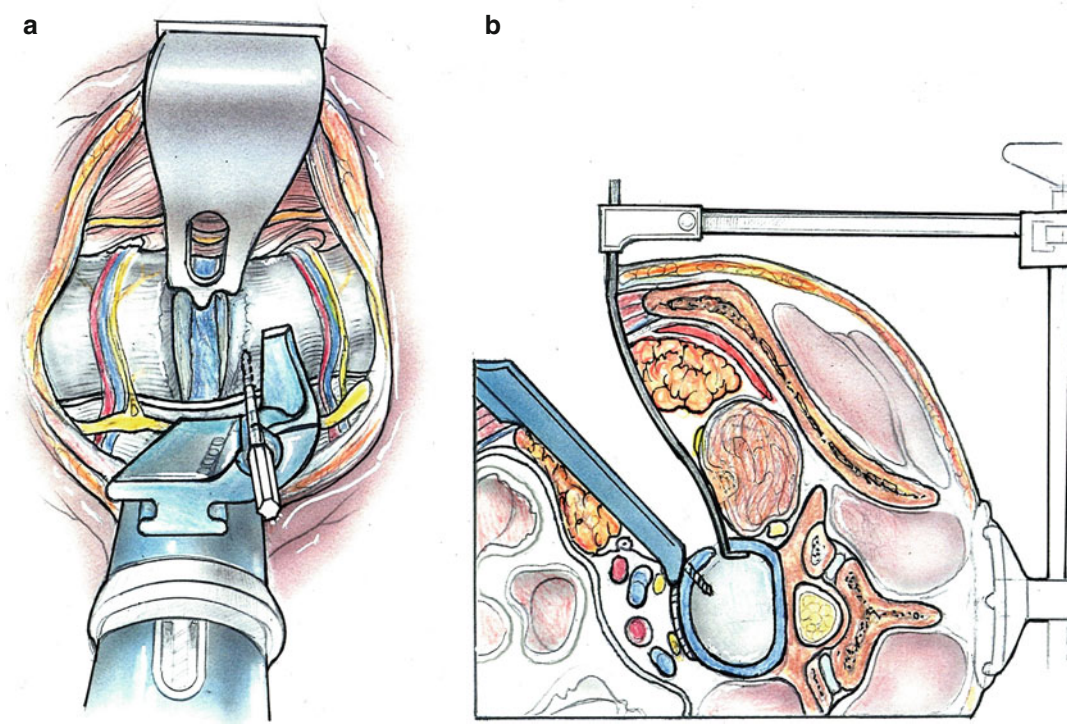


Fig. 15.7 At this stage, psoas is retracted and the end plates identified. The initial retraction with Curvy blade fixed to the disc is improved with repositioning of the blade lateral to the sympathetic trunk with its screw inserted into the inferior vertebral body to secure the blade. The medial blade usually lies close to the posterior edge of the ALL (surgeon's view (**a**) and axial diagram (**b**))

In selected cases supplementation of the cage with a four hole anterior plate placed through the same large window avoids the need for any posterior fixation (Fig. 15.13). Caveats are that patients must have good bone density, adequate lordosis with cage alone, foraminal height restoration is satisfactory and we suggest one or two levels only. Endplates should still be intact. This construct is very similar biomechanically to a standard ALIF construct [3]. The place for a standalone cage without any fixation requires further evaluation [20].

For two level surgery, the second level can be accessed through the same incision, repeating the same procedure. For higher lumbar levels a second superior muscle split may be made in the upper part of the incision, again, in the line of the external oblique muscle fibers. With scoliosis or multilevel surgery doing the uppermost level first may be easier to avoid it moving further up under the ribs.

15.5.5.1 L5/S1

L5/S1 is also accessible using this approach but is more complex not least because this level always requires ligation of the iliolumbar vein and some venous dissection and mobilization prior to retraction of the left common iliac vein medially for the placement of a reasonable cage (Fig. 15.14).

The other option to approach the L5/1 disc space with the patient in a lateral position is through the great vessel bifurcation. The OLIF51™ method from Medtronic is based on a mini-open approach similar to a standard ALIF through the vessel bifurcation using a different retractor system to the OLIF25™. The best technique to approach the L5/1 disc space is operator (and probably patient) dependent. The senior author performs both techniques and currently prefers to have both options available as the individual anatomy and characteristics of the patient appear to be critical, including BMI,

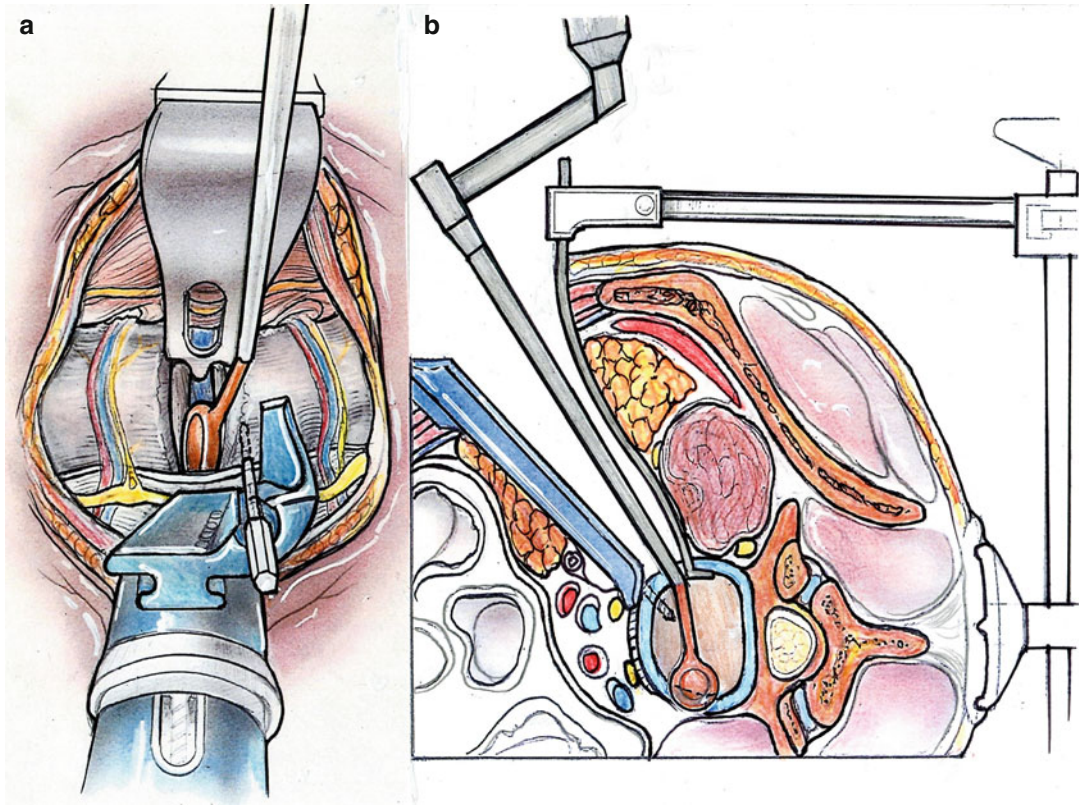


Fig. 15.8 A Cobb elevator is placed in the disc space and impacted through the contralateral annulus and any bridging osteophytes under AP x-ray control (surgeon's view (**a**) and axial diagram (**b**))

the depth of the disc in the pelvis, the sacral slope and the position of the left common iliac vein. With either technique however the exposure is generally inferior to a supine ALIF, but if complete disc clearance is not required and the goal is anterior column support and fusion at L5/S1 as part of a multilevel construct (that will include pedicle screws) then this approach is very helpful in association with oblique surgery at other levels. Unfortunately no peer-reviewed publications are yet available to elevate the discussion beyond personal experience and bias. A significant level of experience is required for either L5/S1 approach, as surgeons have to be able to manage or at very least control vascular "events" until help arrives. Unlike in the transpsoas approach however, vascular control is not difficult as the vessels are on view.

Closure is obtained by suture approximation of muscle layers and repair of the external oblique fascia.

15.6 Discussion

15.6.1 History

The modern oblique approaches OLIF25™ and ATP have their origins in Mayer's 1996 description [11].

15.6.2 Cages

In the last decade the placement of large lateral cages has been shown to provide increased stability to the treated segment, and restore disc

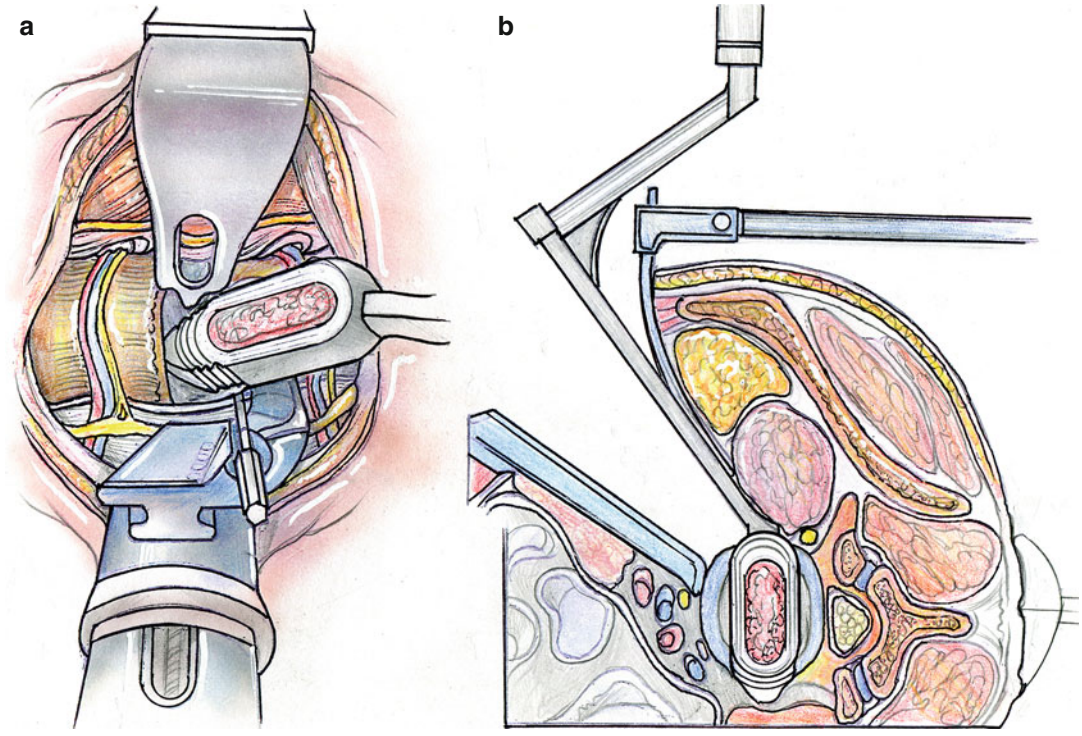


Fig. 15.9 Dingo inserters allow for placement of large lateral type cages with great bilateral end plate coverage, always orthogonal to the spine ((**a**) surgeon's view, (**b**) axial diagram)

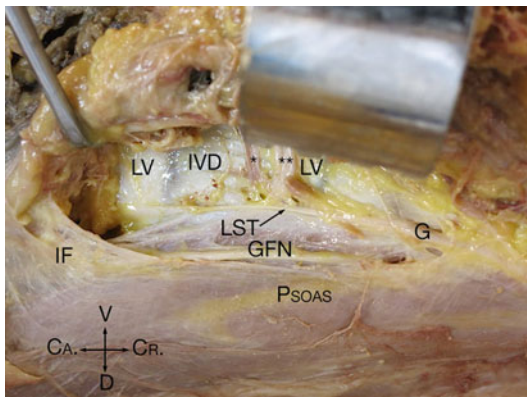


Fig. 15.10 Anatomical dissection demonstrating the position of the GFN right under psoas fascia. *Abbreviations*: *CIV* common iliac vein, *G* ganglion, *GFN* genital branch of genitofemoral nerve, *IVD* intervertebral disc, *IF* iliac fascia, *IVC* inferior vena cava, *LST* right lumbar sympathetic trunk, *LV* lumbar vertebra, *Psoas* psoas major. *: segmental lumbar vein of IVC. **: segmental lumbar artery of aorta. *Cr* cranial, *Ca* caudal, *V* ventral, *D* dorsal

height with good coronal realignment [1]. The standard technique to insert these cages has been a transpsoas approach with neuromonitoring but in many surgeons hands there have been difficulties typically at L4/5, and in male patients with large psoas muscle and a high iliac crest.

In order to address these difficulties, particularly at L4/5, we modified Mayer's 1996 approach late in 2011 [17]. Customized retractor system and offset instruments to avoid the iliac crest were developed with improved cage alignment. Pierre Rousoully's series reported by Silvestre in 2012 described 179 patients operated between 2006 and 2009 [14]. They coined the term OLIF to describe their Oblique Lumbar Interbody Fusion and used a banana shaped TLIF style cage, recommending <30 mm cages to reduce possible damage to the contralateral traversing nerve root. The Medtronic OLIF25™ technique described later in 2012 described the insertion of lateral cages without any fixed psoas retraction using Medtronic's lateral retractor. Cages are inserted with straight instruments into the disc space with the additional step of rotating the cage from an oblique to an "as orthogonal as possible" position. Our experience with such straight

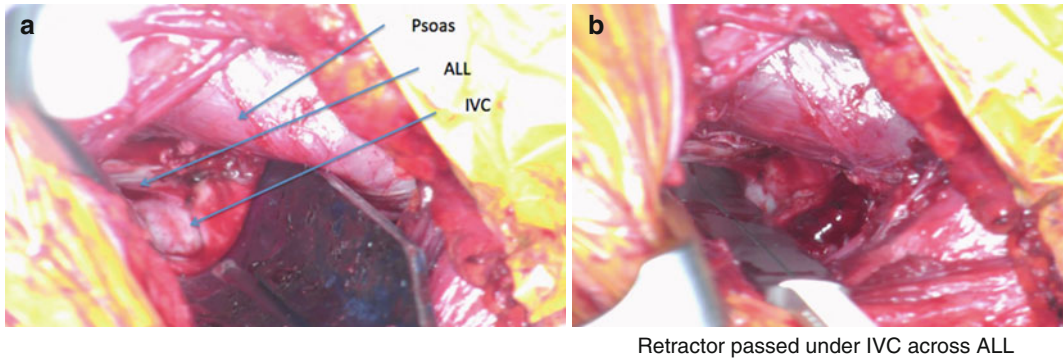


Fig. 15.11 (**a**) Intraoperative photographs showing the exposure of the ALL by this miniopen ATP technique. (**b**) The retractor has been placed under the IVC creating the space to safely release the ALL with a long scalpel

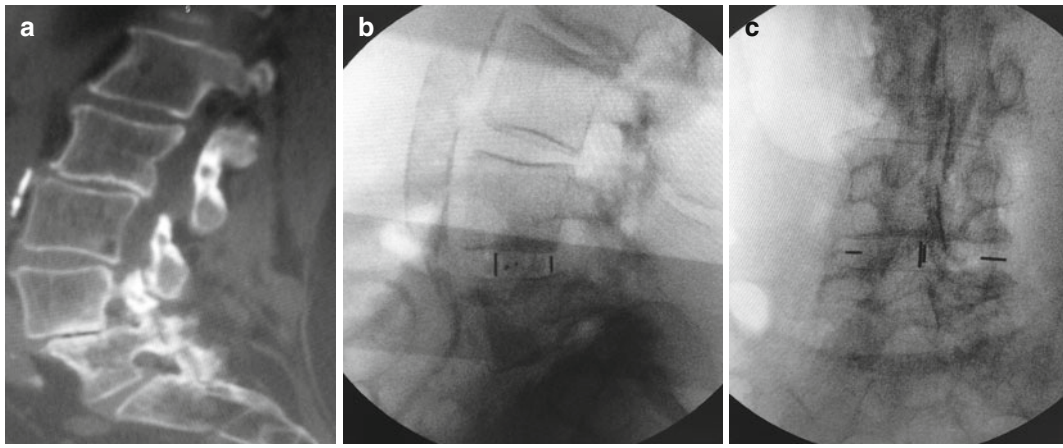


Fig. 15.12 A 75-year-old woman affected by neurogenic claudication and bilateral L4 radicular pain (R > L). Preoperative CT, sagittal reconstruction showing advanced disc degeneration with grade 1 spondylolisthesis at L4/5 (**a**). Intraoperative lateral and AP x-rays showing restoration of the disc height with resolution of the listhesis (**b**, **c**)

instruments led to concerns about contralateral nerve injury as also noted by Sylvestre [14], and led to the design of the Dingo (Australian wild dog – dog legged) instruments, allowing for lateral cages to be consistently placed 90° to the disc space.

15.6.2.1 Clinical Results

The authors' personal series of 100+ cases are in preparation. This lack of published data in general for the oblique approaches reflects the early stage of development and adoption and so the arguments are largely theoretical. This however could also have been said during the early years of transpsoas.

15.6.3 Retractors

All authors have used bone fixed retractors in some form. Mayer described a frame supporting four blades secured to the spine with anchoring screws through the cranial and caudal blades. He also used a table-based system such as Synframe (Synframe; Synthes Oberdorf, Switzerland). Dr Tony Tannoury from Boston has also developed this technique using Synframe (personal communication). Silvestre used four Steinman pins. The Medtronic technique is based on the MAST Quadrant™ lateral retractor system that uses cranial and caudal pinned blades. Our technique uses one bone

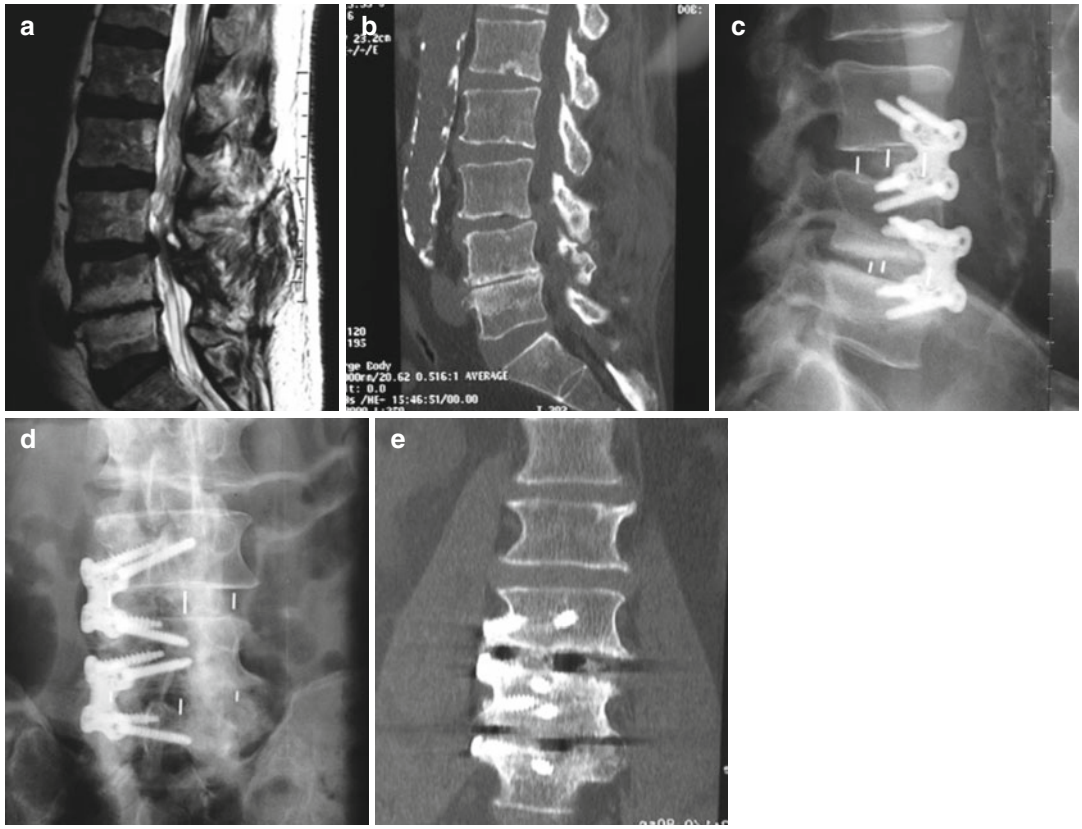


Fig. 15.13 A 76-year-old male with a history of a previous laminectomy at L4/5 for radicular symptoms at the presence of a canal stenosis at L4/5 from which he had good relief of his symptoms for 2 years. He represented after 2 years with worsening symptoms from a worsening stenosis at the L3/4 level that was initially managed with steroid injections and subsequently with an L3/4 interlaminar decompression that only gave him 9 months of relief. The patient medical history included a BMI of 31, HTN, hyperlipidemia, and gout. Upon the last recurrence, he had severe LBP and pain bilaterally in L4 when standing or walking. A sagittal T2WI MRI scan showed a stenosis at L3/4 and disc degeneration at L4/5 with instability (**a**). A sagittal CT reconstruction of the same midsagittal cut (**b**). Early postoperative lateral and AP x-ray films (**c**, **d**). Coronal CT reconstruction showing a solid fusion after 12 months (**e**)

fixed blade anteriorly and a novel self-retaining posterior retractor (G clamp, Relax Retractors, Sydney, Australia). Other blades maybe added but are not usually needed.

15.6.3.1 Neuromonitoring

Generally agreed to be mandatory with transpsoas [2], surgeons using both of the above oblique lateral approaches do not routinely use neuromonitoring although this is described in the Medtronic technique. (Dr Richard Hynes, Melbourne, Florida personal communication). The muscle retraction both superficial and deep is likely to be easier with the use of muscle relaxants, which would otherwise need to be reversed if neuromonitoring was being used.

15.6.4 Psoas Retraction

A theoretical concern with the anterior to psoas approach is that the lumbar plexus maybe stretched or compressed against the Transverse processes. In order to avoid this we limited the psoas retraction at L4/5 to mid body, in addition to periodic release of psoas retraction during surgical delays. As this proved uneventful, we now routinely retract psoas up to the posterior 1/3 of the L4 body.

15.6.5 Levels

The ideal levels for ATP are L4/5 and L3/4. No advantage over transpsoas has been noted at

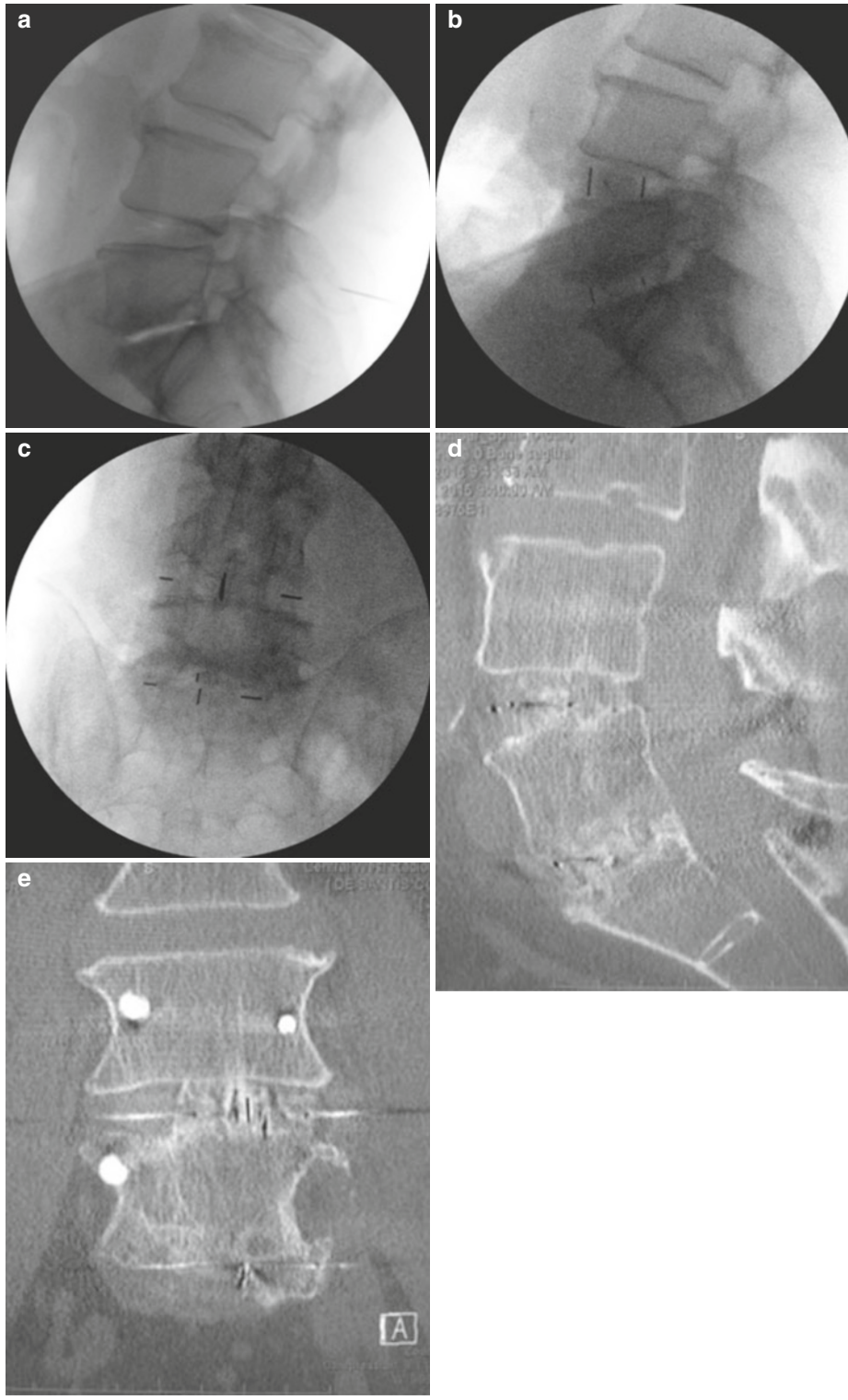


Fig. 15.14 A 65-year-old man with a history of MI and placement of four coronary stents. Upon presentation was still a smoker of a pack/day and was on aspirin. He was limited by severe back pain with bilateral S1 pain (L > R) that persisted despite conservative measures. Lateral x-ray demonstrating and L5/S1 disc degeneration (**a**). Intraoperative lateral and AP x-ray (**b**, **c**). Postoperative CT reconstruction at 12 months demonstrating good alignment and solid fusion (**d**, **e**)

L2/3. An isolated L 1/2 is easier with a direct lateral approach. L 2/3 is straightforward below or anterior to the 12th rib but L 1/2 access varies with individual anatomy.

15.6.6 Vascular Injuries

Vascular injuries are a theoretical risk during an ATP approach. However, a left side approach is usually free from vascular structures and the natural corridor, well seen on MRI, makes possible an approach without any vascular dissection [5]. In Davis's paper there was a mean space of 15 mm between edge of left psoas and vessels, (without psoas retraction) [5].

However, surgeons should be prepared to recognize and be able to divide the iliolumbar vein as rarely this may overlie the L4/5 disc.

The miniopen approach described here anticipates direct visualization of any intra-abdominal structures in the approach.

In comparing the ATP approach to ALIF at L4/5, the absence of vascular dissection and vascular retraction is a major advantage particularly in elderly patients.

By contrast access to the L5/S1 disc space, going anterior to psoas and lateral to the vessels requires the same degree of vascular expertise as for an L4/5 ALIF.

15.6.7 Nerve Injuries

The sympathetic trunk has to be mobilized and our experience has been that this tolerates mobilization and compression by smooth retractor blades quite well, even sacrifice generally only produces warming of the affected leg that is usually unnoticed by the patient and resolves in the first 12 weeks. However in younger patients (and particularly women), the sympathectomy effect can lead to unilateral swelling and much unhappiness.

The genitofemoral nerve is the sensory nerve most obviously at risk, being on the psoas and immediately under the psoas retractor blade, and its injury can produce unpleasant groin neuralgia. Careful placement of the G clamp retractor blade, care to preserve psoas fascia, limited duration of psoas retraction, and retractor stability are all recommended to reduce potential for nerve injury (Fig. 15.10).

15.7 ALL Section

Although only recently reported, *anterior column realignment* (*ACR*) is a technique that is proving very powerful in aiding deformity correction with minimal blood loss compared to posterior osteotomy techniques [18]. This ACR technique exposes the lateral annulus and the lateral edge of the ALL and then divides the ALL from the traditional direct lateral approach within psoas [18, 19]. ATP however with its oblique approach provides direct vision of more of the critical structures, namely, the anterior surface of the spine, ALL, and adjacent major vessels. These theoretical advantages have been confirmed by the relative simplicity of sectioning ALL using this approach (Fig. 15.11a, b). A full discussion of this technique including the use of hyperlordotic cages is beyond the scope of this chapter, but a very good reason to learn ATP is to gain familiarity with the approach to perform a controlled release of the anterior annulus and/or ALL under direct vision, achieving 20° plus segmental corrections at a single level.

Conclusions

The left-sided anterior to psoas approach offers the most natural corridor to the disc space. The novel instruments and methods described here allow for insertion of large lateral cages from L2 to L5, without the problems associated with the transpsoas approach, particularly at L4/5. Once comfortable with the technique, it can be applied equally well on the right although the IVC must be mobilized. It is more logical to perform release of the anterior annulus and ALL by an approach anterior to psoas and anterior oblique to the spine rather than transpsoas and direct lateral.

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Thoracic MIS Retropleural Access

16

Jay Rhee, C. Rory Goodwin, and Daniel M. Sciubba

Key Points

1. It is critical to position the patient in a 90° true lateral decubitus position with high-quality AP and lateral fluoroscopic images.
2. Injury to the underlying parietal pleura should be avoided during the dissection of the rib and while sweeping the lung anteriorly to expose the lateral vertebral column to prevent a postoperative pneumothorax.
3. The side of approach will be significantly influenced by the levels being treated and the anatomy on axial imaging.
4. The segmental vessel must be carefully dissected and sectioned at least 2 cm from the aorta to prevent substantial bleeding.

16.1 Introduction

Surgical approaches to the thoracic spine can occur via anterior, posterior, or the combination of anterior and posterior approaches. The surgical technique employed is typically determined based on the pathologic lesion, location of the lesion, and surgeon's preference. Posterior approaches (e.g., laminectomy) were preferred initially for the treatment of thoracic pathologies, such as thoracic disk herniation; however, unacceptable poor outcomes were key in the development and use of alternative surgical approaches [1]. Transthoracic thoracotomies were employed for the treatment of various pathologies because this approach offers excellent visualization of the ventral spinal column without spinal cord manipulation for anterior-based pathologies [2–4]. Unfortunately, the combination of the large skin incision, need for collapse of the lung, rib resection, and muscle dissection led to significant postoperative pulmonary dysfunction, pain, and morbidity associated with open thoracotomies [5–7]. Thoracoscopic approaches were developed to reduce the drawbacks of the open thoracotomy approach; however, the need for collapse of the lung (similar to open thoracotomy), lack of three-dimensional visualization, steep learning curve, and need for postoperative chest tube were seen as disadvantages of this approach. The advent of minimally

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invasive techniques over the past decades has led to a decrease in the postoperative morbidity associated with the treatment of ventral thoracic pathologies and improved clinical outcomes [3, 8–10]. These minimally invasive approaches range from mini open, percutaneous, and endoscopic approaches via transpedicular, transfacet, and transforaminal approaches [11–13].

McCormick described a lateral retropleural thoracotomy to avoid the morbidity associated with the traditional open thoracotomy and thoracoscopic approaches [14]. The retropleural approach for thoracic pathologies has become more common in its use because it allows for a minimally invasive anterior exposure, gives excellent visualization similar to the thoracoscopic and open thoracotomy techniques, and avoids the spinal cord manipulation associated with posterior approaches. The technique also allows for reduced risks of great vessel injury, damage to the sympathetic plexus, or development of a duropleural CSF fistula because of the extrapleural feature of the approach [14–16]. Additionally, this technique commonly utilizes a single small incision, allows the use of the operative microscope if the surgeon is inclined, and includes less pain postoperatively secondary to paucity of muscle and ligamentous disruption/manipulation. The main disadvantages of this operative approach are the longer operative corridor, which require longer instruments, and make it more difficult to control bleeding or other complications should they arise [17].

16.2 Anterior-Based Approaches

For anterior only pathology or as an adjunct in cases requiring 360° decompression, the thoracic spine can be treated via an anterior approach. The first and rarely the second thoracic levels may be accessed without a sternotomy or manubriotomy in select cases. Access up to T4 can often be achieved with a sternotomy, which typically requires an approach surgeon. The great vessels are at risk in anterior approaches and will limit pathologies extending below T4.

16.3 Posterior-Based Approaches

Posterior approaches to the thoracic spine allow access to the posterior elements as well as the lateral and anterolateral aspects of the vertebrae. These include laminectomy, transpedicular, costotransversectomy, and lateral extracavitary approaches that may be performed unilaterally or bilaterally. Full anterior decompression can be performed through bilateral posterolateral access. Pedicle screws and an anterior cage can be placed allowing 360° stabilization and fixation across multiple segments through a single approach. Limitations to posterior and posterolateral approaches include the need for extensive muscular dissection especially for cases requiring anterior decompression and instrumentation, high postoperative pain, risk of spinal cord injury, high volume blood loss, and risk of injury to the pleura and neurovascular bundles when resecting ribs. A thoracic nerve root is often sacrificed for access when placing an anterior cage following a corpectomy, which is typically well tolerated. Removing calcified midline herniated disks from a posterior approach can be challenging and has been associated with high rates of thoracic cord injury.

16.4 Lateral-Based Approaches

Traditional lateral-based techniques involve a thoracotomy and provide excellent exposure of the lateral vertebral column caudal to T4. Above this level, the scapula obstructs access to the ribs. For upper thoracic levels (T5-T6), right-sided approaches are preferred to avoid injury to the aortic arch. Levels below T6 may be approached on either side taking care to thoroughly review preoperative axial images to assess the location and proximity of the aorta and mediastinum to the vertebral column. Levels near the thoracolumbar junction may be more easily approached from the left to avoid retracting the liver [18].

Lateral transthoracic access involves dissection through the latissimus dorsi and trapezius muscles, resection of up to 15 cm of the rib, and distraction of the rib cage for visualization. For

T8 and above, the rib one level caudal to the target level is typically resected, while more caudal segments may require resection of the rib two levels caudal. Deflation of the ipsilateral lung may be required in cases involving rostral thoracic vertebrae. Open lateral access will place the patient at risk for injury to the pleura, lung, intercostal neurovascular bundle, aorta, and/or azygous vein depending on laterality and increase the potential for postoperative thoracotomy pain.

16.5 Surgical Technique and Anatomic Considerations

16.5.1 Preoperative Planning

A full preoperative workup including medical, neurologic, and radiographic assessments is performed and tailored for each individual patient. MRI and CT scans of the spinal segments of interest are critical for evaluation of the neural and osseous anatomy. Scoliosis and dynamic X-rays may be helpful for Cobb angles and alignment measurements in cases involving spinal deformity. For patients with risk factors for osteoporosis, bone mineral density studies are often obtained.

The side of approach may be dictated by the pathology, but in equivocal circumstances, the anatomy will influence laterality. On axial imaging, a laterally positioned descending aorta may make exposing the left side of the thoracic spine difficult. In the lower thoracic spine, a left-sided approach is often easier and safer as this will avoid working around the liver as well as potential injury to the thin-walled inferior vena cava.

16.5.2 Preparation and Patient Positioning

Standard single-lumen general endotracheal intubation is performed and neuro-monitoring leads are inserted. The patient is placed in a 90° true lateral decubitus position onto a radiolucent table using intraoperative fluoroscopy taking care to properly pad all pressure points and joints. The bed is oriented such that anesthesia is toward the patient's head, the C-arm fluoroscopy positioned anteriorly, and the surgeon(s) positioned behind the patient. The surgical scrub is positioned behind the patient beside the surgeon toward the foot of the patient with the Mayo stand in between the scrub and surgeon. It is critical to obtain high-quality true AP and lateral images of the target vertebral segments prior to incision. Once an AP image of the vertebrae is obtained, the patient is secured to the bed with 2-in. silk tape and straps (Fig. 16.1).

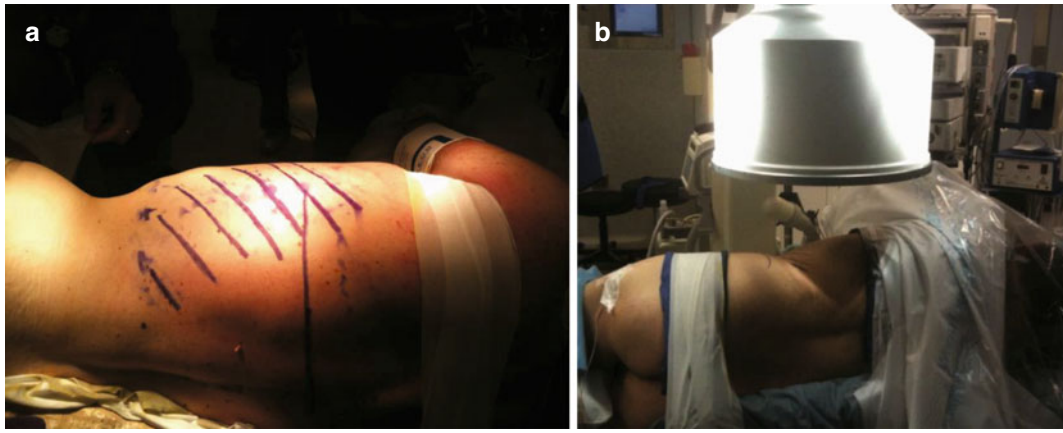


Fig. 16.1 (**a**) Patient placed in a 90o true lateral decubitus position with pre-operative surgical marking of ribs and index level. (**b**) Fluoroscopic X-Ray image of the vertebrae is obtained with the patient is secured to the bed with two inch silk tape and straps

16.5.3 Surgical Approach

The C-arm is adjusted for a true lateral view and a radiopaque marker is placed above the disk space of interest. For single-level fusions, a 4–5-cm incision is marked at the level of the disk space. For two-level fusions or a single-level corpectomy, an incision is marked along the mid-vertebra between the two disk spaces of interest. The skin is incised and the underlying muscles are bluntly dissected to expose the rib overlying the target interspace(s). It is prudent to make the incision over an underlying rib to prevent plunging into the intercostal space. Approximately 4 cm of the rib are dissected from their muscular attachments as well as the parietal pleura and resected with a rongeur or a bone scalpel. Care must be taken to avoid injury to the pleura, intercostal vessels, and nerves on the caudal surface of the ribs.

A finger is inserted into the retropleural space hugging the posterior chest wall, and the lung is swept anteriorly with a sponge stick until the lateral vertebral column is exposed. Appropriately sized retractor blades are chosen and placed onto the correct target disk space under direct visualization. The position of the retractor can be confirmed with an AP fluoroscopic image. The authors use the SynFrame retractor system (DePuy Synthes, Raynham, MA) which employs a table-mounted ring directly above the incision attached to articulated retractor blade holders. Three blades are typically used: one for anterior retraction of the lung and two for rostral and caudal retraction (Fig. 16.2). Alternatively, the table-mounted retractors used for lateral retroperitoneal

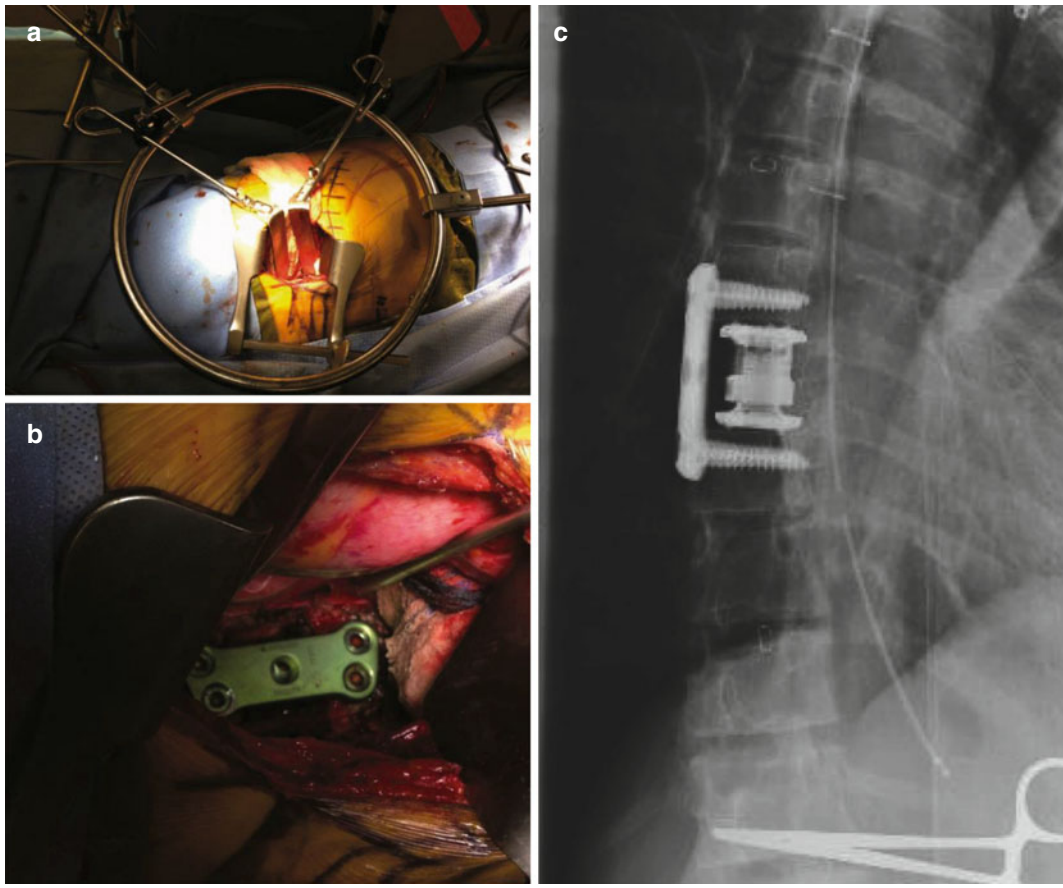


Fig. 16.2 (**a**) Synframe retractor system (Depuy Synthes, Raynham, MA) which employs a table mounted ring directly above the incision attached to articulated retractor blade holders. (**b**) Visualization of thoracic plate through Synframe retractor system. (**c**) Antero-posterior X-ray image of the T8 cage and plate after corpectomy

lumbar access may be used in the thoracic spine in similar fashion (Fig. 16.3).

Once the exposure is complete and the self-retaining retractor is in place, fluoroscopy is used to confirm that the correct level has been exposed. From the lateral view, the disk spaces are elevated compared to the vertebral bodies. The disk space can be palpated with a Penfield dissector for confirmation and the surgeon may commence the diskectomy. For a corpectomy, a diskectomy is performed above and below before the removal of the vertebral body. The segmental artery courses in an anteromedial to posterolateral direction at the mid-position of the vertebral body. This vessel should be dissected, clipped, and cauterized with bipolar electrocautery before sectioning. As the segmental artery arises directly off of the descending aorta, it is critical to section the vessel at least 2 cm distal to the aorta. If the artery is cut too close to the aorta and was not sufficiently clipped or cauterized, it may retract and bleed profusely from aortic back pressure. The anterior border of the vertebral body can be palpated with a Penfield dissector. The neural foramen provides a useful landmark for the posterior border. The rostral/caudal boundaries have been defined by the diskectomies, and the surgeon may commence with the corpectomy.

Once the main procedure is complete, the pleural surface is inspected thoroughly. If the pleura is compromised or there is significant residual bleeding, a 10-French chest tube is placed in the wound and tunneled subcutaneously over several ribs from the incision. The retractor blades are carefully removed allowing the lung to expand to the posterior chest wall. The muscles overlying the rib resection are re-approximated with 0-Vicryl interrupted sutures, and the rest of the incision is closed in standard fashion.

16.5.4 Postoperative Care

If a chest tube is in place, it is connected to a reservoir on water seal or −20 cm of H_2O depending on the severity of the pleural injury. All patients undergo a postoperative chest X-ray shortly after the arrival to the postanesthesia care unit. If a chest tube was placed or a pneumothorax is discovered on the postoperative chest X-ray, a follow-up X-ray is performed on postoperative day 2 for surveillance. The chest tube is weaned and removed as tolerated.

Patients are encouraged to sit in a chair and ambulate on the first postoperative day. All patients have sequential compression devices and are started on heparin prophylaxis for prevention of deep vein thrombosis.

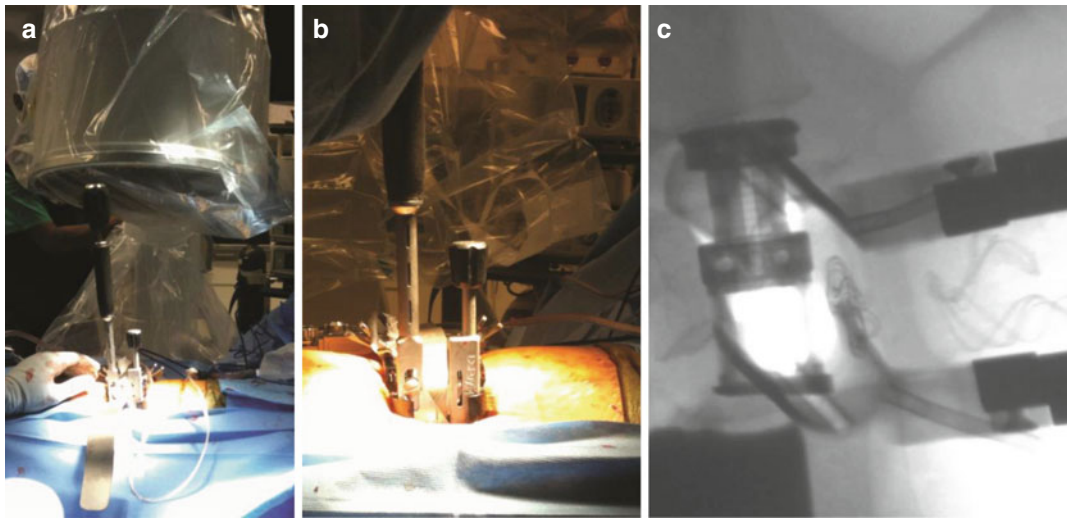


Fig. 16.3 (**a**) Table mounted retractors used for lateral retroperitoneal lumbar access used in the thoracic spine. (**b**) Magnified view of retractor system intra-operatively. (**c**) Antero-posterior X-ray image of the cage placement after corpectomy

16.6 Outcomes Using a Minimally Invasive Anterolateral Approach

Two studies reporting outcomes and complications of MIS retropleural access are available for review at the time this chapter was written. In 2011, Karikari et al. reported their series of 22 patients who underwent MIS thoracic and thoracolumbar lateral interbody fusions for a variety of pathologies using the MaXcess retractor (NuVasive, San Diego, CA) [19]. They report a 95.5 % successful fusion rate among 47 levels treated with three complications, none of which involved neural, vascular, or pulmonary injuries. In another study, Meredith et al. reported a series of 18 patients who underwent MIS lateral thoracic and thoracolumbar interbody fusions with the MaXcess retractor with only one patient failing to fuse [20]. Seven non-pulmonary complications occurred in six patients with none involving neural elements or vessels. Although large-scale studies are required for further evaluation, these early reports show that the MIS anterolateral approach can be used to treat a variety of thoracic pathologies safely with high rates of successful fusion.

16.7 Advantages of the Minimally Invasive Lateral Approach

Currently, there are no large cohort reports comparing outcomes of minimally invasive lateral thoracic vertebral approaches to classic open thoracotomies. However, some potential advantages of the lateral retropleural thoracic approach include:

No approach surgeon
Smaller incision
Less rib resection or muscle dissection
Less rib retraction
Avoidance of single-lung ventilation
Less lung retraction and postoperative atelectasis
Less pain
Shorter hospitalization
Less blood loss

16.8 Limitations of the Minimally Invasive Lateral Approach

More radiation exposure from increased intraoperative fluoroscopy use
Learning curve
Smaller exposure
Longer working corridor necessitating longer instruments

16.9 Summary

For anterior and anterolateral pathologies limited to one to three thoracic levels, an MIS lateral approach provides ample exposure while limiting morbidity.

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Psoas Muscle Management

17

Patrick Reid and Andrew A. Sama

17.1 Introduction

The concept of lumbar fusion is not new. The indications for fusion commonly include the need to realign and stabilize functional motion segments. The direct and indirect decompression of the lumbar nerve roots from a posterior and anterior approach is also widely accepted. The lateral approach has also become more popular in the last decade to address various pathologies of the lumbar spine. This approach has been demonstrated to be a less-invasive and powerful approach that efficiently allows access to multiple levels of the lumbar and thoracic spine for realignment and fusion.

The obvious concern when considering the lateral approach is the risk of injury to the retroperitoneal structures, most notably the lumbar plexus, the femoral nerve, and the great vessels. Understanding the gross three-dimensional anatomy of this region is paramount to performing the lateral approach safely. Preoperative and intraoperative radiographic interpretation is an essential starting point, but intraoperative identification and manipulation of the psoas major muscle and the lumbar plexus within it and the vessels anterior and deep to it are key to the safety of the procedure.

Particularly important is understanding of the psoas muscle itself, including the local gross anatomy, but more importantly the effects of retraction or dissection of the muscle and nerves concealed therein and any potential complications. This chapter will explore the psoas muscle in depth.

17.2 Gross Anatomy of the Psoas Major Muscle (Fig. 17.1)

The iliopsoas muscle consists of three distinct muscles: the iliacus, psoas minor, and psoas major. The psoas minor, absent in 40 % of the population, attaches proximally to the bodies of T12 and L1 and travels anterior and medial to the psoas major, inserting distally in the iliopectineal eminence of the innominate bone and the iliac fascia. The iliacus attaches superiorly at the iliac crest and lumbosacral ligaments, forming a triangle-shaped muscle that attaches inferiorly to the lateral fascia of the psoas major, joining that muscle at the levels of L5 to S2 as it travels deep to the inguinal ligament and attaches to the lesser trochanter. The psoas major attaches proximally to the inferior transverse processes, vertebral bodies, and disks, as well as the intervertebral

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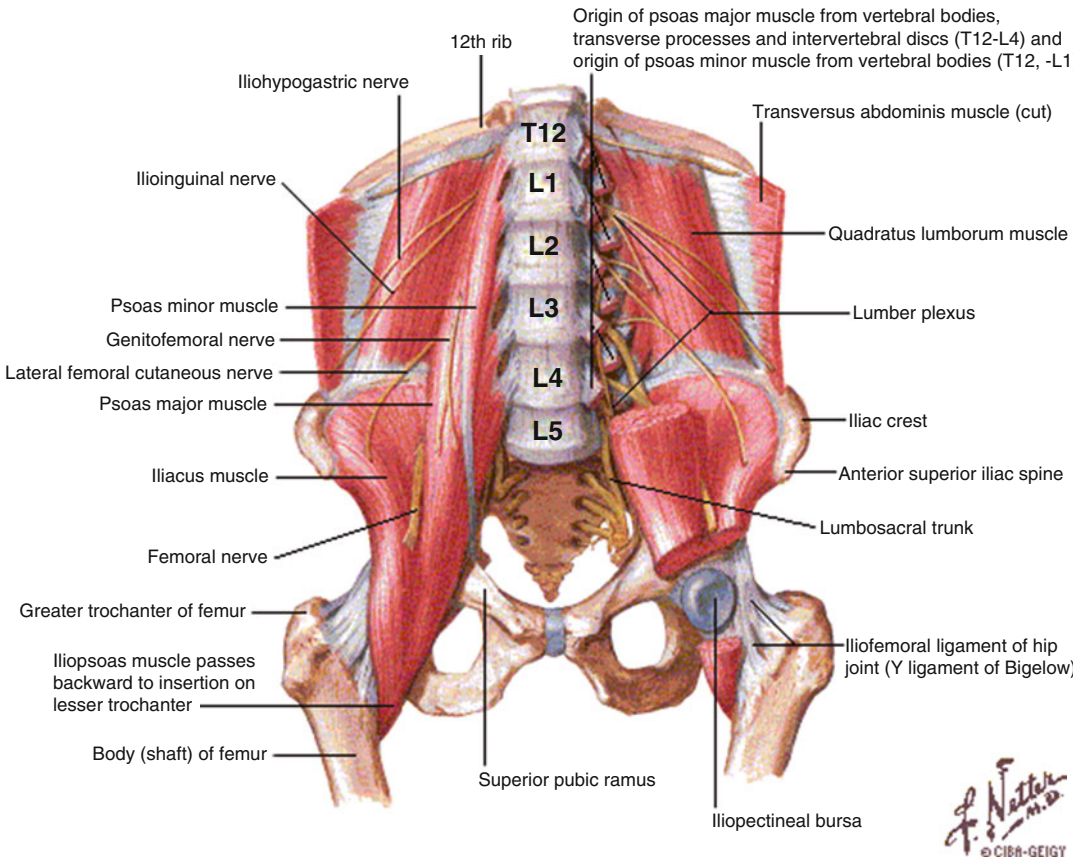


Fig. 17.1 Psoas and iliacus muscles

tendinous arches, from the lower body of T12 down through L5. It travels distally parallel to the lumbar spine and crosses deep to the inguinal ligament and superficial to the capsule of the hip joint, ultimately inserting distally in the lesser trochanter of the femur. The iliopsoas compartment is covered by a fascial layer contiguous with the transversalis fascia laterally, the endothoracic fascia superiorly, and fascia lata inferiorly [10, 23]. Though technically separated by these fascial layers from the retroperitoneal space, the psoas major is frequently referred to as retroperitoneal due to its local relationship with important retroperitoneal structures [10].

The psoas major is innervated by the ventral primary rami of the lumbar roots from L1 to L3. Its blood supply is variable, derived from the lumbar, iliolumbar, obturator, external iliac, and common femoral arteries. The principal supply to the psoas is frequently the lumbar branch of the iliolumbar artery, which arises from the internal iliac [7].

The psoas muscle's primary function is hip flexion. Depending on position, it can also assist in adduction and external rotation of the hip. More controversial are its proposed functions as a "stabilizer" of the lumbar spine, but biomechanical studies have shown function as an erector of the lumbar spine and as an axial de-rotator at the inferior lumbar levels [17, 21].

The lumbar plexus lives within the psoas major. Some of the branches of the plexus perforate and lie superficial to the psoas fascia and include the genitofemoral nerve which is anterior; the lateral femoral which is cutaneous; iliohypogastric and ilioinguinal nerves, which are lateral; and the obturator nerve and the lumbar trunks, which lie medial to the psoas [5].

The precise anatomy of the psoas muscle and its associated structures varies widely from

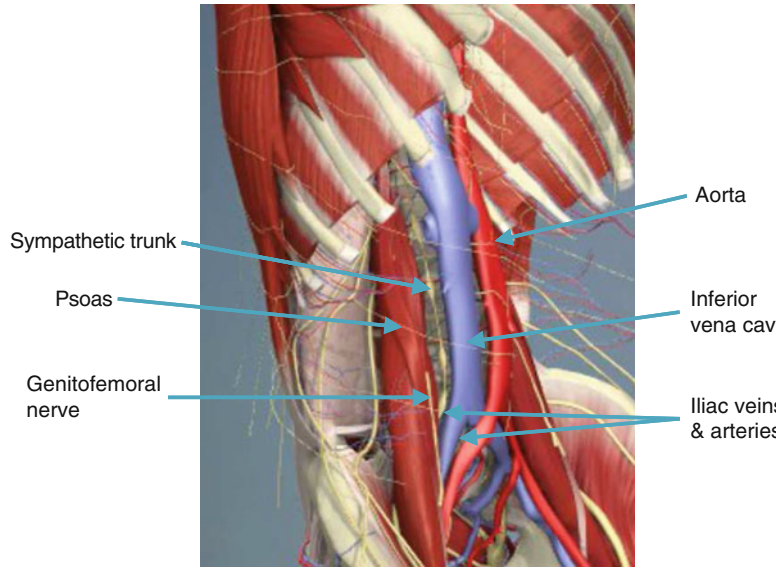


Fig. 17.2 The surgeon must be mindful of the vital vascular and neurologic structures in the vicinity of the spine during the lateral transpsoas approach

patient to patient. Morphometric studies have demonstrated patient-to-patient variability in the location of the aorta, inferior vena cava, common iliac arteries and veins, and lumbar plexus, as well as variability in the shape of the psoas major itself. This variability becomes more important as the so-called safe working zone shrinks at the lower lumbar levels, thereby allowing less room for error in the retroperitoneal approach [5, 8, 24]. This variability can be more of an issue in patients with an element of rotatory deformity. Preoperative imaging, and identification of at-risk structures, is key to safely navigating the lateral approach to the spine [13, 24] (Fig. 17.2).

17.3 Transpsoas Versus ATP

Once the psoas is encountered, the operating surgeon is faced with the choice of dissecting through the psoas major or docking anterior to the muscle, on the vertebral body, and retracting it posteriorly for access to the disk space. Each approach has its own risks and benefits (Fig. 17.3).

The transpsoas approach has the benefit of an *en-phos* lateral approach. This minimizes the risk of an anterior or posterior breach of the disk space during diskectomy and cage placement and concurrently limits danger to contents of the spinal canal posteriorly and the retroperitoneal vessels anteriorly. The cost of this approach to the disk space is the risk of dissecting and retracting the psoas muscle. Manipulation of the muscle itself can frequently lead to temporary weakness. The more significant risk is that to the lumbar plexus, contained in the psoas major from the levels L1 to L5. Defining the working corridors through the psoas muscle has been the subject of much study.

The ventral migration of the lumbar plexus from L1 to L5 has been noted in multiple cadaveric and radiographic studies. This observation lent itself to the notion of "safe working zones" as defined by Uribe et al. When dissecting through the psoas at the level of the discs from L1 to L4, dissection through the middle posterior quartile of the vertebral body ("Zone 3"), and when dissecting at L4/L5 level, dissection in line with the anterior-posterior midpoint of the body [5, 24] are the safety zones.

Dissection through the middle posterior quartile ("Zone 3") at the levels of L1 through L4 and through the midpoint of the body at L4/L5 is thought to minimize risk to the lumbar plexus posteriorly and the genitofemoral nerve anteriorly. Even when working in these "safe zones," care must be taken during both dissection and retraction of the muscle to minimize danger to neurological structures.

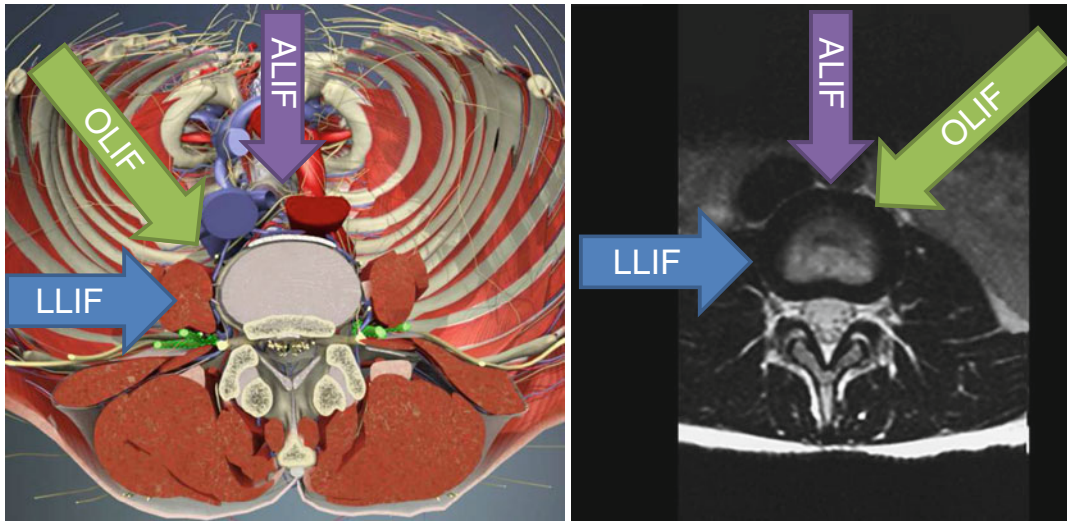


Fig. 17.3 This axial cross-section cartoon (L) and T2 MRI (R) show the common anterior approaches to the disc with respect to position of vital structures

Docking anterior to the psoas muscle and dissecting posteriorly have the advantage of avoiding the posterior lumbar plexus, though care must be taken to minimize manipulation or damage to the genitofemoral nerve, found in the anterior quartile of the psoas at the level of L2/L3 and overlying the anterior aspect of the muscle from L3 down. Also, anterior docking minimizes trauma to the muscle itself, which can cause weakness and confound diagnosis of injury to the superior lumbar plexus and nerve roots.

Additionally, as the approach to the psoas rotates the operative corridor anteriorly, a more anterior skin incision is indicated. As this approach demands a more anterior skin incision and muscle dissection, injury to the iliohypogastric, ilioinguinal, and subcostal nerves is less likely. This decreases the risk of abdominal asymmetry, pseudohernia, or genital numbness—known complications of the direct lateral approach [3, 6, 11].

Anterior docking carries the disadvantage of frequently requiring manipulation and concomitant risk to anterior vascular structures, as well as the sympathetic chain. The oblique approach to the disk space, when contrasted with a more directly lateral, transpsoas dissection, also increases risk to the contralateral nerve root (on the downside), which can be encountered deep in the working area during diskectomy or graft placement. Anterior docking, by rotating the working aperture for diskectomy and graft placement posteriorly, may also increase the risk to structures within the spinal canal itself [9]. These risks may be mitigated by using a banana-shaped cage [6].

17.4 Traversing the Psoas Major

As mentioned above, dissection and retraction of the psoas major in order to gain access to the disk space are fraught with risk to the lumbar plexus. Different techniques have been developed to minimize this risk.

In the original percutaneous XLIF technique, the psoas is traversed using serial dilation. Potential working zones are explored using stimulated discrete threshold electromyography (EMG)—the posterior middle quadrant at L1 through L4, the midline at L4/L5—and docked on the disk space. Once placement of the wire is confirmed with x-ray, and EMG used to detect nearby neurological structures, the psoas can be expanded using dilators of increasing caliber, until a suitable working corridor is available. Both active neuromonitoring and passive neuromonitoring are used throughout to identify poten-

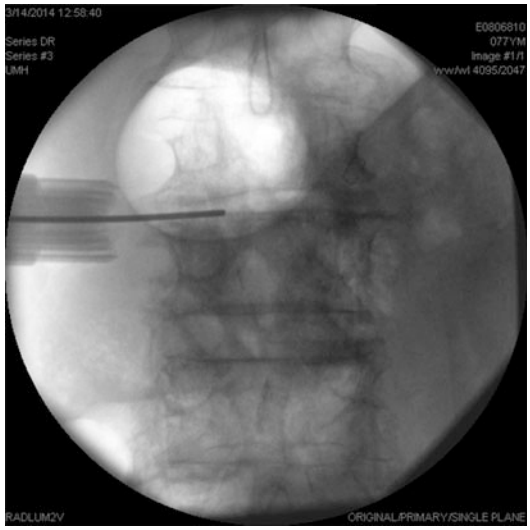


Fig. 17.4 This figure shows an AP radiograph with retractor docked at disc space and guidewire in position

tial damage from blunt dissection to or traction on the lumbar plexus [18].

While anatomic knowledge and neuromonitoring minimize risk to the lumbar plexus, they are not perfect [4]. The "shallow docking" technique allows for direct visualization of the psoas muscle dissection—thereby eliminating the need for blind passage of blunt instruments through the muscle. Direct visualization allows another opportunity to identify nerves and vessels that may otherwise be injured by retractors [1, 22] (Fig. 17.4).

Different modalities of neuromonitoring can also minimize injury to nearby nerves. While triggered EMG is commonplace, adjunctive use of spontaneous EMG, motor evoked potentials, or spontaneous somatosensory evoked potentials can also be helpful in detecting blunt injury or, more frequently, excessive traction resulting in stretch injury.

Minimization of retraction time is also important. Traction on nerves has the potential to cause injury, and that likelihood increases with time. These injuries may not be detected with monitoring [19]. Brisk diskectomy and graft placement will minimize nerve traction and the risk therein. Avoiding electrocautery is another technique to minimize risk [25]. Heat injury to nerves just out of view, especially from monopolar cautery, is another potential complication to be avoided [2, 16].

Even in the absence of injury to neurological structures, dissection of the psoas major can lead to weakness of hip flexion. This weakness is transient and self-resolving over periods ranging from hours to months, but is nonetheless suboptimal for patient mobilization, and also confounds the diagnosis of nerve injury [14]. Avoiding trauma during dissection and minimizing retraction time may decrease the incidence of muscle-generated weakness as well. The use of IV steroids has been reported to reduce the incidence of this sort of weakness, and the use of topical steroids or anesthetic agents at the operative site in the muscle may also decrease the incidence of psoas major weakness [12, 15, 20].

In conclusion, the lateral approach to the lumbar spine requires mastery of the three-dimensional local anatomy of the psoas muscle and the surrounding neurological, vascular, and visceral structures. The concept of three-dimensional triangulation, similar to that used in arthroscopy, is also of paramount importance to allow safe access to this area of the spine in order to optimize outcomes and minimize risks.

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Part IV

Pathologies

18 The Extreme Lateral Minimally Invasive Approach to Pure Degenerative Lumbar Disk Disease

Antonino Raco and Massimo Miscusi

18.1 Introduction

Although significant technical progress has been made in spine surgery over the last decade, interbody fusion techniques for degenerative disk disease (DDD) are still a controversial indication in the current literature [1–7]. Good clinical results have been reported in several randomized clinical trials for a variety of fusion procedures in the treatment of lumbar DDD, with visual analog scale (VAS) improvement of 22–77 % and Oswestry Disability Index (ODI) improvement of 19–79 % [7, 8].

In our opinion, the lack of clear indications in the treatment of lumbar DDD and the opportunity to fuse may be partially attributed to the invasiveness of open surgical approaches, which often seem to be overly aggressive procedures for a disease that has been shown to benefit even from conservative treatment [9]. Nevertheless, the emerging diffusion of minimally invasive spine techniques is progressively changing the indication for treating patients with lumbar DDD because they can achieve mono- or plurisegmental interbody fusion, allowing much faster recovery with a very low rate of complications.

The lateral minimally invasive approach to lumbar spine surgery is an alternative minimally invasive technique for performing interbody fusion at levels above L5. Lateral interbody fusion (LIF) was first described in 2001 by Pimenta et al. and became popular among spine surgeons because of its theoretical advantages over both posterior and anterior approaches [10–12].

Few studies have reported good short- or middle-term outcomes specifically for patients with lumbar DDD following LIF, but its benefits include less tissue dissection with preservation of bony and ligamentous structures; smaller incisions; decreased operative time, blood loss, hospital stay, and postoperative pain; and enhanced fusion rate due to the possibility of placing a footprint intervertebral cage larger than TLIF and PLIF cages [11, 13–23]. The main reported risk of such an approach is damage to the lumbar nerves along the lateral side of the lumbar vertebral column inside the major psoas muscle, which is violated and dissected.

As not all patients with lumbar DDD could benefit from LIF, it should be proposed in only select cases, and knowledge about the anatomical distribution of lumbar nerves and electrophysiological monitoring during surgery are mandatory to avoid surgical complications.

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18.2 The Rome Experience

We reviewed our experience with patients who underwent LIF for pure lumbar DDD above the level of L5–S1 at a single academic institution between January 2010 and December 2013. Preoperative radiological evaluation included lumbar MRI, CT scan, and dynamic X-rays. All cases had radiographic evidence of intervertebral disk dehydration >50%, disk space collapse, and/or Modic end plate changes without significant deformity. Segmental coronal deformity with mono- or bilateral vertical foraminal narrowing due to asymmetric disk collapse was not a reason for exclusion, but patients with radiologically demonstrated frank segmental instability were excluded from the present study. All patients presented with chronic axial low back pain exacerbated by prolonged standing and trunk mobility and previous conservative treatment for a period of at least 6 months failed. Patients with acute radiculopathy due to a frank radicular conflict with the disk or spondylosis, and those with lateral and/or central stenosis, were excluded from the study.

Clinico-neurological evaluations with clinical test VAS, ODI, and SF-36 were routinely performed before the intervention and repeated at follow-up to evaluate the clinical course and quality of life. Only patients with at least 18 months of follow-up were included in the analysis. Statistical analyses were performed using SPSS version 15 software (Chicago, IL, USA). $P < 0.01$ was considered significant.

18.2.1 Surgical Technique

Surgery is performed under general anesthesia; a fast-acting neuromuscular blocking agent can be used during intubation but no neuromuscular block should be used during neuromonitoring. The needle recording electrodes for EMG monitoring should be placed after the patient is asleep but before the final positioning.

The patient is placed on a Jackson or equivalent table in the lateral decubitus position, so the top of the iliac crest is directly over the table break; an axillary roll is placed and the top leg flexed to relax the psoas muscle. Care is taken to avoid pressure injury to the soft tissues, and soft padding is generally placed between the arms and legs. Tape is positioned to secure the patient (1) just beneath the iliac crest, (2) over the thoracic region, (3) from the iliac crest to the knee and then to the table, and (4) from the table to the knee, past the ankle, and then secured to the table. The operative table is then broken, allowing the opening of the disk space to be operated on and increasing the distance between the lower rib and the iliac crest. A-P and L-L X-ray images are obtained to identify the level to be treated and to confirm that the patient is in a true lateral position, checking if the pedicles are equidistant from the spinous process on the A-P scan and if the end plates have double or single contours.

The skin incision is marked. For single-level procedures, a 3–4 cm horizontal, vertical, or oblique incision is centered on the cutaneous projection of midsection of the disk. For multilevel procedures, both multiple incisions and one longer vertical incision can be made, keeping in mind that each level should be reached through a different transpsoas route.

After the skin incision, subcutaneous tissue layers are dissected and the external oblique fascia divided; using blunt scissors and finger dissection, the fibers of the external oblique, internal oblique, and transversalis muscle are carefully spread until a loss of resistance indicates that the transversalis fascia has been opened and the retroperitoneal space entered. Using the index finger, the peritoneum is swept anteriorly and, following the posterior peritoneal wall posteriorly, the quadratus muscle, the tip of the transverse processes, and then the psoas muscle progressively reached. Abrupt advancement should be avoided in every step of the dissection to avoid entering the abdominal cavity.

After arriving at the psoas muscle, the initial dilator is positioned and L-L and A-P radiographs obtained to verify the positioning of the dilator with respect to the lumbar level: the exact position is at the center of (or just posterior to) the disk space. The next step is transpsoas access. The lumbar nerve roots are located in the posterior third of the psoas muscle; thus, the dissection should be carried out between the anterior and middle third

of the muscle. We think that direct visualization of the lumbar nerves eventually encountered inside the psoas, coupled with accurate EMG monitoring, represents the best way to reduce the incidence of postoperative neurological deficits. There are several neuromonitoring systems for the lateral approach, but we usually prefer that our neurophysiologist, who is extensively trained for OR neuromonitoring, assists and guides us during the entire procedure using free-run EMG monitoring and nerve stimulation. Bilateral platinum-iridium needle electrodes are used. When a nerve trunk is visualized traversing the operative field, nerve stimulation is performed and the surgical route eventually modified. Similarly, if the free-run EMG shows the response of some muscles during a particular surgical maneuver, such as dilator positioning or retractor expansion, we can modify our technique, administer anti-inflammatory medications, and temporarily stop the surgery.

The dissection is performed using Penfield or Cobb dissectors and suction, keeping in mind that the lumbar nerves are likely located in the posterior area of the surgical field. After arriving at the intervertebral space, fluoroscopy should confirm the exact position. Under strict continuous neuromonitoring, subsequent dilators are introduced to spread the psoas fibers, and retractor blades are positioned on the lateral border of the spine. X-rays are then obtained to check the final position of the instrumentation and the retractor blades expanded to the desired aperture; the expansion should be in the anterior direction considering the more frequent posterior location of the lumbar nerves.

Under direct visualization, a diskectomy centered on the anterior half of the disk space is performed using standard instrumentation (i.e., pituitary rongeurs, curettes, scrapers). The disk removal should include the contralateral annulus, whereas the posterior annulus is usually left intact. The end plates are prepared, interbody distraction is performed as needed, and a sized trial is inserted to assess the cage dimensions. Finally, the interbody cage, packed with bone chips, is positioned. A-P and L-L radiographs are obtained to evaluate the position of the implant; the ideal placement is centered across the disk space from a mediolateral perspective and near the center of the disk space from an anterior-posterior perspective. The surgical field is irrigated, the retractor removed slowly, and hemostasis verified. Fascial layers, subcutaneous tissue, and the skin are closed in standard fashion.

18.3 Results

Twenty-one patients (9 men and 11 women, mean age of 47.7 years) met the inclusion criteria for this study. Twelve patients presented with pure primary lumbar DDD, whereas nine patients were affected by lumbar DDD secondary to a previous lumbar surgery (e.g., diskectomy, laminectomy, or failed posterolateral fusion) or adjacent segment disease (ASD) after lumbar fixation. The L2–L3 level was affected in four cases (12.1%), L3–L4 in 19 cases (57.6%), and L4–L5 in ten cases (30.3%). Twelve patients presented with two levels of lumbar DDD.

LIF was performed in all 21 patients, for a total of 33 treated segments. In all cases, a posterior minimally invasive procedure was performed to achieve circumferential segmental fusion. Percutaneous pedicular fixation was performed in 15 patients, and 4 patients with a single level underwent interspinous fixation. Two other cases were revisions of a previous pedicular fixation and did not receive any adjunctive posterior approach. Table 18.1 summarizes the general clinical information.

There were no major surgical complications. Immediate postoperative hip flexion weakness and transient upper thigh numbness due to transitory nerve injury during the transpsoas approach were present in 53% of patients but extremely variable. These complications were generally resolved within the first 4–6 weeks after surgery. Only one patient presented with a postoperative L4 motor deficit, which persisted 1 year before the final incomplete recovery.

Seventy percent of patients presented with pain and functional impairment of thigh flexion and intrarotation due to psoas contracture. These symptoms generally resolved in 2–4 weeks with the aid of NSAIDs and myorelaxants. Table 18.2

Table 18.1 Epidemiological and clinical data

Epidemiology		
	Patients, *n*	21
	Sex ratio (M/F)	9/12
	Mean age, years	47.7
Clinical		
DDD	Pure	12 (57.1 %)
	Revision	9 (42.9 %)
Level[a]	L2–L3	4 (12.1 %)
	L3–L4	19 (57.6 %)
	L4–L5	10 (30.3 %)
Posterior fixation[b]	PeSFix	15 (78.9 %)
	InterFix	4 (21.1 %)

PeSFix percutaneous screw fixation, *InterFix* interspinous fixation
[a]12 patients presented with a double level of pathology
[b]19 patients only needed posterior fixation

Table 18.2 Complications

Death	0
Hip flexion weakness	3 (11.1 %)
Upper thigh numbness	9 (42.9 %)
Radicular deficit	1 (4.8 %)

shows the early postoperative approach-related complications.

The mean follow-up time was 32 months (range 18–48 months). Table 18.3 summarizes the results of the clinical test VAS, ODI, and SF-36. All of the tests were administered during the preoperative period, postoperative period (30 days after surgery), and at the last follow-up.

18.3.1 Demonstrative Cases

18.3.1.1 Case 1

A 51-year-old man presented with chronic axial low back pain. From 6 months the pain was unbearable. He underwent physical therapy without resolution of the symptoms. MRI revealed DDD at L4–L5 with no signs of instability in the dynamic X-ray. The results of the preoperative clinical tests were as follows: ODI = 54 %, VAS = 7.1, SF-36 mental = 33.68 mental, and SF-36 physical = 35.23. He underwent LIF at L4–L5 and received a posterior interspinous stabilization device.

Table 18.3 Evaluation tests

ODI			VAS			SF-36		
Pre-op	0–20	0 (0 %)	Pre-op	0–2	0 (0 %)			
	40	2 (9.5 %)		4	3 (11.1 %)	Mental	Pre-op	37.50 %
	60	8 (38.1 %)		6	8 (38.1 %)		Post-op	56.35 %
	80	9 (42.9 %)		8	9 (42.9 %)		FU	60.22 %
	100	2 (9.5 %)		10	1 (4.8 %)	*p*-value		0.0012
	Mean	65.7		Mean	6.97	Physical	Pre-op	29.72 %
p-value		0.0001	*p*-value		0.0005		Post-op	42.58 %
Post-op	Improved	13 (61.9 %)	Post-op	Improved	11 (57.1 %)		FU	55.15 %
	Stable	8 (38.1 %)		Stable	9 (42.9 %)	*p*-value		0.009
	Worse	0 (0 %)		Worse	0 (0 %)			
	Mean	37.5		Mean	4.97			
p-value		0.0005	*p*-value		0.0012			
Follow-up	Improved	20 (95.2 %)	Follow-up	Improved	21 (100 %)			
	Stable	1 (4.8 %)		Stable	0 (0 %)			
	Worse	0 (0 %)		Worse	0 (0 %)			
	Mean	16.8		Mean	2.35			
p-value		0.0013	*p*-value		0.002			



18.3.1.2 Case 2

A 77-year-old woman presented with intense chronic low back pain. It was 10 years before stabilization at L4–L5 due to a degenerative spondylolisthesis (Steffee Implant). X-ray examinations demonstrated breakage of the L5 right screw and a collapse of the disk space. The results of the preoperative clinical tests were as follows: ODI = 84 %, VAS = 8.2, SF-36 mental = 31.32, and SF-36 physical = 31.45. She underwent L4–L5 LIF with restoration of the foramina height, but she complained of postoperative transient upper thigh numbness.



18.3.1.3 Case 3

A 39-year-old woman presented with progressively low back pain. She underwent extensive physical and cognitive therapy without resolution of the symptoms. MRI examinations revealed DDD at L4–L5 with indirect signs of microinstability but no listhesis in the dynamic X-ray. The results of the preoperative clinical tests were as follows: ODI = 63 %, VAS = 6.1, SF-36 mental = 39.37, and SF-36 physical = 35.40. She underwent XLIF at L4–L5 with posterior percutaneous stabilization and achieved complete resolution of symptoms.



18.4 Discussion

The extreme lateral approach has been successfully proposed for treating DDD in the thoracolumbar spine, but the indications are still controversial and the literature lacks consistent and long-term clinical results [24]. Although few studies have reported outcomes specifically for DDD patient cohorts following XLIF, the minimal invasiveness of the surgical approach with careful patient selection and preoperative evaluation of both radiographic and clinical symptoms seem to be determinant factors for obtaining the best results.

In Marchi et al.'s series of 22 patients treated with XLIF, the fusion rate was 93 % with 70 % improvement in back pain and 53 % improvement in ODI. Patients in this series also experienced short operative times (average 72 min), low mean blood loss (50 mL), and short length of stay (1 day) [21]. Berjano et al. reported on the preliminary clinical results of a series of 97 patients, 80 % of whom were classified as having DDD. In their study, clinical improvement was reported to be 61.3 %, leg pain improved 64 %, and ODI improved 55 %. Only a few complications were described, such as L4 transient weakness that resolved in 1 month and transient crural or tight hypoesthesia in 11 patients [22].

Interestingly, Khajavi et al. compared their results for patients undergoing XLIF for DDD with an adjunct minimally invasive posterior approach to results obtained by Gassman et al. with patients undergoing standard open surgery for DDD. Patients treated with XLIF had improved clinical outcomes at the last follow-up (24 months postoperative), 46 % for ODI, 65 % for low back pain, 55 % for leg pain, and 45 % for the physical component of SF-36. Furthermore, at the 24-month follow-up, the scores for patients who underwent XLIF were favorable to the scores of patients who underwent standard posterior open surgery, with the exception of ODI [8, 25, 26].

Our results confirm that XLIF is an alternative and safe approach for DDD. In our opinion, XLIF should be used as part of a surgical strategy to achieve circumferential arthrodesis in select cases of DDD above L5. The procedure allows successful anterior column fixation with brilliant coronal realignment, but it must be followed by minimally invasive posterior approaches, such as percutaneous pedicular or interspinous process fixation and fusion.

Interspinous process devices can be used in single-segment DDD, whereas pedicular fixation is recommended in the case of multiple levels, especially those with coronal deformity. In our opinion, DDD associated with coronal deformity due to asymmetrical disk collapse, with or without narrowing of the neural foramina, represents a clear indication for XLIF. In the case of associated coronal deformity, we approach the degenerated disk from the convex side; coronal alignment and vertical height of the foramina can be restored through the cage insertion.

From a clinical point of view, we prefer the lateral approach in cases of mono- or plurisegmental pure DDD producing axial pain and exacerbated by prolonged standing and axial loading, but not in the case of pure radicular pain. Furthermore, the surgical option should be offered to patients who experienced failed conservative treatment for at least 6 consecutive months.

The lateral approach has the major advantage of allowing, through a minimally invasive route, direct visualization of more than one disk with a single surgical approach, and it should be preferred to other minimally invasive approaches in the case of plurisegmental DDD. Conversely, in our current practice, in the case of monosegmental DDD, especially when radicular involvement is present, TLIF represents our first option for anterior column fusion. Acute radicular pain due to a clear radicular conflict with the herniated disk (intracanalar or intraforaminal) and *claudicatio neurogena* with stenosis of the lumbar canal are two contraindications for the lateral procedure. In such cases, we prefer to obtain interbody fusion using the TLIF approach, which can assure better direct visual control of involved roots or the dural sac, allowing neurolysis.

Nevertheless, in the literature the lateral approach has been proposed as a stand-alone procedure to treat monosegmental DDD associated with central or foraminal stenosis based on evidence that it can effectively restore disk height and foraminal height, achieving indirect

decompression of neural elements with symptomatic improvement [12, 20, 27]. In particular, Oliveira et al. presented a small series of patients with DDD and stenosis, showing substantial dimensional improvement in all radiographic parameters in 15 patients undergoing stand-alone lateral cage insertion, but 2 patients (13 %) required a second surgery for posterior decompression. The authors noted that XLIF may not be appropriate for congenital stenosis, and its stand-alone utility can be limited in patients with stenosis and implant subsidence [20].

Another clear indication in the literature for the lateral approach in lumbar DDD is "revision surgery" [28]. In patients who already underwent diskectomy, laminectomy, or previous posterolateral fixation, the lateral approach has significant advantages over other posterior approaches because the lateral approach allows for the avoidance of scar tissue, access to the spine through a "virgin" anatomical plane, and the prevention of further paraspinal muscle atrophy and fibrosis. Khajavi et al. reported a series of 72 patients who underwent the lateral approach for revision surgery secondary to an adjacent segment disease or post-laminectomy syndrome, and the clinical outcomes compared favorably to those reported for open or posterior approaches [8, 25]. In our series, 9 of the 22 patients have undergone the lateral approach for revision surgery. Two of the patients had been treated years before in another neurosurgical center with standard open surgery. The good results with this particular class of patients are in line with the literature. The cases operated on for a single-level lateral approach are usually revision surgery cases because this technique is not needed for a single level.

The lateral approach is also a surgical option for treating ASD. Wang et al. reported a small series of patients who had undergone stand-alone minimally invasive LIF and fusion to achieve successful indirect decompression and stabilization for ASD without supplemental pedicle screw fixation. The main criticisms against the lumbar lateral approach are based on anatomical considerations. Anatomy limits the indication for the lateral approach, which, in our hands, can be proposed from L1 to L5; L5–S1 is not easily approached because of the anatomical barrier represented by the iliac crest and sacrum. Nerve injury during the transpsoas approach is the most common and potentially most devastating complication of the procedure; several studies have attempted to define "safe" working zones in which the psoas muscle can be manipulated and split without the risk of nerve injury. There is a general trend of progressive ventral migration of the plexus inside the muscle, in the disk space from L2–L3 to L4–L5 and approaching the lumbar disks, and the psoas muscle should always be split and crossed in its anterior three quarters [29–31].

Anatomical studies demonstrate that at L4–L5, the root approximates the center of the disk in 15 % of specimens; therefore, splitting the psoas and inserting the cage at this level may expose the patient to a higher risk of direct nerve damage or stretching injury [32]. Although Ozgur et al. reported no complications in their first 13 patients in 2006, the incidence of thigh discomfort and numbness was reported to be as high as 74 %. This was particularly true when the lateral approach was proposed for the L4–L5 level [33, 34].

Knight et al. published an early complication profile in 2009 for 58 patients who underwent mostly one- and two-level fusions for degenerative lumbar disease. The overall complication rate was 22.4 %, and most complications were approach related. However, two patients continued to have L4 motor deficits 1 year after surgery. Unfortunately, clinical outcomes were not discussed in more detail [31]. Out of 14 patients who underwent XLIF, Papanastassiou et al. reported two patients who developed the unusual complication of contralateral femoral nerve compression [35]. Rodgers et al. reported the largest series of XLIF procedures to date and demonstrated a 6.2 % complication rate in the early (6 weeks) postoperative period for 600 procedures [28]. Specifically, they observed four transient, but no permanent, neurological injuries.

In our series, we have patients who presented with complications related to transitory nerve injury. In eight cases (38.1 %), the complication followed the L4–L5 level approach. Therefore, in our learning curve, we progressively changed our indication for approaching the L4–L5 level, and the TLIF approach is currently our first option. Interestingly, we also had electrophysiological

evidence of transitory nerve injury contralateral to the side of the approach, probably due to hammering the cage. To reduce the risk of lumbar plexus injury during the psoas muscle splitting, we strongly suggest dissecting and manipulating the muscle and nerve under direct visualization and establishing specific and dedicated electrophysiological monitoring. To emphasize the role of direct visualization of the nerve root during the approach, we report the experience of Hardenbrook, who treated 87 lumbar levels in 65 subjects (mean age 57 years, 34 females) by approaching the psoas muscle under direct visualization without neuromonitoring. The mean operative blood loss was 255 mL (range, 40–1,200), and patients were discharged from the hospital in 3.2 days (range, 1–10). Following treatment, back pain was assessed with a VAS improved 48 % and back function assessed with the ODI improved 34 %. No nerve, vascular, or intra-abdominal injuries were noted [36].

Concerning electrophysiological monitoring, our system is far more complete than the standard EMG offered by some of the companies producing instrumentation for the lateral approach. We can use up to 40 channels to monitor all the main muscles in both legs and to obtain the amplitude and latency of evoked muscle potential and up to 12 channels for stimulation, which can be set up differently in terms of trigger, intensity, length, and interval according to need.

Another important issue with the lateral approach to the lumbar spine is the prevention of transitory, but troubling, postoperative psoas contracture and failure, which may produce nagging pain and functionally impair thigh flexion and intrarotation for several weeks. According to our experience, psoas contracture is generally due to the muscle manipulation during the approach, especially in the case of hypertrophic muscle, and to blood collection inside the muscle. To reduce postoperative symptoms due to psoas failure, we strongly suggest gently dissecting and manipulating the muscle under direct visualization and, at the end of procedure, placing drainage inside the muscle to prevent any blood collection. Interestingly, in our series, after the introduction of routine postoperative drainage in the psoas muscle, we observed a significant reduction in pain and functional impairment due to psoas contracture. We also suggest avoiding the excessive use of bipolar cauterization, which may induce muscle degeneration due to devascularization.

Conclusion

The lateral retroperitoneal approach is a well-established procedure to treat degenerative disk disease. Our surgical and long-term results confirm what has been previously published on the subject. A carefully planned preoperative surgical evaluation together with attention to surgical details makes this a straightforward procedure capable of adequately solving multilevel degenerative disk disease of the lumbar spine.

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Lateral Approach for Spondylolisthesis

19

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19.1 Introduction

Spondylolisthesis describes the anterior translation of one vertebral segment in relation to the adjacent, immediately caudal segment (Figs. 19.1 and 19.2). While the underlying etiology of the malalignment is variable, the most common cause is progressive segmental degenerative spondylolisthesis. Spondylolisthesis is categorized based on both the severity of the displacement and on its underlying etiology. Meyerding published the most commonly used grading system (Table 19.1) based on the degree to which one vertebral body has subluxed compared to the immediately caudal segment [15]. More than half a century ago, Wiltse published his classification of spondylolisthesis (Table 19.2) based on the underlying etiology of the listhesis [26, 27]. Outside of the setting of acute trauma, the spine surgeon most commonly evaluates patients with type 2, isthmic, or type 3, degenerative spondylolisthesis.

Patients with symptomatic spondylolisthesis typically present with back, leg pain, or neurogenic claudication. Particularly in patients with dynamic instability, the back pain is often described as mechanical – low back pain initiated by axial loading, even with physiologic loads. Leg pain may be radicular and associated either with traversing or exiting nerve root compression. Neurogenic claudication, classically described as bilateral or unilateral calf, buttock, or thigh pain precipitated by walking and prolonged standing, results from central spinal canal stenosis.

19.2 Treatment

Large, multicenter, randomized, prospective clinical trials have consistently reported improved outcomes for patients with symptomatic spondylolisthesis who undergo surgical decompression and fusion [24]. Initially, patients' symptoms may be managed more conservatively with nonsteroidal anti-inflammatory medications, physical therapy, local injections, weight loss, and exercise. In cases where a reasonable trial of nonsurgical therapy fails, operative intervention has

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Fig. 19.1 Preoperative lateral x-ray in neutral position of a patient with grade I spondylolisthesis at L4–L5



Fig. 19.2 Preoperative lateral standing scoliosis x-ray of a patient with grade I spondylolisthesis at L4–L5

Table 19.1 Meyerding grading system of spondylolisthesis

Grade I	25 % sagittal translation of vertebral body
Grade II	50 % sagittal translation of vertebral body
Grade III	75 % sagittal translation of vertebral body
Grade IV	100 % sagittal translation of vertebral body
Grade V	Spondyloptosis: >100 % sagittal subluxation

Table 19.2 Wiltse classification of spondylolisthesis [27]

Type 1	Dysplastic or congenital spondylolisthesis
Type 2	Isthmic spondylolisthesis (IS): defect in the isthmus or pars interarticularis
2A	Lytic: fatigue fracture of the pars interarticularis
2B	Elongated pars: which may result from pars fracture with subsequent union in the distracted position
2C	Acute fracture: traumatic fracture of the pars
Type 3	Degenerative spondylolisthesis (DS): resulting from long-standing instability
Type 4	Traumatic spondylolisthesis: acute fracture of a posterior element (pedicle, lamina, or facets) other than the pars interarticularis
Type 5	Pathologic spondylolisthesis: structural weakness of the bone secondary to a disease process such as a tumor or other bone disorders
Type 6	Postsurgical

been shown, reproducibly, to offer patients substantial relief of symptoms [25].

For more than a generation, posterior decompression including bilateral facetectomies was thought to be necessary to treat symptoms related to neuronal compression from spondylolisthesis [9]. More recently, studies have documented that such extensive posterior boney resection and wide muscle dissection predisposed patients to progressive deformity, spinal instability, and symptom recurrence. Spinal fusion with decompression has since become the standard of care for symptomatic spondylolisthesis [8, 14, 20].

Since 2005, several studies have compared the efficacy of various techniques, some of which

introduce the placement of lumbar interbody devices. To date, the lack of Level 1 studies proving efficacy has made it difficult to guide standard of care [17, 18]. Minimally invasive surgical techniques have also been employed to address patients with symptomatic spondylolisthesis. One of these techniques, extreme lateral interbody fusion (XLIF) or direct lateral interbody fusion (DLIF), has been demonstrated to be a safe, minimally invasive alternative to traditional open fusion procedures to treat spondylolisthesis [2, 16, 19].

19.3 Surgical Technique

Lateral lumbar interbody fusion (LLIF), either XLIF or DLIF, is a true lateral retroperitoneal approach to the spinal column that allows for large interbody graft placement and excellent disk height restoration and provides indirect decompression at the stenotic motion segment [4]. The patient is positioned in the right lateral decubitus position with the left side up. Using the left side is preferred to access the spine as the aorta and iliac arteries are sturdier than the vena cava and iliac veins and are more likely to withstand surgical handling without being injured. In patients with scoliosis, the aorta may lie on the lateral aspect of the vertebral bodies and thus would require access from the right side.

The intended surgical level is localized by fluoroscopy. The surgical site is marked, prepped, and draped in sterile fashion. Baseline EMG recordings are performed. Following the skin incision, the abdominal musculature is bluntly divided. Gentle blunt dissection allows one to traverse the retroperitoneal space with minimal disruption of the surround tissues. As the psoas muscle is approached, the lumbosacral plexus is localized by the use of automated electrophysiology. Directional EMG is used to ensure the surgeon docks the retractor anterior to the femoral nerve [22]. Establishing a safe corridor through the psoas muscle requires imaging, real-time EMG, understanding of the regional anatomy with its variations, and surgeon experience. In an approach to the L4–L5 disk space in the well-aligned spinal column, the access corridor is slightly more anterior than that at rostral levels. In a patient with anterolisthesis, however, the regional anatomy may be altered, underscoring the importance of directional EMG as a navigational tool [21].

Preservation of the anterior and posterior longitudinal ligaments and avoidance of the neural foramen are critical to the success of LLIF for symptomatic spondylolisthesis. Exposure is achieved with an expandable three-bladed retractor, which allows for direct illuminated visualization facilitating diskectomy and complete anterior column stabilization using a large load-bearing implant. After the diskectomy and interbody graft placement, fusion is achieved by either placement of vertebral body screws and plate or from posterior lateral pedicle screw fixation (Figs. 19.3 and 19.4). For high-grade spondylolisthesis, restoration of disk height by the interbody cage often provides only partial reduction of the listhesis; the rest of the correction can be performed using a cantilever maneuver during posterior supplementation [2].



Fig. 19.3 Postoperative lateral x-ray in neutral position of a patient with grade I spondylolisthesis at L4–L5 after LLIF



Fig. 19.4 Postoperative lateral standing scoliosis x-ray of a patient with grade I spondylolisthesis at L4–L5 after LLIF

Another option is the oblique lumbar interbody fusion (OLIF) procedure, which is an alternative to the traditional anterior lumbar interbody fusion (ALIF) procedure with the convenience of the less-invasive lateral approach. Utilizing an oblique lateral trajectory (Fig. 19.5) away from the posterior nerves within the psoas muscle, this procedure is an alternative to approaches dependent on neuromonitoring to traverse the psoas muscle. By utilizing an oblique lateral approach to the spine, this procedure enables placement of a large interbody graft into the disk space



Fig. 19.5 Gaining access to disk space during oblique lumbar interbody fusion (OLIF)

(Fig. 19.6) for anterior column support and segmental sagittal alignment while minimizing the nerve, muscle, and bone obstacles associated with traditional direct lateral approach. At the same time, this approach also avoids the risk of injury to the aorta, iliac vessels, and genitourinary structures that are encountered in a traditional anterior approach [7].

19.4 Outcomes

Several studies, albeit with limited sample sizes, have reported excellent radiographic and clinic outcomes in patients with symptomatic spondylolisthesis treated with an LLIF procedure. The studies published clinical outcomes such as estimated blood loss, operative time, length of hospital stay, integrity of construct, complications, fusion rates, and improvement in visual analog scale (VAS) of LLIF and compared the results to other fusion procedures, including anterior lumbar interbody fusion (ALIF), posterior lumbar interbody fusion (PLIF), and transforaminal lumbar interbody fusion (TLIF). Like many other minimally invasive techniques, LLIF has been associated with less blood loss, shorter hospitalizations, and earlier mobilization of patients than similar open surgery.

The additional advantages of LLIF include being able to decompress the neural elements via indirect decompression of the spinal canal and



Fig. 19.6 Placement of interbody graft during oblique lumbar interbody fusion (OLIF)

restoring disk height without violating the stabilizing posterior structures of the spine. Another advantage of LLIF is the ability to place a large interbody graft, which can improve fusion rates, restore disk height, and improve lumbar lordosis. Segmental lumbar lordosis is improved through the restoration of disk height with larger lordotic interbody cages, which is possible in both ALIF and LLIF. Unlike ALIF, LLIF avoids the need to retract the great vessels. One challenge with traditional techniques such as PLIF and TLIF is the anterior placement of the interbody cage, which can be crucial to the restoration of segmental lordosis [3].

Ahmadian et al. reviewed patients with grade I and II L4–L5 spondylolisthesis who had undergone elective LLIF between 2008 and 2011. The results focused on 26 adults with grade I and 5 adults with grade II L4–L5 spondylolisthesis who had undergone elective LLIF and subsequent posterior percutaneous pedicle screw fixation without surgical manipulation of the posterior elements (laminectomy, foraminotomy, facetectomy). No motor weakness or permanent neurologic deficits were reported. Transient anterior thigh numbness was noted in 22.5 % of patients. All patients exhibited radiographic and clinical evidence of fusion as determined by static and dynamic radiographs, or CT scans when available, at 6 months [2].

In another study, 63 patients with grade II spondylolisthesis and spinal stenosis were treated with LLIF with supplemental posterior pedicle screw fixation and were available for 12-month follow-up. Early postoperative transient upper thigh pain and hip flexion weakness were common, as expected consequences to operative trauma to the psoas muscle, but these symptoms were not persistent. There were no neurologic deficits. Two (3.4 %) patients of the total cohort underwent further surgery within 1 year: both for adjacent segment disease, one treated with posterior fusion, the other with LLIF. At 12 months, there was no radiographic instability noted on dynamic radiographs, and all patients appeared to have bridging bone across the interbody space [19].

Posterior pedicle screw placement following LLIF provides a construct that promotes circumferential fusion while resisting graft subsidence [10]. LLIF access to the intervertebral space without disrupting posterior musculature or facet joints has permitted the use of stand-alone constructs in a carefully selected patient population. Some authors have presented data that suggests that stand-alone MIS-LIF can be considered for those patients without significant preoperative instability and with high operative/anesthetic risk for traditional or MIS-open hybrid techniques. In patients with mobile spondylolisthesis on dynamic films, or with pars interarticularis defects, stand-alone constructs are contraindicated. Marchi et al. suggested that stand-alone lateral constructs are feasible in low-grade (Meyerding grade I/II) listhesis with a 13 % revision rate largely related to graft subsidence and persistent instability [13]. Lateral interbody fusion should be avoided for high-grade spondylolisthesis (grade III), especially as an anterior alone fusion as there have been rare cases of vertebral body split fracture and cage migration. One study concluded that LLIF alone might prove beneficial for treatment of neurogenic symptoms by indirect decompression [1] in elderly patients where direct decompression could lead to progression of sagittal deformity and avoid open instrumentation, which is associated with a higher complication rate due to patients' preexisting medical comorbidities.

19.5 Complications

Although lumbar LLIF has been effectively used to treat adult degenerative spinal deformity, concerns remain as to whether the lateral approach exposes the lumbosacral plexus to injury as it travels within the psoas muscle. The nerves of the lumbosacral plexus pass through the psoas muscle fibers and may be unknowingly damaged when accessing the spine using a transpsoas approach. Thigh symptoms such as numbness, pain, and weakness have been noted to be relatively common postoperatively, especially when involving the L4–L5 level [6, 23]. The rates of thigh symptoms vary significantly from 0.7 to 62.7 % among published studies [5, 6, 11, 12].

According to the case series by Le et al., they found the overall incidence of postoperative ipsilateral thigh numbness to be 19.7 % for a single surgeon during a 3-year study period. With increased experience over time, the most recent incidence of postoperative numbness decreased to 10.7 %. Of the patients who had postoperative ipsilateral thigh numbness, 35.7 % had symptom resolution by 3 months and 57.1 % had resolution by 6 months and 64.3 % by 1 year. Of the remaining patients, one patient had resolution from 12 to 24 months, and 28.6 % (four patients) had persistent sensory symptoms beyond 2 years. All patients with numbness had a fusion construct that involved L4–L5.

Thirty-nine (54.9 %) of the 71 patients developed postoperative motor weakness involving the iliopsoas muscle. All patients had complete resolution during the postoperative period. Thirty-six (92.3 %) of the 39 patients had complete resolution by 3 months, 37 (94.9 %) of the 39 patients had complete resolution by 6 months, 38 (97.4 %) of the 39 patients had complete resolution by 1 year, and 39 (100 %) of the 39 patients had complete resolution by 2 years [11].

Conclusion

Lateral interbody fusion is a minimally invasive approach by which the spine surgeon may treat patients with symptomatic spondylolisthesis. There is mounting evidence, based on both relevant clinical and radiographic follow-up data, that LLIF constructs provide patients with good radiographic outcomes. Long-term follow-up studies that demonstrate improved functional outcome in patients undergoing lateral interbody fusion for treatment of spondylolisthesis would add to the current literature.

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Lateral Lumbar Interbody Fusion (LLIF) for the Treatment of Adult Spinal Deformity (ASD)

20

Joseph M. Zavatsky, David Briski, and Juan S. Uribe

20.1 Introduction

Adult scoliosis (AS) may be defined as a coronal deformity with a Cobb angle >10° in a skeletally mature patient. Although AS can develop from the progression of idiopathic scoliosis (IS) in adolescence, more commonly AS develops as the result of a degenerative cascade later in life that terminates in asymmetric disc collapse, vertebral body wedging, facet degeneration, spondylolisthesis, and rotary subluxation. This degenerative cascade has the potential to lead to spinal stenosis, instability with progressive deformity in the coronal and sagittal planes, loss of lumbar lordosis, and the development of sagittal imbalance. Patient symptoms can include radiculopathy, neurogenic claudication, and back pain [1].

Advances in medical science and patient care have dramatically improved over the last 50 years, which has significantly increased the life expectancy of Americans. With an increasing aging population, the prevalence of degenerative disorders, including adult degenerative scoliosis (ADS), has also increased. Although the prevalence of scoliosis in the adult population has been reported as ranging from 2 to 32 %, a recent study targeting elderly volunteers showed a prevalence of more than 60 % [2]. With an increasingly aging population in the United States and an increased focus on maintaining patients' quality of life, adult scoliosis is becoming a considerable healthcare concern.

Aside from the aesthetic considerations of scoliosis in the adult, significant pain and disability can develop [3]. Several authors have correlated radiographic parameters with clinical symptoms in adults [1, 4]. Loss of normal lumbar lordosis can lead to sagittal plane imbalance, which has been associated with increases in pain and decreases in quality of life measures [1, 5]. Surgical restoration of a patient's sagittal spinal balance can lead to improvements in quality of life measures [6]. The main goals for the treatment of adult degenerative spinal deformity are neural element decompression, correct and maintain global sagittal and coronal balance, and arthrodesis. Restoration of spinal balance is associated with improved outcomes and is one of the principal goals of ADS surgery.

Operative interventions require evaluation of the unique needs and goals of each individual patient. ADS surgery is technically challenging and poses significant risk to patients, particularly those who are elderly and with medical comorbidities. Complication rates have been reported as

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high as 61 % and can vary with a given procedure. More complex procedures, including longer fusion constructs and osteotomies, are associated with higher complication rates [7]. Complication rates increase with older patient populations [8] and have been reported as high as 95 % in patients older than 70 years [9]. More senior patients often have multiple medical comorbidities, which are associated with higher preoperative American Society of Anesthesiologists (ASA) grades. Higher ASA scores have been associated with an increase in perioperative complication rates [10, 11]. Complications can result in increased patient morbidity, hospital readmission, and reoperation [12, 13] which can negatively impact health-related quality of life (HRQOL) outcomes [12]. Despite the high rates of complications seen in ADS surgery, overall patient HRQOL and functionality improve postoperatively, even in the older patient population [14].

Traditional approaches used to treat spinal deformity include anterior-posterior approaches and posterior-only approaches, both of which have been shown to be effective [15–17]. However, open anterior thoracoabdominal approaches are associated with up to 40 % risk of complications including incisional pain, abdominal hernia, vascular injury, ileus, retrograde ejaculation, ureter and bladder injury, and ilioinguinal and iliohypogastric nerve injuries [17, 18]. Open posterior approaches incorporate dissecting most of the musculotendinous structures of the posterior bony spine resulting in a large open wound with dead space and increased blood loss. Pedicle screw instrumentation, decompressive laminectomies, interbody fusion, and osteotomies can then be performed after the open exposure. Interbody fusion and graft placement have traditionally been achieved through anterior lumbar interbody fusion (ALIF), posterior lumbar interbody fusion (PLIF), or transforaminal lumbar interbody fusion (TLIF).

Over the past decade, minimally invasive surgical approaches to neural decompression and fusion have been popularized and recently have been utilized in the treatment of adult spinal deformity. Minimally invasive surgery (MIS) of the spine not only implies surgery performed through smaller incisions but also seeks to reduce approach-related perioperative complications and morbidity associated with traditional open surgical techniques [19–21]. MIS often utilizes smaller incisions, which can reduce soft-tissue trauma and intraoperative blood loss. This can result in decreased rates of complications including surgical site infection, postoperative pain, and narcotic consumption, along with quicker patient mobilization after surgery [22]. Perioperative morbidity is compounded by the complexity of the ADS surgical procedure, as well as patient-specific comorbidities [23–26]. Smith et al. reported that outcome measures after ADS surgery in elderly patients improve more dramatically than in younger patients [14], and with an increasing elderly population, MIS techniques may provide a safer surgical alternative in qualified candidates.

Recent advances in surgical techniques and instrumentation allow for long-segment fusion constructs to be placed less invasively and still allow segmental spinal manipulation in select ADS patients [27]. Posterior pedicle screw instrumentation can be performed through percutaneous incisions, which does not require stripping off the spine's soft-tissue envelope. Posterior or posterior lateral fusion is difficult to achieve when performing MIS pedicle screw instrumentation and requires interbody augmentation to obtain arthrodesis. Prior reports have shown that minimally invasive spinal fusion may result in higher rates of pseudarthrosis if interbody fusion is not performed at every lumbar level [28–31]. Interbody augmentation in MIS ASD surgery can be accomplished through MIS anterior lumbar interbody fusion (ALIF), transforaminal lumbar interbody fusion (TLIF), or lateral lumbar interbody fusion (LLIF) techniques. Interbody augmentation can provide anterior structural support, assist in deformity correction, restore lumbar lordosis, and increase fusion rates [32–36].

The transpsoas LLIF approach provides an alternative to more traditional ALIF, PLIF, and TLIF interbody techniques. The theoretical advantages that make this technique attractive include powerful deformity correction particularly in the coronal plane, decreased blood loss, more complete discectomy larger graft placement which can span the stronger ring apophysis decreasing subsidence and increasing fusion rates, and avoidance of the spinal canal resulting

in decreased risk of nerve and dural injury. Although the LLIF technique is not without risk, it does use a corridor that is designed to protect the vital structures both anterior and posterior to the vertebral body. The use of the MIS LLIF approach may decrease the morbidity of traditional anterior approaches while decreasing the invasiveness of the posterior approach. The risks and benefits of the MIS LLIF technique in the treatment of adult scoliosis will be the focus of this chapter.

20.2 MIS Treatment Algorithm

Unlike patients with adolescent idiopathic scoliosis (AIS) where the decision for surgical intervention is driven by curve magnitude, patients with adult degenerative scoliosis (ADS) are treated based on clinical symptoms including a declining quality of life and increasing pain with disability [37]. Primary degenerative scoliotic curves are located in the lumbar spine as opposed to progressive adolescent idiopathic scoliotic curves that often have an additional thoracic deformity. Degenerative scoliosis can have both rotation and rotary subluxation, with the apex commonly at L3–L4 (Fig. 20.1).

Additionally, there can be a loss of the normal lumbar lordosis, and patients can become sagittally imbalanced and lean forward. To compensate and regain balance in order to stand erect and bring their head over their pelvis, patients will attempt to maximize hip extension and retrovert their pelvis (tucking their buttocks). In severe cases of positive sagittal imbalance, patients will also flex their knees to stand erect. Patients with >5 cm of positive sagittal imbalance often report

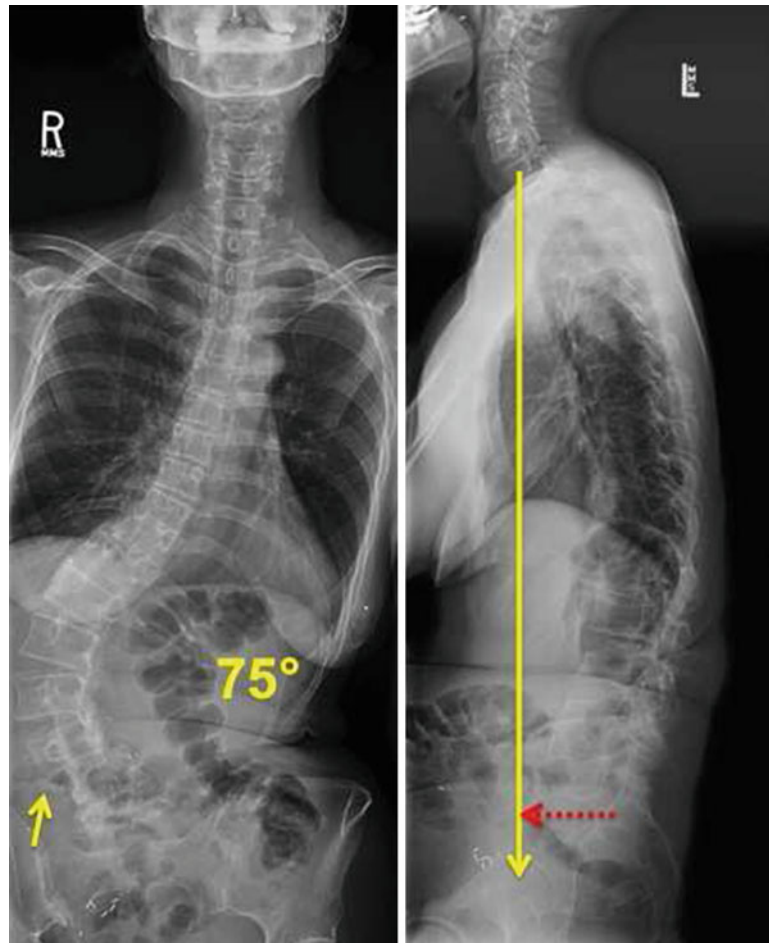


Fig. 20.1 (**a**) Full-length scoliosis AP x-ray revealing significant coronal (75°) and rotational deformity, along with rotatory subluxation at L3–L4 (*yellow arrow*). Lateral x-ray demonstrating loss of the normal lumbar lordosis and a positive sagittal vertical axis (SVA) of +7 cm

a significant functional decline due to the energy expenditure required to maintain spinal sagittal homeostasis. Patients can experience early fatigue, intolerance of standing, and walking with compensation through other joints. This constant hip extensor and quadriceps eccentric contraction can lead to muscle fatigue and intolerance of most activities.

Understanding the etiology, anatomic features, and clinical presentation of the adult patient with scoliosis is important in determining an appropriate surgical strategy.

However, not every adult patient with spinal deformity can be managed with MIS techniques. Prior reports have shown that MIS techniques have limitations in the ability to adequately correct and restore sagittal spinal parameters, along with increased pseudarthrosis rates if interbody fusion is not performed at every lumbar level [28–31, 38, 39]. Appropriate patient selection for less invasive correction techniques is critical to optimize successful patient outcomes in the treatment of adult deformity. Relative contraindications for this approach include previous retroperitoneal dissection, previous pyogenic kidney infection, or retroperitoneal infection. This may result in adhesions of the kidneys, peritoneum and bowel, and vasculature. Additionally, unfavorable anatomy may restrict access to the planned operative level.

Full-length scoliosis x-rays capturing the base of the skull down to the femoral heads, along with magnetic resonance imaging (MRI) and computed tomography (CT) scans of the planned instrumented areas, should be obtained for preoperative planning. Careful review of the imaging should be performed to identify any obstacles to the planned surgical levels. High-riding iliac crests may block access to L4–L5 and can usually be detected on preoperative x-rays, but may also be identified intraoperatively with fluoroscopic x-ray. Ankylosed facets can be identified on computed tomography (CT) scans and may limit the ability of the LLIF technique to restore disk height, lordosis, and coronal Cobb angle due to facet hypertrophy, osteophytes, or fusion. Additionally, unrecognized ankylosed facet joints may result in endplate and ring apophysis violation when performing the disk preparation or implant insertion resulting in suboptimal deformity correction and indirect decompression (Fig. 20.2).

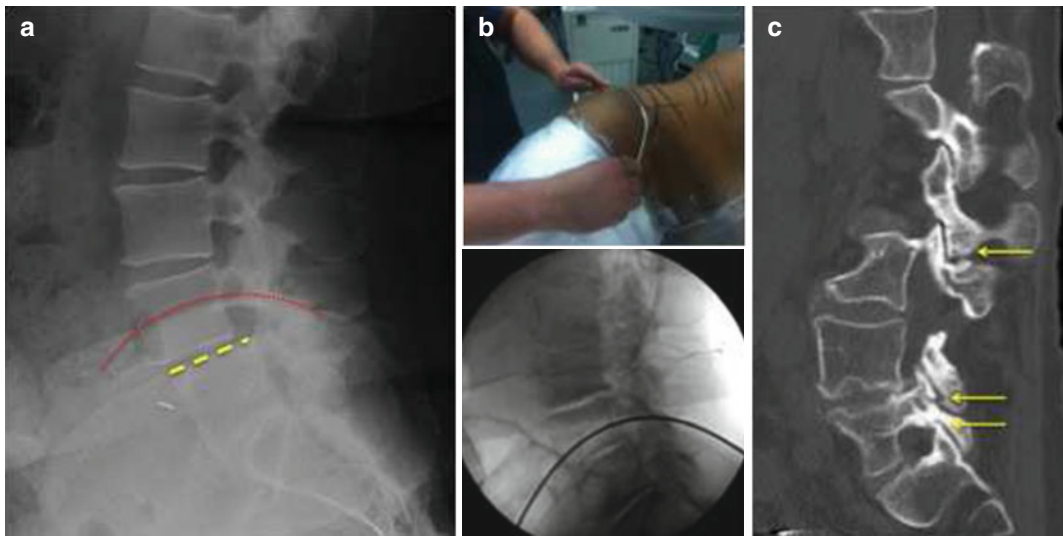


Fig. 20.2 (**a**) Preoperative standing x-ray revealing the iliac crest (*red line*) blocking access to the L4–L5 disk space (*yellow line*). (**b**) Intraoperative fluoroscopic x-ray with a flexible guide wire held against the patient's skin outlining the iliac crest, which is blocking access to L4–L5. (**c**) CT scan of the lumbar spine reveals hypertrophic, osteophytic, ankylosed facet joints, which could limit the restoration of disk height, lordosis, and deformity correction, (*Arrows)* reveal hypertrophic, osteophytic, ankylosed facet joints, which could limit restoration if disc height, lordosis, and deformity correction utilizing the LLIF technique

The rotational component of the deformity may alter the normal anatomy placing nerves, visceral organs, and vascular structures in direct line with the surgical approach placing them at greater risk for injury (Fig. 20.3). An axial MRI of the planned surgical levels can identify any anomalous anatomy and assist in surgical decision-making (Fig. 20.4). The anatomic variations, stiffness, rotary olisthesis, and extensive osteophyte formation make attention to detail extremely important in surgical planning. This approach relies on excellent preoperative imaging studies to make appropriate technical decisions and to ensure safety when approaching the spine. In cases where the lumbar plexus cannot be clearly defined, particularly in rotatory scoliosis, magnetic resonance neurography (MRN) can better delineate the anatomic location of the nerves by optimizing selectivity for their unique MRI water properties (Fig. 20.5).

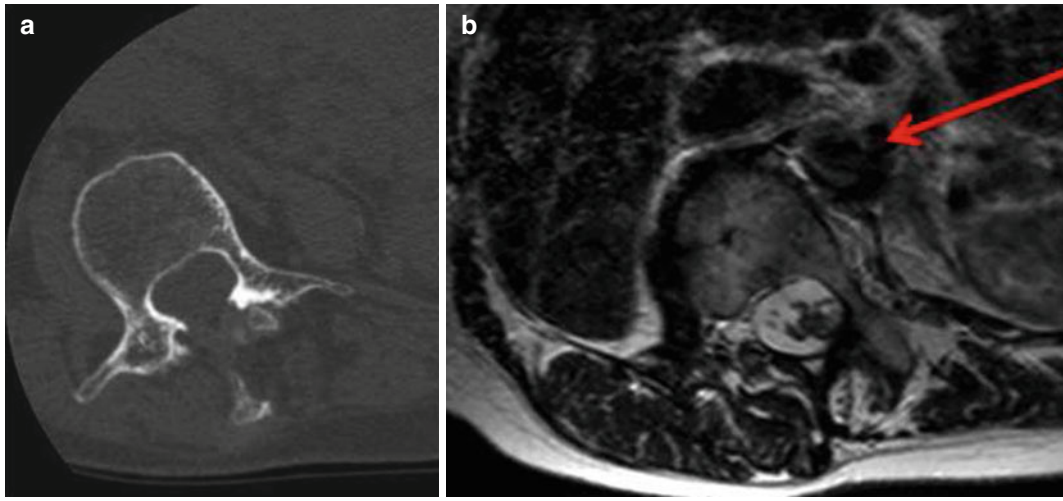


Fig. 20.3 (**a**) Axial CT scan of the lumbar spine revealing a rotational deformity. (**b**) Axial MRI of the lumbar spine reveals the great vessels in the operative field adjacent to the optimal docking site at the anterior 1/3 of the disk as a result of the rotational deformity of the lumbar spine (*Arrow)* reveals the great vessels in the operative field adjacent to the optimal docking site at the anterior 1/3 of the disc space as a result of the rotational deformity of the lumbar spine.

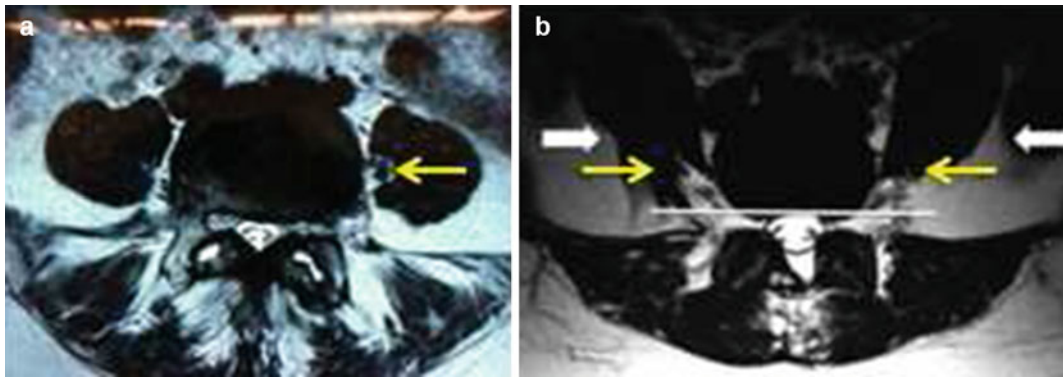


Fig. 20.4 (**a**) Axial MRI of the L4–L5 level revealing a more anterior L4 nerve in the middle of the disk space, which may prevent safe access to this level. (**b**) Axial MRI of the L4–L5 level demonstrates a rising psoas sign or Mickey Mouse ears. The psoas muscle (*white arrows*) is rising away from the vertebral column as opposed to its typical location immediately lateral to it. This finding is consistent with the trend of progressive ventral migration of the lumbar plexus (*yellow arrows*) throughout the lumbar spine from cephalad to caudad placing nerves more at risk [40].



Fig. 20.5 Magnetic resonance neurography (MRN) is the direct imaging of nerves by optimizing selectivity for unique MRI water properties of nerves. It may be useful in delineating the anatomy of the lumbar plexus in complicated scoliosis cases or in those with unique anatomy like a rising psoas sign

Degenerative scoliosis typically develops over time. As the "major" curve worsens and the patient is no longer in coronal spinal balance, they compensate to keep their head centered over their pelvis. This compensation can result in the development of curves above and/or below the "major" curve. With age these curves can worsen and become stiff. The curve that develops below a major lumbar curve is called the fractional curve and is usually located at the lumbosacral junction on the opposite side of the major curve's concavity. Obliquity at L5–S1, due to severe degeneration, congenital deformity, or leg-length inequality, can actually be the primary deformity and result in a major compensatory lumbar curve above it. Although the LLIF technique is not contraindicated in patients with fractional and stiff thoracic curves, these scenarios deserve particular attention. If the fractional and stiff thoracic curves are not identified and considered in the preoperative plan, worsening of the patient's coronal balance can result (Fig. 20.6). Utilizing the LLIF technique in patients with stiff thoracic curves can "push" them further out of coronal balance. Additionally, if the L5–S1 interbody fusion is performed on the same side of the major curve's concavity in patients with fractional curves, the coronal imbalance can worsen.

Proper patient selection is the key to successfully treating adult patients with deformity using MIS techniques. Regardless of the utilization of open or MIS techniques, the goals of adult degenerative spinal deformity surgery are the same and include neural element decompression, establishing and maintaining sagittal and coronal global balance, and arthrodesis. Before the surgical application of MIS techniques is utilized to treat adult deformity, several qualifying questions need to be answered. First, can MIS techniques adequately decompress the neural elements? Second, can the spinal instrumentation be placed using MIS techniques? Third, can global coronal and sagittal balance be adequately restored? Lastly, can a solid arthrodesis be obtained?

Several classification schemes including treatment levels have previously been described for adult spinal deformity [21]. In 2010, Silva and Lenke published a treatment-level guide detailing six treatment levels (degrees of severity) for the traditional open surgical management of spinal deformity, based on clinical and radiographic findings [41].

Of the six Lenke-Silva treatment levels, treatment levels I–IV could effectively be treated with current minimally invasive techniques based on published data [28, 29, 31].

Mummaneni and colleagues modified the Lenke-Silva scheme to create an algorithm for the minimally invasive treatment of spinal deformity, which is termed the MiSLAT (Mummaneni, Wang, Silva, Lenke, Amin, Tu)

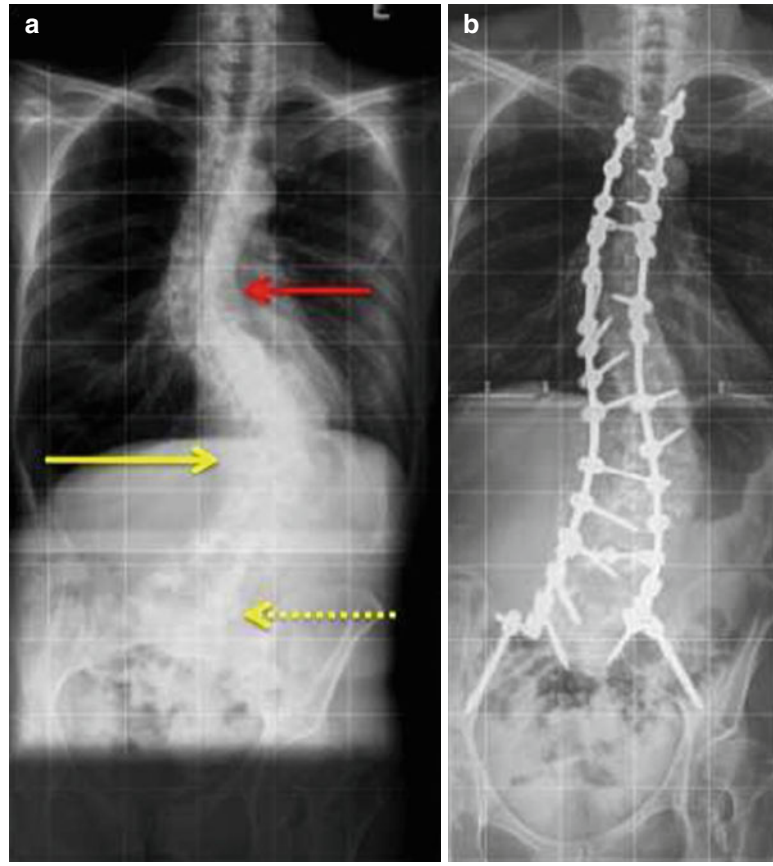


Fig. 20.6 (**a**) Preoperative scoliosis AP x-ray of a patient who had adolescent idiopathic scoliosis that progressed into adulthood. Bending x-rays revealed a stiff thoracic dextroscoliosis (*red arrow*) and major thoracolumbar scoliosis (*solid yellow line*). The fractional curve is located at the lumbosacral junction (*yellow dashed line*). The patient is coronally imbalanced to the left. (**b**) Postoperative x-ray after a five-level LLIF (T12–L1, L1–L2, L2–L3, L3–L4, L4–L5) and an L5–S1 TLIF performed on the right side in the convexity of the fractional curve (opposite the *yellow dashed line*). The patient's coronal imbalance is slightly worsened

algorithm [42] (Fig. 20.7). The authors propose that adult deformity falling into MiSLAT treatment levels I through IV could be addressed utilizing MIS techniques. However, more severe and fixed deformities that fell in the MiSLAT treatment levels V and VI require more traditional open approaches to reliably correct the deformity.

Mummaneni's MiSLAT classification for the MIS treatment of spinal deformity is cumbersome and has a low interobserver and intraobserver reliability. His group subsequently created a less complex scheme, the minimally invasive spinal deformity surgery (MISDEF) algorithm to assist spine surgeons in selecting an appropriate surgical approach for spinal deformity [43]).

The MISDEF algorithm incorporates patient's preoperative radiographic parameters and was simplified into three general surgical approaches, ranging from MIS direct or indirect decompression to open deformity surgery with osteotomies. This simplified approach resulted in substantial inter- and intraobserver agreement.

A Class I approach involves an MIS or mini-open muscle-sparing decompression alone or MIS fusion of a single listhetic level, regardless of curve apex. The Class I approach is accomplished either through small fixed tubular retractors (MIS) or via expandable tubular retractors placed through a muscle-sparing Wiltse or lateral approach (mini-open). Instrumentation may be placed through the expandable tubular retractor or via a percutaneous method. A Class II approach entails an MIS or mini-open decompression and interbody fusion of the curve apex or the entire coronal Cobb angle of the major curve. A Class III approach entails a traditional open surgical approach involving osteotomies and/or extension of the fusion into the thoracic spine. Navigation through the algorithm

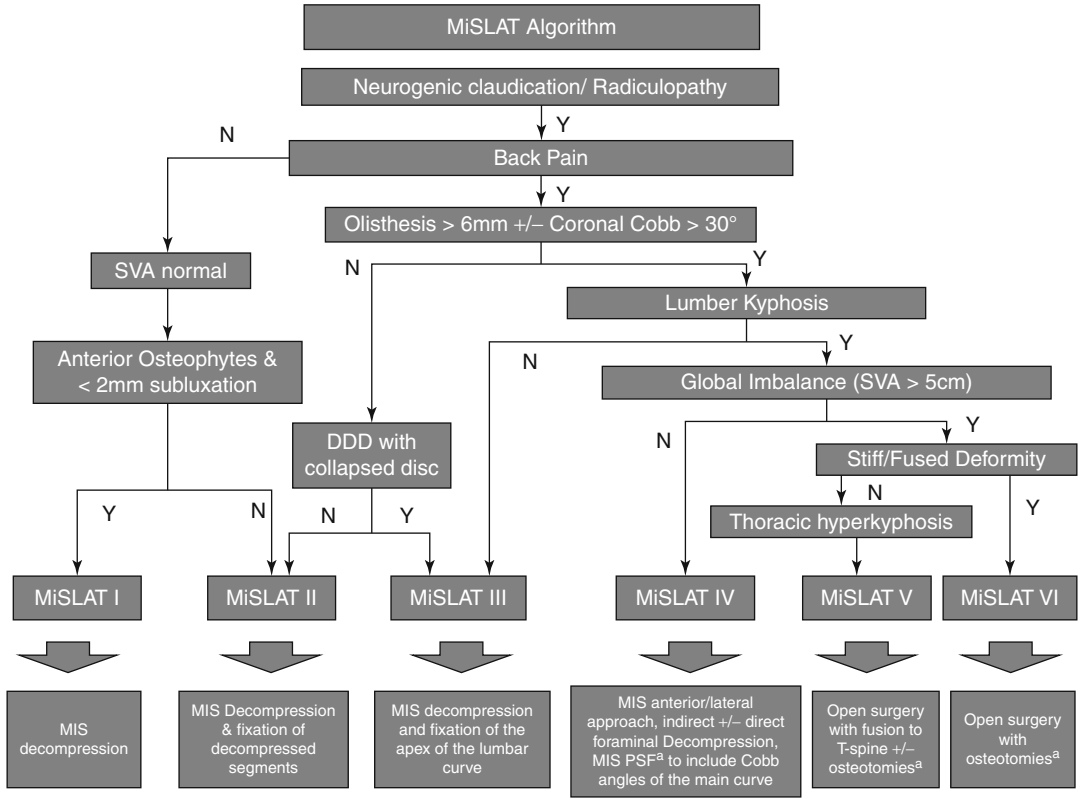


Fig. 20.7 MiSLAT algorithm for MIS treatment of adult degenerative deformity. MiSLAT I = decompression only; MiSLAT II = decompression and limited pedicle screw fixation of a portion of the coronal curve with posterolateral bone graft or TLIF; MiSLAT III = decompression and pedicle screw fixation of the apex of the lumbar curve with posterolateral bone graft or TLIF/extreme lateral interbody fusion (XLIF)/direct lateral interbody fusion (DLIF); MiSLAT IV = decompression and pedicle screw fixation of the lumbar spine with TLIF/XLIF/DLIF to include Cobb angles of the main curve; MiSLAT V = decompression and pedicle screw fixation and fusion extending into thoracic region for thoracic hyperkyphosis ± osteotomies; MiSLAT VI = correction of thoracolumbar scoliosis with three-column or multiple-facet osteotomies and multisegmental pedicle fixation and fusion. Iliac screw insertion is suggested for constructs extending longer than L2 to S1 (Adapted from Mummaneni et al. [42])

is based on established ideal sacropelvic parameters and global spinal balance. In general, progressively worse deformity requires higher-class approaches in the algorithm.

Not all deformity cases can be appropriately treated with MIS techniques. Due to the limitations of MIS in restoring significant sagittal plane imbalance, Class III deformities cannot be easily corrected using MIS techniques, as patients often require osteotomies, which can be extremely challenging using MIS techniques. The minimally invasive spinal deformity surgery (MISDEF) algorithm may provide a reliable and reproducible tool for surgeons to achieve their desired surgical goals when considering MIS versus open techniques in the treatment of adult spinal deformity.

20.3 Surgical Technique

The transpsoas lateral lumbar interbody fusion (LLIF) surgical approach can be more complicated when utilized for deformity correction in the scoliotic spine due to the associated coronal and rotational deformities. Not only can the

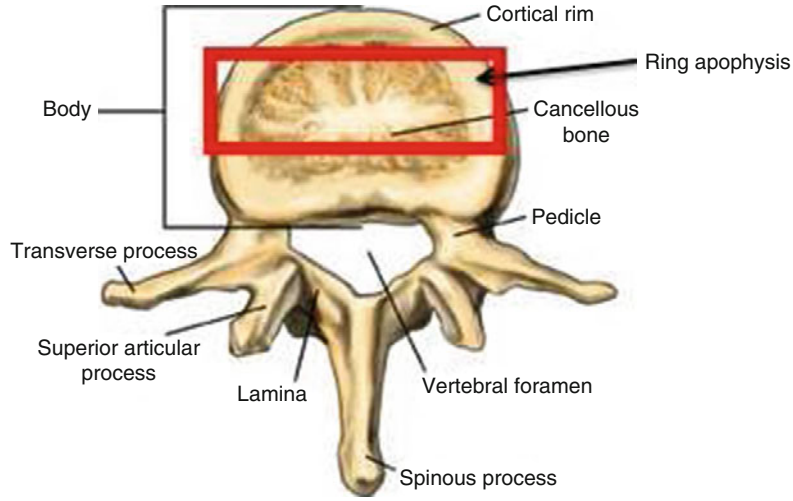


Fig. 20.8 The ring apophysis is the strongest portion of the vertebral endplate composed of dense cortical bone located circumferentially at the periphery. The *red rectangle* illustrates the optimal position of the LLIF cage resting at the anterior 1/3 of the disk space spanning the ring apophysis

bony anatomy be altered making radiographic identification challenging, but also other critical structures can rotate into the normal surgical path placing them at risk. The LLIF procedure has advantages over the traditional direct anterior lumbar interbody fusion (ALIF) technique. Open anterior thoracoabdominal approaches are associated with up to 40 % risk of complications including incisional pain, abdominal hernia, vascular injury, ileus, retrograde ejaculation, ureter and bladder injury, and ilioinguinal and iliohypogastric nerve injury [17, 18]. Proper surgical LLIF technique allows for an aggressive diskectomy and release of the contralateral annulus. The anterior longitudinal ligament (ALL) is preserved, which preserves stability but can also limit lordosis restoration. A more aggressive and thorough discectomy can be performed, which can prepare a larger graft bed for the LLIF implant resulting in a larger surface area for fusion. Proper implant sizing allows for spanning the vertebral annular ring apophysis, which is the strongest portion of the endplate [44]. This outer rim of the dense cortical bone is stronger than the more central, weaker portions of the endplate where ALIF and TLIF cages rest (Fig. 20.8).

In addition to a greater area of endplate preparation, Tatsumi and colleagues found that the LLIF approach resulted in a significantly lower risk of endplate violation when compared to the TLIF approach (4 % vs 48 %) [45]. If the endplate is not violated during disc preparation and the implant properly spans the ring apophysis, this can facilitate deformity correction, indirect decompression of the spinal canal and neuroforamen, and interbody fusion.

When the LLIF technique is utilized in the treatment of adult deformity, there are multiple critical factors to consider prior to the actual surgical procedure itself. After the patient's preoperative imaging is critically reviewed and they have been determined an optimal candidate for LLIF deformity correction, proper patient positioning and intraoperative fluoroscopic x-rays are essential for a safe and successful outcome.

20.3.1 Patient and Bed Positioning

Patient positioning is critical, but often overlooked, when performing the LLIF procedure for deformity correction. Prior to placing the patient on the operating room (OR) table, an extension piece can be placed at the foot of the table. Once the extension piece is in place, the OR table can be reversed, or turned around, so that the patient's head is placed on the extension located at the true end of the bed. The extension maximizes OR table length and gives the surgeon more room caudally. The bed can then be maximally

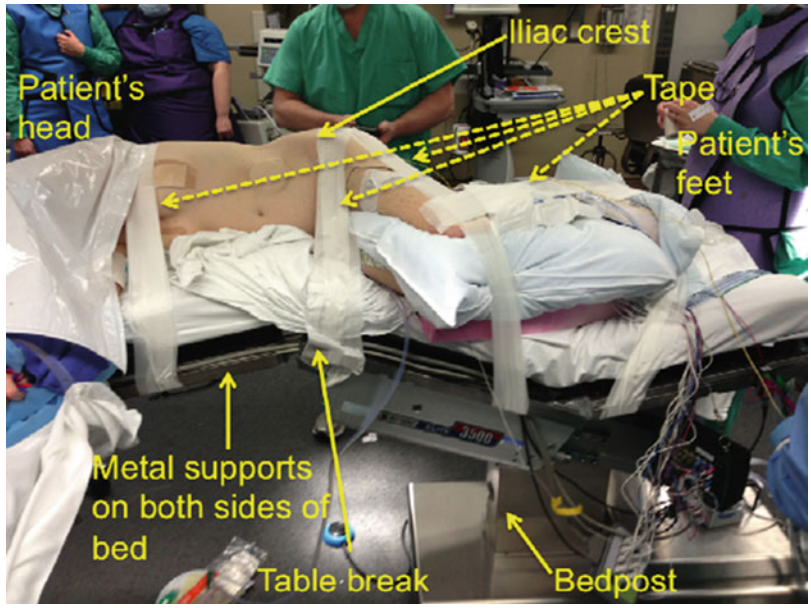


Fig. 20.9 Reversed OR bed translated maximally toward anesthesia to allow room for proper visualization of the caudal lumbar vertebra with C-arm. The patient's iliac crest is placed at the break in the OR table with the hips and knees flexed. Tape is placed across the chest and pelvis, as well as over the thighs and legs

translated away from the central metal bedpost (toward anesthesia). The placement of the extension piece, reversing and translating the OR bed, can result in more room under the table caudally and less restriction for the fluoroscopic C-arm relative to the OR table bedpost. This can result in better visualization of the caudal lumbar vertebra and pertinent bony anatomic landmarks (Fig. 20.9).

Patients should be positioned in the lateral decubitus position with their iliac crest at the break of the table with all bony prominences well padded. A true lateral decubitus position is essential to this procedure. This position will allow for the abdominal contents to fall forward and away from the psoas more easily during peritoneal release from the retroperitoneal space, which can decrease the risk of injury to the peritoneum and its contents. Placing the patient's iliac crest at the break of the OR table allows for flexing (breaking) the table, which can allow better visualization and access to the caudal lumbar levels, particularly L4–L5. It may also aid in the correction of the coronal deformity if the surgical approach is through the concavity of the lumbar curve. Most surgeons stand at the patient's back when performing LLIF surgery, so the patient's back should be positioned close to the posterior edge of OR table so that the surgeon does not have to lean considerably over the patient to visualize the operative field. Care has to be taken not to position the patient too far posterior so that the spine overlaps the metal bars on the side of the OR table. This can be particularly problematic when the bed has to be rotated toward the patient's back due to the scoliosis in order to obtain neutral lateral x-rays. Rotating the patient posteriorly will rotate the metal bar on the side of the bed under the patient, possibly blocking C-arm visualization (Fig. 20.10).

The patient's hips and knees should be flexed to approximately 60 and 90°, respectively, which takes tension off the psoas muscle and more importantly the lumbar plexus that lies within it. Femoral nerve strain at L4–L5 can increase with breaking the OR table by putting the psoas muscle and lumbar plexus on stretch.

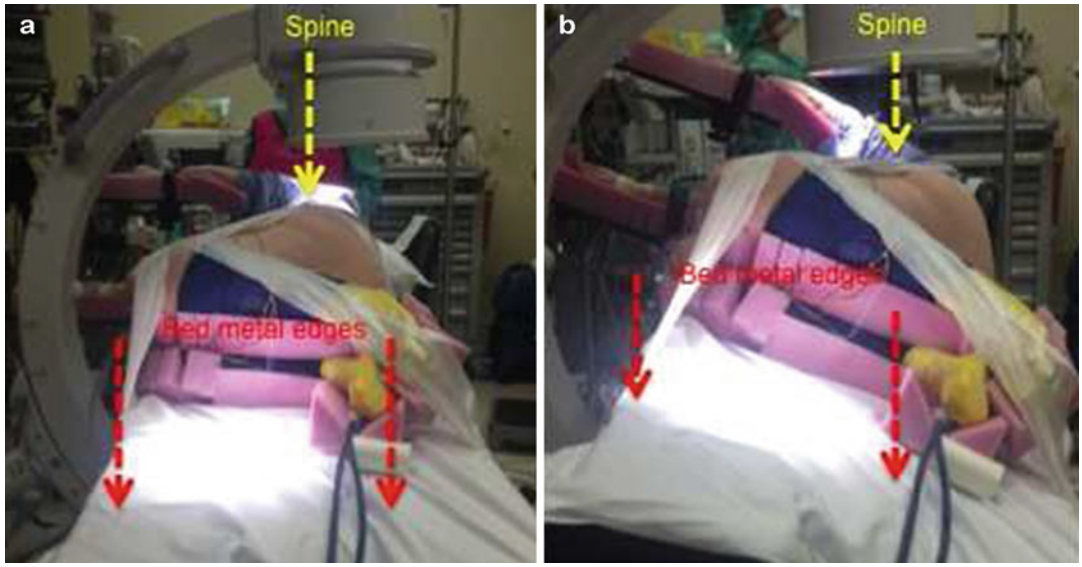


Fig. 20.10 (**a**) The OR bed is level and the metal bars on the side of the bed are not in the x-ray visual field. (**b**) Obtaining a true lateral of the planned operative level in a scoliotic spine often requires rotation of bed, which can bring the metal bars located on the side of the OR table under the spine interfering with x-ray visualization, (*yellow dashed lines*) identify location of the spine. (*Red dashed lines*) identify location of the metal bars located at the edges of the operating room bed.

O'Brien and colleagues demonstrated in a cadaveric model that table flexion results in preloading the femoral nerve when approaching L4–L5 [46]. With 40° of table flexion at the pelvis, there was anterior displacement of the nerve by approximately 1.5 mm resulting in the highest nerve strain (average, 6–7 %) compared with 0°. Strain in the femoral nerve decreased with increasing hip flexion for both table flexion angles (40 and 0°). Flexing the hips and knees relaxes the psoas muscle and nerves minimizing the effects of breaking the table when required. Additionally, flexing the hips and knees may permit increased mobilization of the psoas and lumbar plexus allowing more displacement when the retractor is placed and opened, decreasing stretch and possibly neurological injury.

An axillary roll should be placed to prevent brachial plexus injury. Padding should be placed between the OR table and down leg to protect the peroneal nerve and the skin from breakdown over the bony prominences. A pillow should be placed between the patient's legs. Additionally, an arm board should be placed to support the patient's down arm. An arm holder or a pillow can be placed to support the patient's up arm. Once the patient is provisionally positioned, tape should be applied across the patient's upper chest and lower hips to secure them to the OR table outside of the planned operative field. This prevents the patient from shifting or rotating intraoperatively. Tape should also be applied to the patient's thighs and legs to secure them in flexion (Fig. 20.9). Tape can be applied multiple times, even circumferentially around the patient and bed to prevent patient migration during the procedure.

Once the patient is secured to the OR table, the table can be flexed at the iliac crest for optimal visualization of L4–L5. The bed should be extended at the patient's feet to prevent the hips and knees from extending. The bed can be placed in reverse Trendelenburg to compensate for the breaking in the table to level the patient's torso.

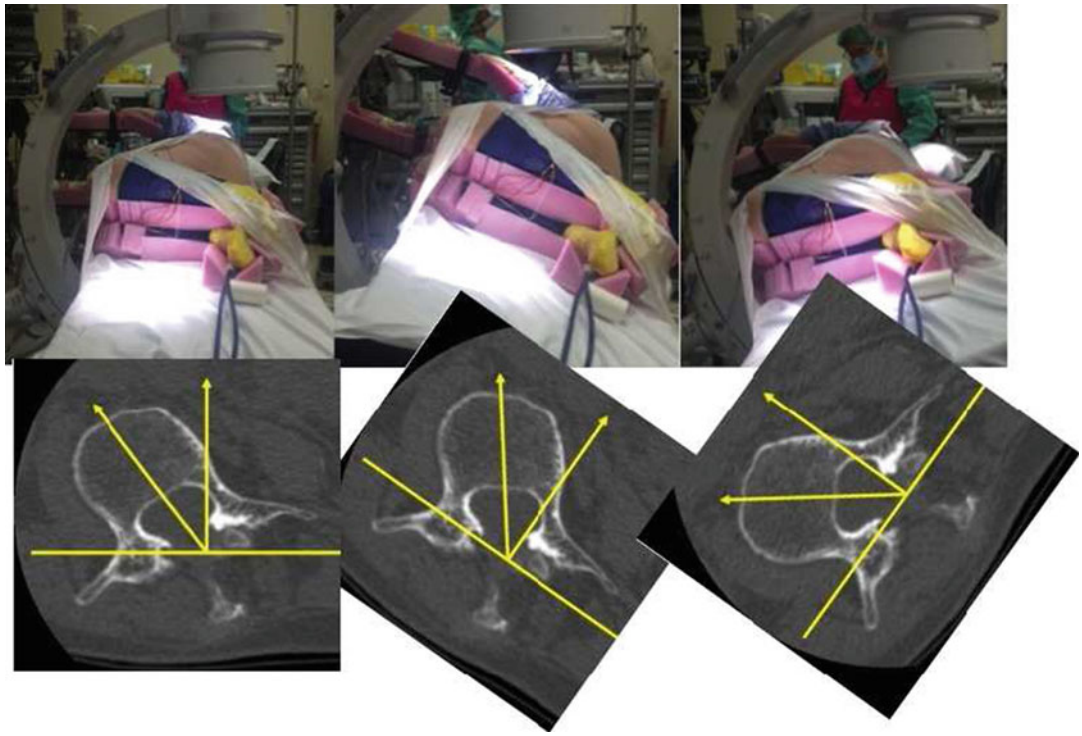


Fig. 20.11 The scoliotic spine often has rotational deformity. With the bed level, there is significant rotational deformity. Rotating the patient posteriorly results in an AP view of the spine with the C-arm in the lateral position at 90°. Rotating the patient anteriorly, keeping the C-arm at 90°, results in a true lateral view of the spine

20.3.2 Fluoroscopic Imaging

Given the segmental deformities often seen in scoliosis, the OR table and fluoroscopy often need to be adjusted at each level to ensure optimal radiographic imaging (Fig. 20.11). It is the authors' recommendation that the bed, not the C-arm, should be adjusted to obtain true AP and lateral x-rays of each individual operative level. With the C-arm locked at 0°, the bed can be rotated until a true AP image is obtained, and the spinous process of each level is in perfect midline position between the two pedicles and the endplates are parallel (Fig. 20.12). With the C-arm locked at 90°, the bed can be inclined or declined (Trendelenburg vs. reverse Trendelenburg) until a true lateral image is obtained with parallel endplates and overlapping pedicles and facet joints (Fig. 20.13). Moving the table and not the C-arm allows the surgeon an easier reference point of a true AP (surgeon's hand perfectly horizontal and parallel to the floor) and lateral (surgeon's hand perfectly vertical and perpendicular to the floor). True lateral x-rays can help prevent endplate violation during disk prep and implant placement, which can eliminate the advantage of deformity correction and indirect decompression of the LLIF technique. More worrisome, without true AP x-rays, vertebral rotation can lead to implant encroachment posteriorly in the neuroforamen and nerve injury, or anteriorly resulting in catastrophic vascular injury.

After draping the operative field with 10×10 drapes, the skin can be prepped with alcohol. Prior to the incision, each planned LLIF surgical level should be visualized with a true AP and lateral x-ray to ensure all planned operative levels can be visualized and accessed. The bony ribs can be palpated and marked on the skin. A flexible radiopaque guide wire can be used to identify the disks of each planned operative level, along with outlining the iliac crest on the skin to identify any bony restrictions, particularly the iliac crest restricting access to L4–L5 (Fig. 20.14).

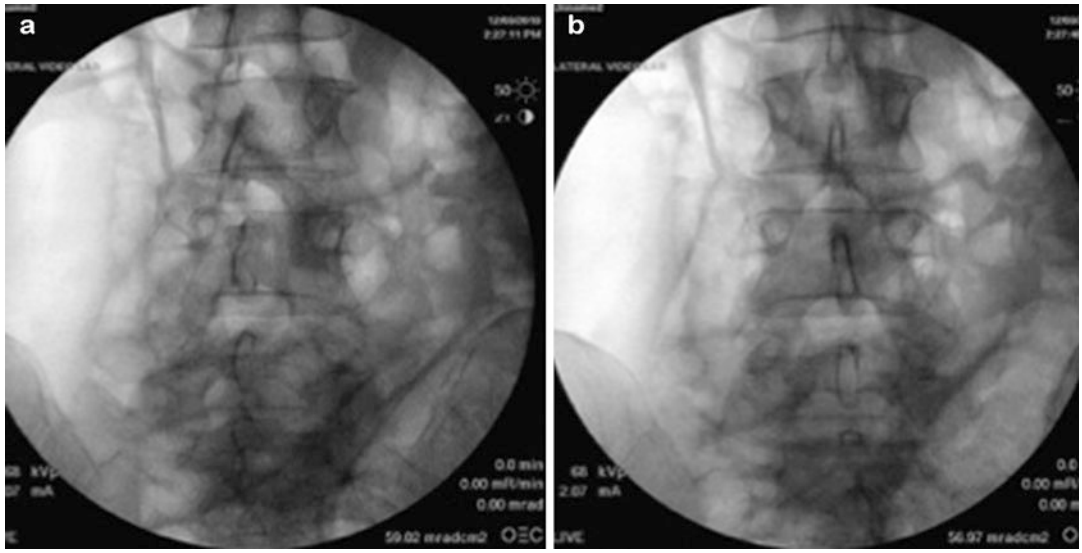


Fig. 20.12 (**a**) Rotation of the spine. (**b**) True AP x-ray with the spinous process of L4 equally bisecting the pedicles with parallel endplates

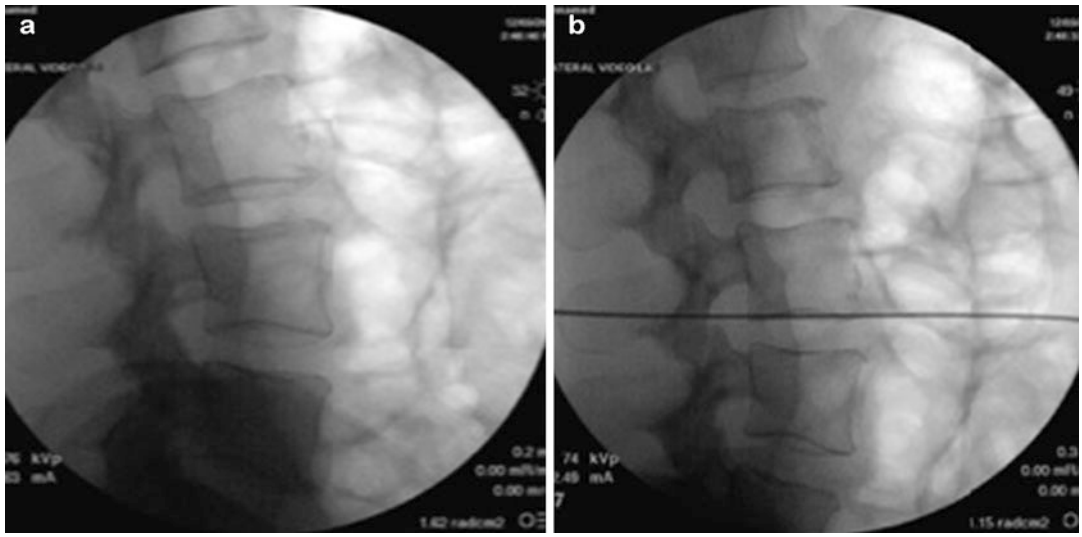


Fig. 20.13 (**a**) Parallax resulting in endplate double densities. (**b**) True lateral x-ray with parallel and overlapping endplates, pedicles, and facet joints

Tape can be used to mark the floor relative to the position of the C-arm, which allows the C-arm machine to be moved in and out of the operative field with precision (Fig. 20.15). Additionally, the position of the C-arm gantry identifying true AP and lateral x-rays for each planned operative level can be marked with tape and the levels labeled (Fig. 20.16). This preoperative marking of the skin can minimize the skin incision, and labeling the floor and C-arm gantry with tape can expedite the intraoperative localization process of each planned surgical level and provide a reproducible guide for other radiology technologists who may not have been present at the beginning of the case.



Fig. 20.14 Skin markings identifying operative levels and possible limitations to access. Using fluoroscopic C-arm, four operative levels, the ribs and iliac crest are marked on the skin. A flexible guide wire is placed along the iliac crest, and fluoroscopy is used to identify access of L4–L5

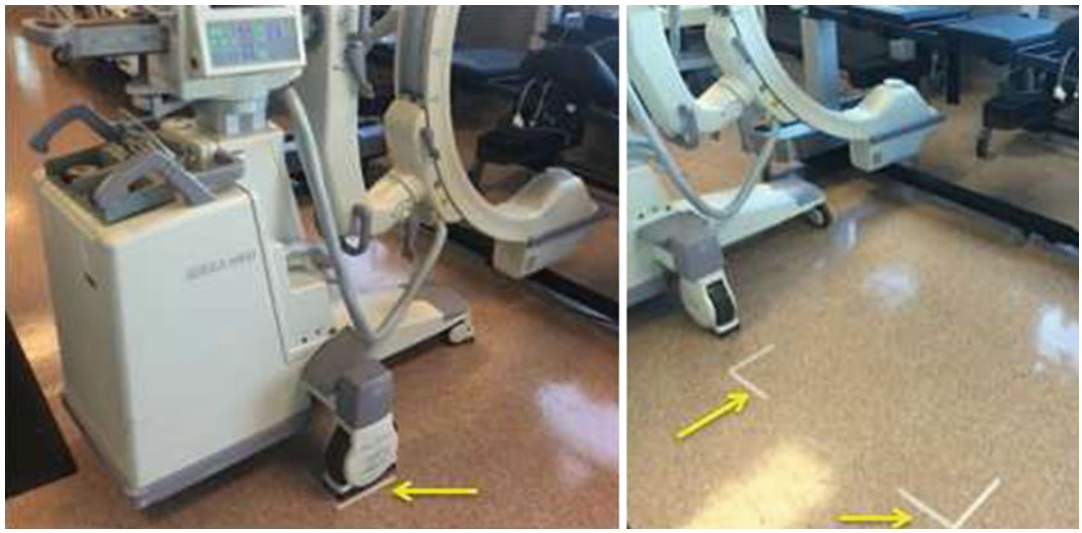


Fig. 20.15 Tape (*yellow arrows*) marking the OR floor where true AP and lateral x-rays are obtained to allow efficient and reproducible access into and out of the operative field

20.3.3 Access to the Psoas

Access to the lateral lumbar spine can be performed using a one- or two-incision technique. Regardless of the technique, the skin incision over the planned operative level is made first, exposing the subcutaneous fat, which is dissected and retracted out of the operative field. The external oblique (EO) muscle is the first muscle encountered, and its muscle fibers run obliquely toward



Fig. 20.16 Tape marking the C-arm gantry with each planned operative lumbar level labeled. This provides reproducible guide for visualization of each planned surgical level throughout the operation, even with different radiology technologists

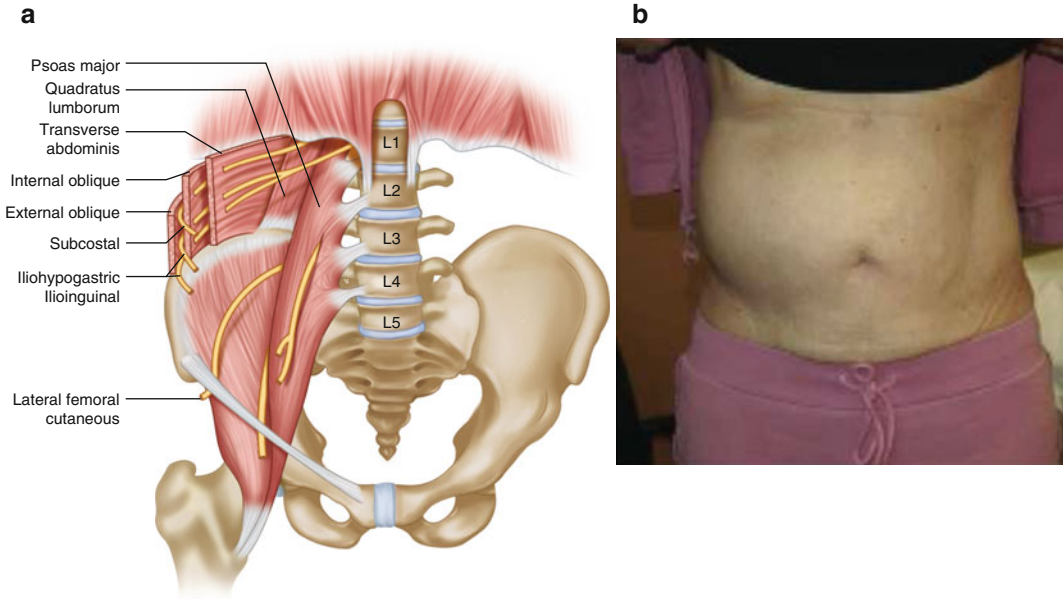


Fig. 20.17 (**a**) The abdominal wall and its innervation. The subcostal, iliohypogastric, and ilioinguinal nerves are labeled. (**b**) Patient with right abdominal paresis after a right-sided LLIF approach that resolved a 6-month post-op

the umbilicus. This muscle layer can be bluntly dissected to expose the internal oblique (IO) muscle, whose muscle fibers run perpendicular to the EO muscle. The IO can be bluntly dissected over each individual lumbar disk level to reveal the transverse abdominal muscle or it can be cut. Care must be taken to bluntly dissect the IO muscle first to avoid injuring the subcostal, iliohypogastric, and ilioinguinal nerves, which originate from the T12 and L1 nerve roots and course anteriorly and inferiorly and pierce and innervate the abdominal wall musculature. Injury to any of these nerves can result in abdominal wall paresis causing an abdominal bulge or droop, which can be permanent or temporary depending on the degree of nerve injury (Fig. 20.17). Cahill and

colleagues reported a 4.2 % incidence of postoperative abdominal wall bulge, which they related to permanent injury to the motor nervous supply to the lateral abdominal wall [47]. Once the IO muscle is dissected, the transverse abdominal (TA) muscle is visualized and dissected. As its name contends, the TA fibers run transversely or horizontally. Immediately deep to the TA muscle is the transversalis fascia. This aponeurotic membrane can be distinct and lies between the inner surface of the TA muscle and the parietal peritoneum. Once this is dissected, the retroperitoneal fat can be visualized.

Access can also be obtained through a two-incision technique. After the first incision located directly over the planned surgical disk space is performed, dissection is carried to the transversalis fascia as described above. A second small incision can then be placed a finger-length posterior to the first incision and can be used as a direct access point to the retroperitoneal space. Once the second incision is made, blunt muscle dissection is performed to the transversalis fascia posteriorly, which can be penetrated with a pointed clamp into the retroperitoneal space (Fig. 20.18). Through the second more posterior incision, blunt finger dissection can sweep the peritoneum, fat, and any adhesions off the transversalis fascia and psoas muscle. The transverse process is a bony landmark that can be palpable for localization confirming the position in the retroperitoneal space. Once blunt dissection is performed, the same finger can be directed to the first incision and used as a visual marker for dissection of the transversalis fascia ensuring entry into the retroperitoneal space. The initial dilator can then be placed through the first incision using the finger in the second incision to guide the dilator to the retroperitoneal space and psoas muscle.

The retroperitoneal fat can be swept anteriorly to visualize the fascia enveloping the psoas muscle. The genitofemoral (GF) nerve lies directly on top of the psoas fascia. The GF nerve originates from the upper L1 to L2 segments of the lumbar plexus and passes caudally and emerges from the anterior surface of the psoas muscle. It can be encountered in the center on the LLIF operative field commonly at L3–L4. The nerve continues downward and divides into two branches, the genital branch and the femoral branch. The genital branch passes through the deep inguinal ring and enters the inguinal canal. The genital branch con-

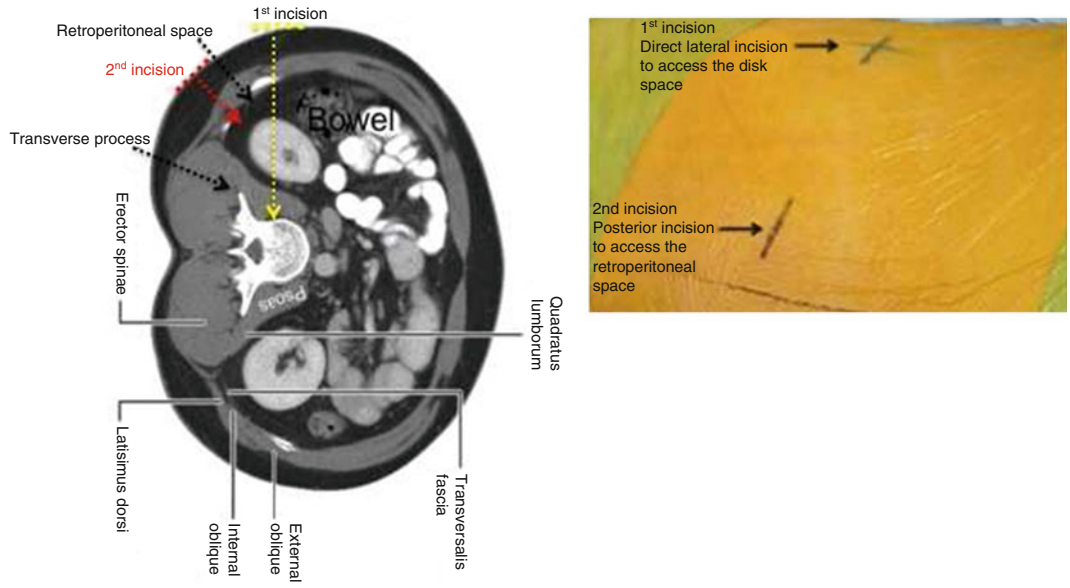


Fig. 20.18 Two-incision technique. The first incision allows access to the LLIF level. The second incision allows access to the retroperitoneal space and guidance from the first incision to the psoas muscle

tinues down and supplies the scrotal skin in men and accompanies the round ligament of the uterus terminating in the skin of the mons pubis and labia majora in women. The femoral branch passes underneath the inguinal ligament, traveling adjacent to the external iliac artery, supplying the skin of the upper anterior thigh and groin. Whether each operative level is approached with individual small dissections through the muscle layers and fascia or a mini-open incision is performed for better visualization, the psoas fascia should be released to expose the muscle fibers beneath it. Using a "no-look" approach, moving the initial dilator 2–3 mm cranially and caudally, in-line with the muscle fibers, can release the fascia as the dilator is advanced into the psoas muscle and docked (Fig. 20.19). This can decrease the risk of dragging the fascia and GF nerve into the psoas causing stretch with dilator advancement or compression with retractor opening, both of which can cause injury and anterior thigh symptoms. Wanding the initial dilator more than 2–3 mm cranially and caudally could result in nerve injury.

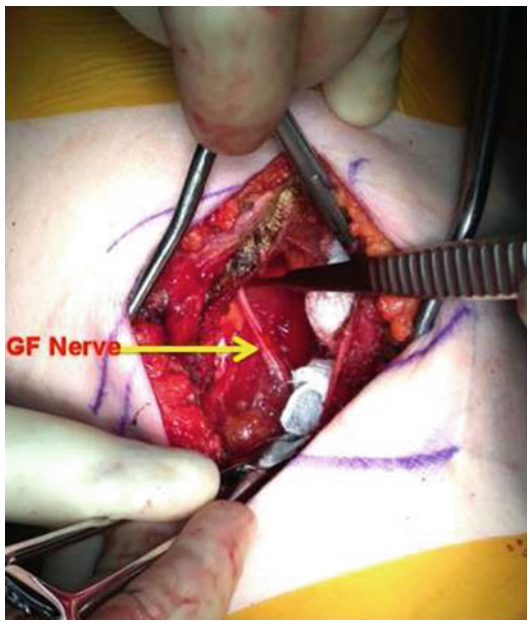


Fig. 20.19 The genitofemoral (GF) nerve crossing the psoas muscle at L34. The psoas fascia has been released, exposing the psoas muscle fibers and freeing the GF nerve prior to dilator insertion

20.3.4 Transpsoas Approach and Retractor Docking

Sequential dilation of the psoas muscle can then be performed for each planned operative level using biplanar fluoroscopy and directional electromyography (EMG) or mechanomyography (MMG) neuromonitoring. The initial dilator is placed through the psoas and docked at the anterior 1/3 of the disk space where it is secured with a guide wire and confirmed with lateral x-ray. Sequential dilation of the psoas muscle is performed followed by placement of the retractor, which is fixed to the operating table. Each dilator should be monitored with directional EMG or MMG. Neuromonitoring alerts using triggered EMG or MMG can allow repositioning of the dilators and retractor to avoid nerve injury. Most nerve injuries are associated with instrumentation at the L4–L5 level [48–52].

Surgeons can start at increasing thresholds of 15–20 milliamps (mA), which may provide a safer transpsoas working corridor. If a response is obtained, the mA can be lowered until a response is not elicited. Feedback can be provided visually from the patient with muscle jerk of the extremity and from the neuromonitoring technologist, with thresholds below 5 mA usually indicating direct nerve contact [53]. Threshold responses between 5 and 10 mA indicate close proximity, and responses greater than 10 mA usually are indicative of a safe working distance away from the motor nerves [54, 55].

Prior to placing the retractor, the finger of a sterile latex glove can be cut off and placed over the retractor, which can allow retractor opening while preventing retroperitoneal fat and psoas muscle from entering the operative field. Additionally, angling the retractor fixation arm vertically, instead of horizontally, can apply additional downward pressure and stability and may eliminate the need for a bone fixation pin or shim in the disk (Fig. 20.20). This can prevent retractor migration and creep of the psoas muscle under the retractor blades. Vertebral body blade fixation pins can result in unrecognized bony bleeding or segmental artery injury, and disk shims fix the posterior retractor blade, which is in close proximity

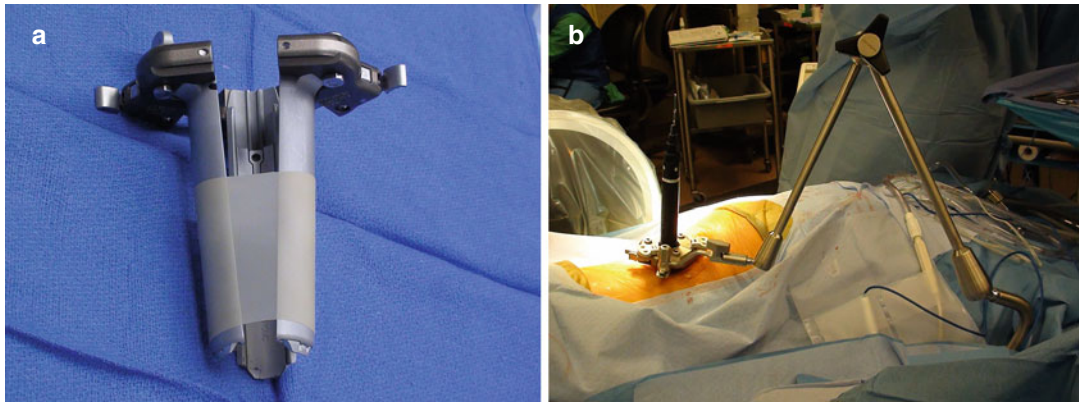


Fig. 20.20 (**a**) A finger can be cut off of a sterile latex glove and placed over the retractor blades. This can prevent retroperitoneal fat and muscle from entering the operative field while still allowing the retractor to open. (**b**) Angling the retractor fixation arm vertically can apply additional downward pressure preventing retractor migration and may eliminate the need for bone fixation pins or disk shims



Fig. 20.21 Excessive retractor opening can result in stretch and compression of the lumbar plexus and/or injury to the segmental vessels

to the lumbar plexus risking injury. AP and lateral images are then used to confirm position of the working corridor.

Once the retractor is placed and a safe working corridor is established and confirmed with x-ray, the discectomy can be performed. Minimize retractor opening to prevent stretch of the lumbar plexus or injury to the vertebral segmental vessels located at the midportion of the vertebral body (Fig. 20.21).

The retractor is opened just enough for adequate visualization and cage placement, the limits of which are usually just cranial and caudal to the endplates. Additionally, be conscious that excessive posterior blade retraction can compress the nerve between the retractor blade and the transverse process. Work quickly to decrease the risk of compressive or ischemic injury to the nerve due to prolonged psoas retraction. In a prospective multicenter trial, Uribe and colleagues evaluated whether triggered EMG monitoring could predict postoperative symptomatic neuropraxia (SN) throughout the retraction process during LLIF procedures. Postoperatively, 13 of 323 (4.03 %) patients had a new motor weakness that was consistent with SN of the lumbar plexus on the approach side. Retraction time was significantly longer in those patients with SN versus those without (32.3 vs. 22.6 min, $p = 0.031$) [56]. Chaudhary et al. observed diminished motor evoked potentials (MEPs), not at the time of initial retractor placement, but after prolonged retractor opening in patients with postoperative motor nerve injuries. Prolonged mechanical

compression and stretch were felt to be the mechanisms of injury [57]. This proposition is supported by studies that have reported a higher likelihood of nerve injury with increasing surgical times [31].

Even with meticulous conscientious dilator and retractor placement in relation to the lumbar plexus, nerve and psoas muscle irritation is a potential side effect even in single-level LLIF procedures. Suggestions to reduce the risk of nerve injury include preoperative administration of gabapentin or Lyrica, along with 10 mg IV dexamethasone may prophylactically combat the inflammatory cascade in nervous and muscular tissue limiting the extent of injury [58, 59]. In cases where extended psoas retraction is required, such as in multilevel deformity cases, releasing the retractor and allowing for the muscle and soft tissue to relax may decrease the likelihood of such injury. Lastly, shallow docking above the psoas muscle allows dissection of the psoas with a Penfield dissector allowing direct visualization of lumbar plexus prior to dilator placement [60].

As with most minimally invasive techniques, there is a learning curve to overcome. We have found, as have others, that the risk of nerve injury declines steadily with greater experience [61]. Le et al. reported a significant reduction in the incidence of postoperative numbness of nearly 60 % (26.1–10.7 %), with their refined technique over a 3-year period [62]. Experience and evolution of a surgeon's technique can minimize the risk of iatrogenic nerve injury resulting in dramatic changes in patient outcome.

20.3.5 Preparing the Disk Space

With the retractor in place and opened, the dilators are removed leaving the guide wire in place. The guide wire can provide a reference point for the annulotomy. Using an EMG or MMG probe, the annulus and remaining strands of psoas muscle around the guide wire and edges of the retractor blades are stimulated to ensure there are no nerves crossing the operative field. A bipolar cautery and Penfiled dissector can be used to facilitate removing the remaining strands of muscle providing clear identification of the annulus. The annulus can then be incised vertically with a scalpel both dorsal and ventral to the guide wire delineating the AP working space for cage insertion (Fig. 20.22).

Annulotomy size is based on the selection of the width of the LLIF cage. Cage widths range from 18 to 27 mm, but more common widths include 18, 21, and 22 mm. Marchi et al. reviewed the incidence and effect of subsidence in patients with stand-alone short-segment 1- or 2-level lateral lumbar interbody fusions with two different width cages, 22 and 18 mm [63]. Patients who had wider 22 mm cages had greater lordosis correction, along with lower rates and grades of subsidence. At 12 months, 70 % in the standard group (18 mm) and 89 % in the wide group (22 mm) had Grade 0 or I subsidence, and 30 % in the standard group and 11 % in wide group had Grade II or III subsidence (Fig. 20.23). Subsidence was detected early at 6 weeks postoperatively and correlated with transient clinical worsening in VAS scores. Progression of subsidence was not observed after the 6-week time point. Additionally, subsidence occurred predominantly (68 %) at the inferior endplate. Although fusion rate was not affected by cage dimension ($p > 0.999$) or by the incidence of subsidence ($p = 0.383$), most patients requiring secondary revision spinal procedures experienced Grade II and III subsidence (six of ten patients).

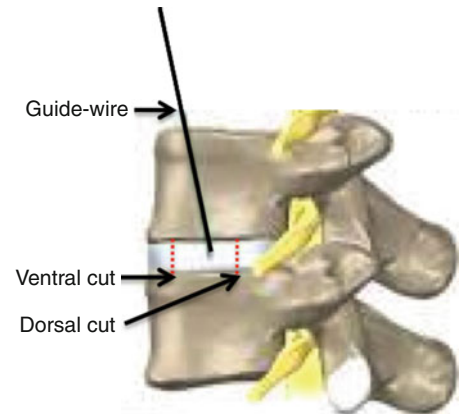


Fig. 20.22 Leaving the guide wire in place until the ventral and dorsal annulotomies are performed provides a constant reference point for localization

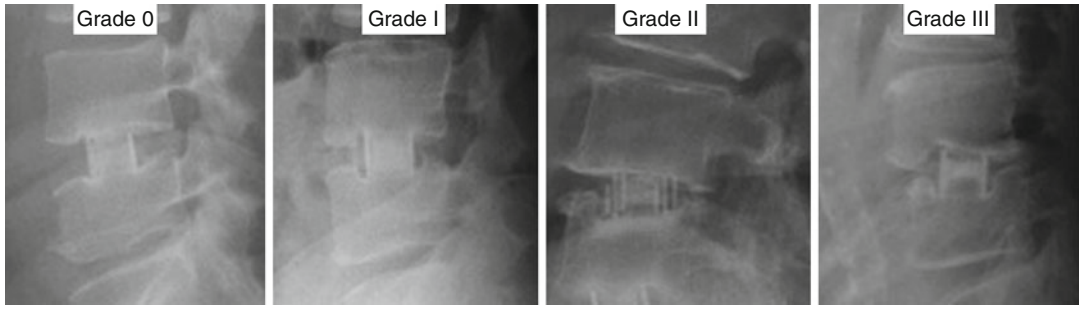


Fig. 20.23 Subsidence is classified based on the percent loss of postoperative disc height. Grade 0, 0–24 % loss of postoperative disk height; Grade I, 25–49 %; Grade II, 50–74 %; and Grade III, 75–100 %



Fig. 20.24 A blunt intradiscal spreader (8 mm shown) can facilitate the discectomy without the risk of endplate violation seen with shavers (12 mm shown)

This illustrates the importance of not violating the endplates and limiting subsidence.

After the annulotomies, the guide wire can be removed, and pituitary rongeurs are used to remove the annulus and perform the discectomy. A Cobb elevator or disk shavers can be used to dissect the cartilage of the endplates and assist in the discectomy, but there is an increased risk of violating the endplates particularly in patients with poor bone quality. Alternatively, sequential blunt intradiscal spreaders (6, 8, 10, 12, and 14 mm high) can be used to free up the disk material until there is resistance against the endplates (Fig. 20.24).

This technique can be very effective at freeing up the disk material without the risk of endplate violation seen with sharp-edged instruments such as the Cobb or shavers. The disk material can be removed with pituitary rongeurs, and the cartilage can be removed with up-going, down-going, and stirrup curettes. To ensure good bleeding, endplates preparation can be completed with a rasp. Once the endplates are prepared, the contralateral annulus should be released. The contralateral annulus should not be released until the diskectomy is fully completed. This can decrease the risk of expelling disk material, which can compress the contralateral nerve resulting in radiculopathy. A Cobb elevator is used to release the contralateral annulus both at the superior and inferior margins of the endplates. After the Cobb pierces the annulus, rotate the Cobb approximately 30°, ensuring complete release cranially and caudally to maximize release and deformity correction (Fig. 20.25). This is a critical step in the disk preparation process as it can maximize mobility at each disk level allowing for maximal correction of disk height, lordosis, rotation, and coronal deformity.

With the disk completely prepared and released, the intradiscal spreaders can again be utilized to size the height and length of the cage for each level (Fig. 20.26). Spanning the LLIF cage over the strongest portion of the endplate, the ring apophysis, can maximize deformity correction and disk height restoration, decrease subsidence, and improve stability and fusion rates [44, 64]. Oversizing the length of the cage 10 mm longer than the radiographic width of pedicles ensures that the cage spans the entire ring apophysis to facilitate maximum contact with the

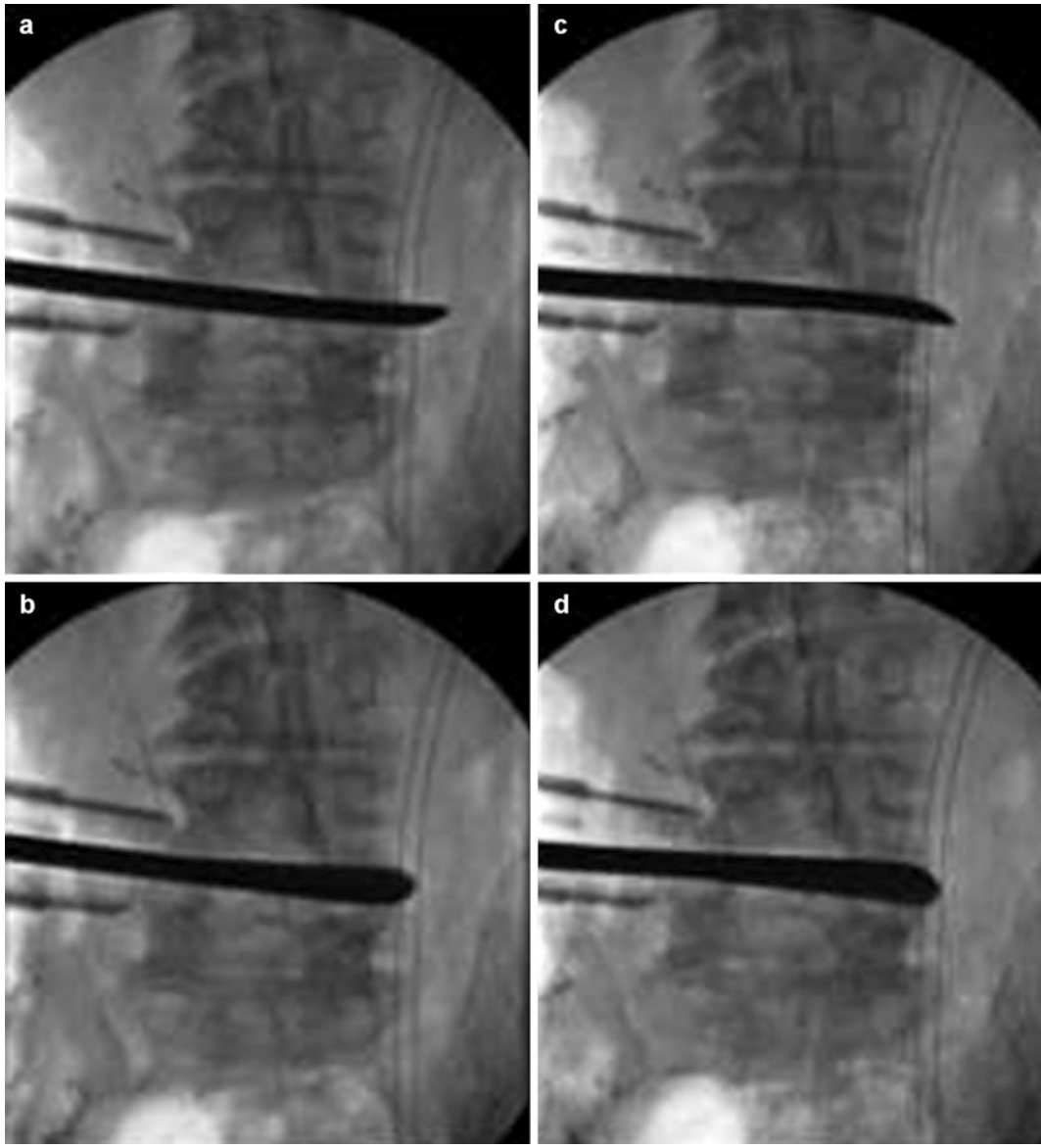


Fig. 20.25 (**a**) Cobb elevator releasing the cranial annulus. (**b**) Cobb rotation 30° to maximize release. (**c**) Cobb elevator releasing the caudal annulus. (**d**) Cobb rotation 30° to maximize release

periphery of the endplate. Using the pedicles is a more reproducible radiographic reference point due to osteophytes seen in most scoliotic spines making the true end of the vertebral bodies difficult to identify (Fig. 20.26).

Cage height should be determined based on the amount of resistance with rotation of the intradiscal spreader and the endplates. There should be a snug fit between the intradiscal spreader and the ring apophysis and confirmed with fluoroscopic guidance. Forced rotation of the intradiscal spreader could result in endplate violation. Additionally, placing a cage that is sized too aggressively in height can result in adjacent vertebral body fractures [65–67] (Fig. 20.27).

A trial can be placed to ensure proper sizing of the cage, but runs the risk of endplate violation.

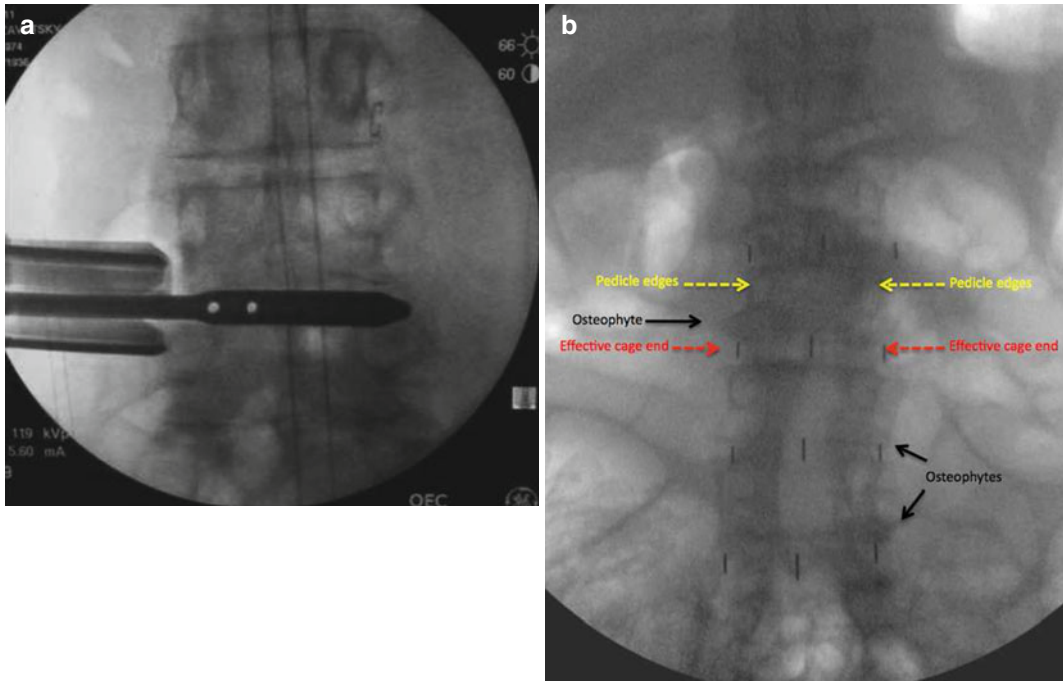


Fig. 20.26 (**a**) A blunt intradiscal spreader being utilized to facilitate the discectomy and sizing of the LLIF cage. (**b**) The lateral border of the pedicles (*yellow arrows*) are a more reproducible radiographic marker for cage sizing due to the presence of osteophytes (*black arrows*), which can distort the normal anatomy. Sizing the LLIF cage 10 mm longer than the width of the lateral border of the pedicles can ensure spanning the ring apophysis

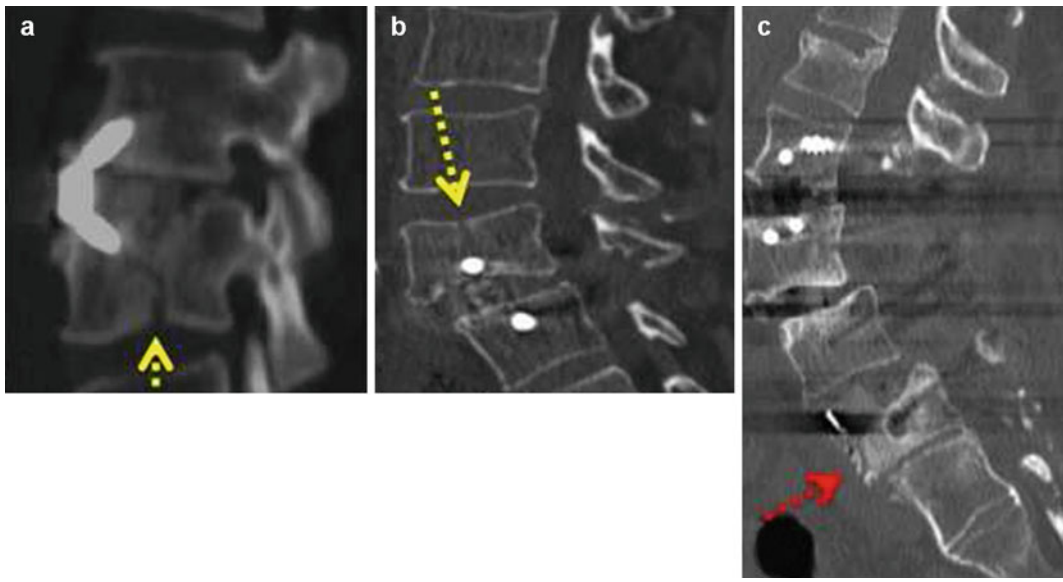


Fig. 20.27 (**a**, **b**) Vertebral coronal split fractures after LLIF instrumentation. (**c**) Significant compression fracture of the inferior endplate below the LLIF instrumentation, (*yellow dashed lines*) identify the coronal split fractures. (*Red dashed lines*) line identifies a compression fracture below the LLIF cage.

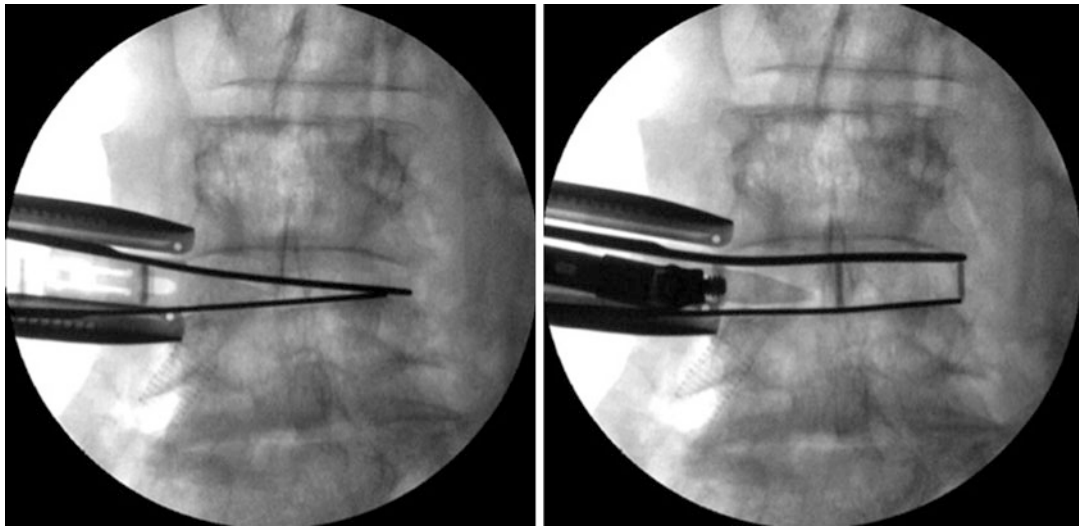


Fig. 20.28 Skids can be utilized to assist cage insertion in tight disk spaces decreasing the risk of endplate violation

The final cage can be placed immediately after sizing with the intradiscal spreader without trial placement, reducing the risk of endplate or ring apophysis damage. Once the optimal final cage size has been determined, it can be prepared on the back table with the surgeon's preference of graft material. The disk space should be thoroughly irrigated and suctioned to remove any debris. The implant is then placed into the disk space under direct fluoroscopic guidance in the AP view to ensure the cage does not violate the endplates. The surgeon's hand and the cage insertion handle should be straight up in the air, perpendicular to the floor, to ensure the cage is not directed posterior into the neuroforamen or anterior out the front of the vertebral body. Skids can be utilized to assist cage insertion in very collapsed disc spaces, and they can also prevent graft dislodgement from the cage when malleting the cage into the disk space (Fig. 20.28). Once the cage is in place, fluoroscopic AP and lateral images are obtained prior to removing the retractor in the event adjustments have to be made.

20.3.6 Maximizing Correction

Maximizing deformity correction is one of the main goals of scoliosis surgery. Nevertheless, exactly how to maximize the correction of the lumbar rotation, coronal deformity, lordosis, and sagittal vertical angle (SVA) utilizing the lateral approach is a topic of debate. Variability in radiological outcomes may result from the lack of a standardized technique for discectomy and annular release as discussed previously. Additionally, optimal cage sizing and placement can affect the amount of correction achieved. Lastly, there is a lack of data analyzing the risks and benefits of approaching the lumbar curve through its concavity vs. convexity.

The LLIF technique is very powerful at correcting the coronal deformity, but has reported limitations in global sagittal realignment, lordosis correction, and derotation [38]. To maximize lordosis, coronal correction, and derotation, the surgeon must perform an aggressive discectomy, not violate the endplates, completely release the contralateral annulus both cranially and caudally, and properly size and place the cage (Fig. 20.29) Segmental lordosis correction using the LLIF technique has been reported to range from 2 to 5° [35, 68]. Placing a lordotic LLIF cage in the anterior 1/3 of the disk space can maximize segmental lordosis correction. Kepler and colleagues reported that the mean lordosis increased 3.7° at instrumented segments, increasing from 4.1° preoperatively to 7.8° postoperatively. Anterior cage placement resulted in the largest lordosis gain (+7.4°/level), while

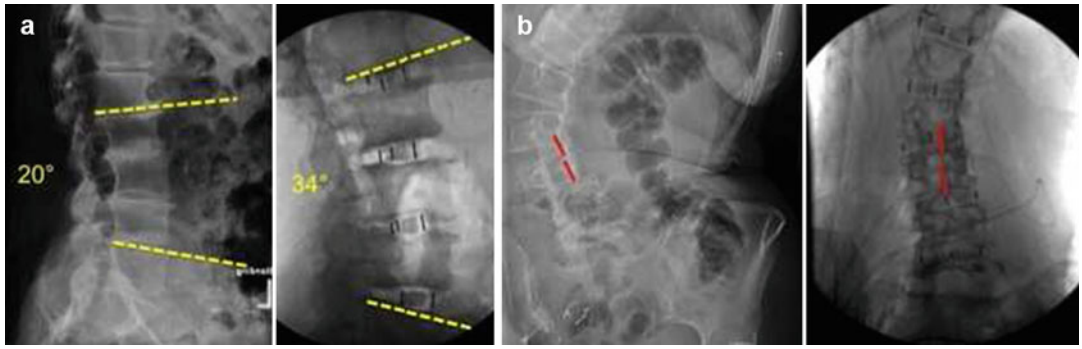


Fig. 20.29 (**a**) Preoperative lordosis of 20° vs. 34° of intraoperative lordosis after four-level LLIF procedure, prior to posterior instrumentation. (**b**) Preoperative coronal Cobb of 75° vs. 40° intraoperatively and significant derotation after a five-level LLIF procedure, prior to posterior instrumentation

posterior placement was pro-kyphotic (−1.2°/level). The authors concluded that anterior cage placement results in greater lordosis, while middle or posterior placement has minimal effect on sagittal alignment.

20.3.7 Approach Through the Concavity vs. Convexity

In adult patients with degenerative thoracolumbar scoliosis, the decision to approach the curve apex from either the concave or convex side is a topic of debate. There are numerous studies demonstrating the considerable benefits of the LLIF technique, resulting in significant radiographic correction and improved clinical outcomes, with a minimal complication profile [29, 69–72]. However, these studies either did not report or varied the side of approach with respect to the curve apex, so data is lacking.

Sheer et al. performed a retrospective review comparing approach-related (convex vs. concave) neurological complications and magnitude of correction in patients undergoing LLIF, prior to any other supplemental procedures, in the treatment of adult scoliosis [73]. Patients were grouped based on the approach through the curve apex concavity (CAVE) or the convexity (VEX). There were 32 patients reviewed (CAVE, 17; VEX, 15) with a mean age of 65.5 years and follow-up of 17.0 months. There were eight postoperative neurological complications in eight patients (25.0 %) and seven reoperations for six patients (18.8 %; CAVE, 4/17 [23.5 %]; VEX, 2/15 [13.3 %]). The CAVE group had 6 of 17 neurological complications (35.3 %; four ipsilateral and two contralateral to approach side) and VEX had 2 of 15 (13.3 %; one ipsilateral and one bilateral to approach side; $p > 0.05$). All patients significantly improved in the mean regional and segmental Cobb angles ($p < 0.05$), except for T11–T12 ($p > 0.05$). There were no significant differences between the groups for any of the radiographic parameters measured ($p > 0.05$). The authors concluded that approaching the curve apex from either the concave or convex side resulted in significant improvements in correction, which were similar in magnitude. Although not statistically significant, the CAVE patient group had more postoperative neurological complications, and they suggested that surgeons should exhibit additional caution when approaching from the concave side. Due to spinal rotation, the psoas muscle and lumbar plexus can translate anteriorly in the concavity of the lumbar curve placing them in a more direct path with the normal docking site for the retractor, theoretically placing them at higher risk. Unfortunately, there were limitations of the study, including the number of patients analyzed. Additionally, the CAVE group had a larger number of patients who had the L4–L5 level instrumented utilizing the LLIF technique and underwent posterior osteotomies when compared to the VEX group. Both of these factors can increase the risk of nerve injury, which can skew the results.

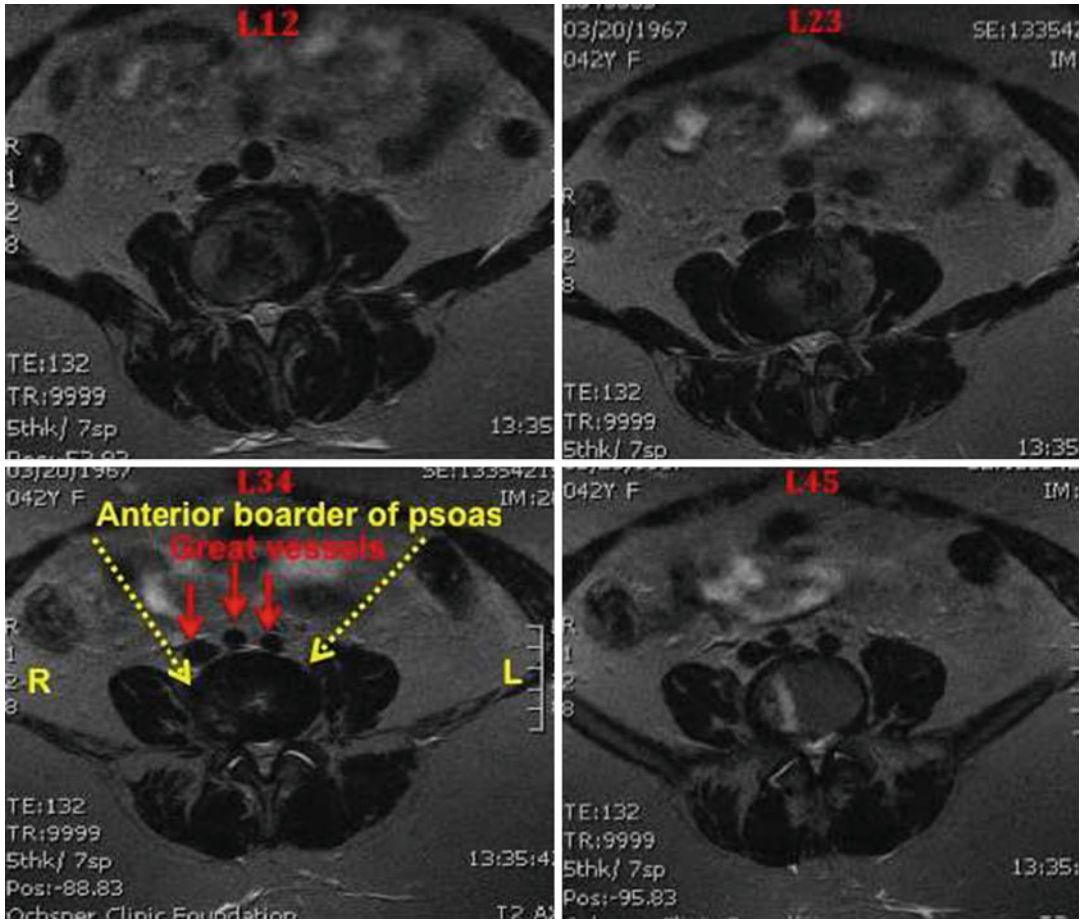


Fig. 20.30 Axial MRI of a non-scoliotic lumbar spine revealing the proximity of the great vessels relative to the anterior border of the psoas

Several other factors should be considered when determining whether to approach the deformity through the concavity or convexity. In the anatomically straight spine, the great vessels are usually located more ventral on the left, away from the operative field, providing a larger surgical corridor for retractor placement between the lumbar plexus posteriorly and the vessels anteriorly (Fig. 20.30). Although the left hemidiaphragm normally sits approximately 2 cm lower than on the right, the liver may push the right hemidiaphragm into the operative field if approaching through the concavity of a lumbar levoscoliosis.

The rotational component of the deformity may also alter the normal anatomy, placing nerves, visceral organs, and vascular structures in direct line with the surgical approach to the spine and at greater risk for injury. The vascular structures of importance include the abdominal aorta, the iliac arteries and veins, and the vena cava. Regev et al. outlined the changes that can be expected with regard to the neurovascular anatomy in patients with adult deformity [74]. As the vertebral body rotates toward the convexity, the vessels (aorta, iliac vein and arteries, and vena cava) rotate toward the concavity. The psoas similarly covers less of the vertebral body and lies more posterior on the concavity. The superficial sensory nerves including the genitofemoral and lateral femoral cutaneous nerves take the same course, making them more prone to injury (Fig. 20.31).

The more the spine is rotated, the more important it is to pay attention to the preoperative imaging

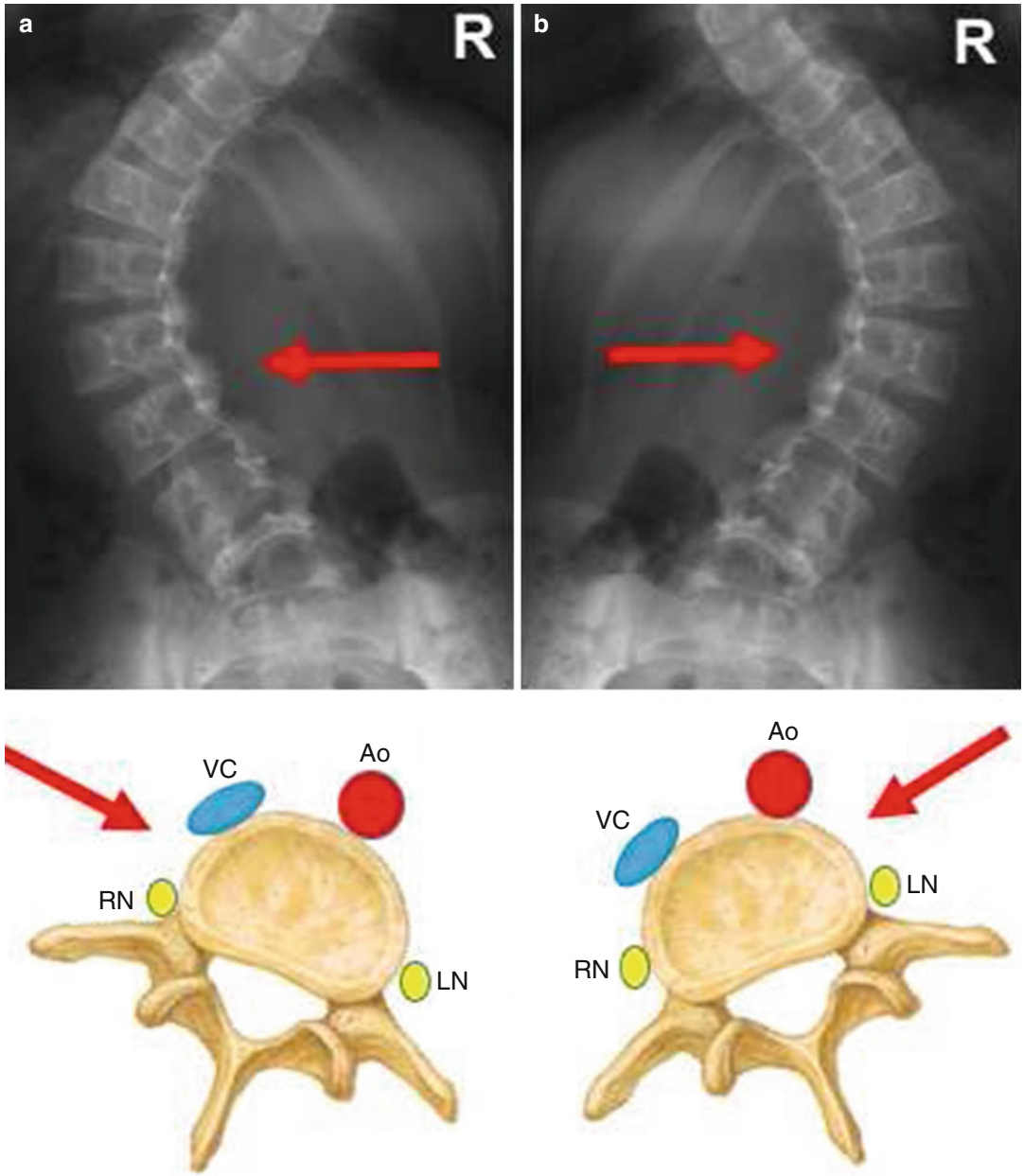


Fig. 20.31 (**a**) Apex-left with clockwise (*left*) rotation of the vertebra results in a relative anterior position of the left nerve (LN) root and a relative posterior position of the right vessel and nerve root (*red arrows* pointing at the concave side of the deformity). (**b**) Apex-right scoliosis with counterclockwise (*right*) rotation of the vertebra results in a relative anterior position of the right nerve (RN) root and posterior position of the left vessel and nerve root. *LN* left nerve root, *RN* right nerve root, *VC* vena cava, *Ao* aorta, (*solid red lines*) in the x-rays identify the approach through the concavity of the lumbar curve, which correlate with the red lines in the illustrations below and the associated structures at risk.

and intraoperative fluoroscopic x-rays to make appropriate clinical adjustments perioperatively to avoid injury to these vital structures. A careful review of the preoperative axial MRI and CT is essential in understanding the location of the neurovascular structures during the lateral approach that could prevent safe access to all the planned operative levels (Figs. 20.3 and 20.32).

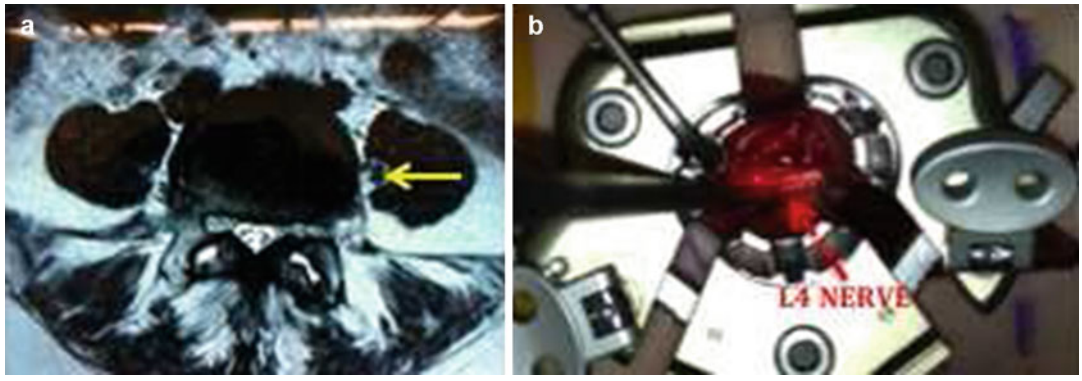


Fig. 20.32 (**a**) MRI of the lumbar spine demonstrating the left L4 nerve (*yellow arrow*) in the middle of the disk space blocking safe access to L4–L5. (**b**) Looking down through the lateral retractor visualizing the L4 nerve seen on the MRI in (**a**) Safe MMG thresholds could not be obtained and the LLIF procedure had to be aborted, and an MIS TLIF was performed

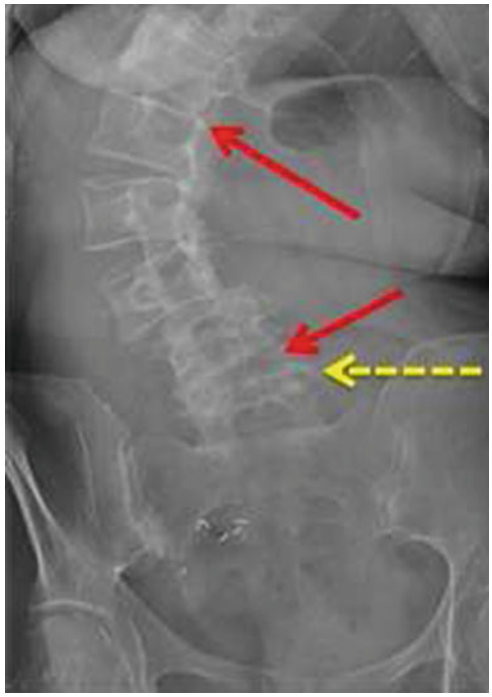


Fig. 20.33 When approaching through the concavity, the most caudal (usually L4–L5) and cranial (T12–L1 or L1–L2) levels may be uncovered from the iliac crest and ribs, respectively, allowing surgical access. In the convexity, the pelvis blocks access to L4–L5, and the T12–L1 disk would have to be accessed through the chest and diaphragm, The scoliotic curve "presents" the cranial- and caudal-most LLIF levels identified by the solid (*red lines*). The (*yellow dashed line*) identifies how the iliac crest could block access to the L4-L5 level.

Whether through the concavity or convexity, the approach that provides access to the greatest number of levels will allow the ability for maximal deformity correction. With the lumbar plexus being most at risk at L4–L5, the approach that provides safe access to this level should be considered. Additionally, approaching from the concavity allows access to the upper lumbar levels (T12-L1 and L12) with less likelihood of entering the chest (Fig. 20.33). Lastly, breaking the OR table with the concavity up can also facilitate intraoperative correction of the scoliosis.

We recommend approaching the spine from the concavity for several reasons. The deformity often presents each disk to a more concentric area on the skin allowing the surgeon access to multiple levels from one well-placed incision (Fig. 20.34). The iliac crest can prevent access to L4–L5. The L4–L5 level can be uncovered in the concavity allowing for an easier approach, where the iliac crest typically obstructs access from the convexity (Fig. 20.33). Additionally, the concavity is the site of foraminal narrowing, bony compression, and soft-tissue contracture. A more comprehensive soft tissue and bridging osteophyte release can be performed on the side of the spine that is contracted. Releasing the deformity from the concavity may allow for deformity correction, restoration of foraminal height, and indirect neural decompression without violating

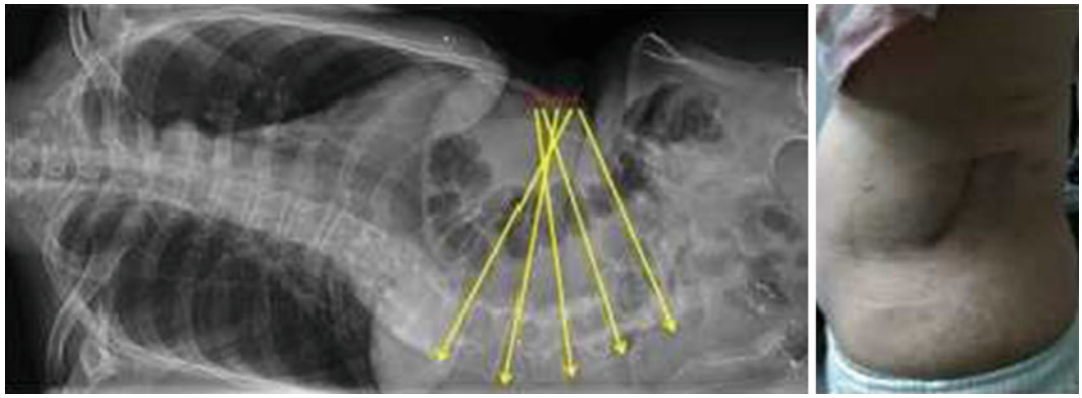


Fig. 20.34 (**a**) Approaching the deformity through the concavity of the curve often presents multiple levels to a more concentric area allowing a smaller skin incision. This patient had five levels (T12–L1, L1–L2, L2–L3, L3–L4, L4–L5) surgically corrected through the concavity of the curve with a 3″ skin incision

the endplates, particularly in patients with poor bone quality. Care must be taken when releasing the bridging osteophytes to avoid damage to the ring apophysis and endplates. Using fluoroscopic guidance in the AP view can minimize bony injury when an osteotome is used to release the osteophytes.

20.3.8 Sequence of LLIF Instrumentation

Once the decision to approach from the concavity has been made, the surgeon should consider addressing the most caudal and cephalad levels first, rather than correcting the apical levels. Before any coronal deformity correction, the most caudal and cranial levels are oblique and uncovered from the iliac crest and ribs, respectively. If the central apical levels are performed first, coronal deformity correction may displace the most caudal level into the pelvis and cranial level under the ribs blocking access (Fig. 20.35). Angled instrumentation can also be utilized to access and prepare oblique disk spaces. Once the most caudal and cranial levels are instrumented, the apical levels can then be addressed.

After each of the planned surgical levels is instrumented, the operative site should be thoroughly irrigated prior to retractor removal to remove the debris that could irritate the nerves and to evaluate for any copious venous or arterial bleeding. Lykissas and colleagues performed a retrospective outcome analysis in patients undergoing the LLIF approach with and without the use of recombinant human bone morphogenetic protein-2 (rhBMP-2) over a 6-year period [75]. Patients with previous lumbar spine surgery or follow-up of less than 6 months were excluded. Patients were divided into two groups, Group 1 (rhBMP-2 use; $n=72$) and Group 2 (autograft/allograft use; $n=72$), and were matched according to the age at the time of surgery, gender, weight, body mass index, side of approach, total number of treated spinal segments, use of supplemental posterior fusion, and length of follow-up. A sensory deficit was recorded in 33 patients in Group 1 and 35 patients in Group 2 (odds ratio [OR] 0.895; 90% confidence interval [CI] 0.516–1.550; $p=0.739$). At the last follow-up, a persistent sensory deficit was identified in 29 patients whose LLIF procedure was supplemented by rhBMP-2 and 20 patients in whom autograft/allograft was used (OR 1.754; 90% CI 0.976–3.151; $p=0.115$). A motor deficit was recorded in 37 patients immediately after the rhBMP-2 procedure and 28 patients treated with autograft/allograft (OR 1.661; 90% CI 0.953–2.895; $p=0.133$). However, a persistent motor deficit was recorded in 35 and 17 patients in Groups 1 and 2, respectively, at the last follow-up (OR 3.060; 90% CI 1.681–5.571; $p=0.002$). During the first postoperative office examination, 37 patients in Group 1 and 25 patients in Group

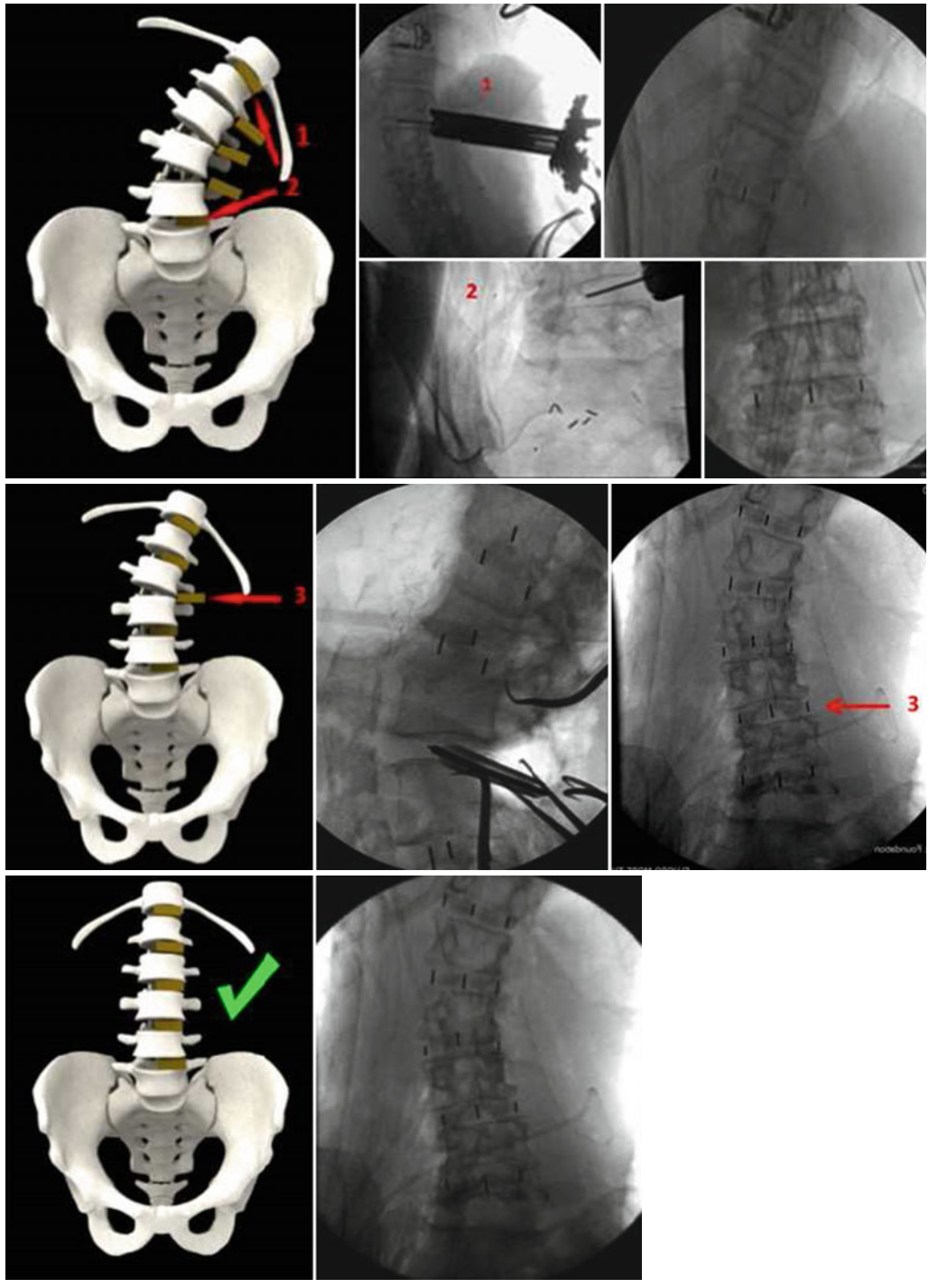


Fig. 20.35 Images illustrating the suggested sequence of LLIF instrumentation through the concavity. Begin with instrumentation at the most cranial (*1*) or caudal (*2*) levels as the deformity is uncovering them from the ribs and iliac crest, respectively. After the cranial and caudal levels are completed, then instrument the levels at the apex of the deformity (*3*). Utilizing this technique can maximize the amount of levels that are accessed and the amount of coronal deformity correction. Instrumenting the levels at the apex of the deformity could straighten the spine making the most cranial and caudal levels inaccessible

2 complained of anterior thigh or groin pain (OR 1.987; 90% CI 1.133–3.488; $p=0.045$). At the last follow-up, there were a significantly higher number of patients in Group 1 who complained of persistent anterior thigh or groin pain than Group 2 (8 vs. 0 patients) (OR 16.470; 90% CI 1.477–183.700; $p=0.006$). The authors concluded that there was an increased rate of postoperative neurological deficit and anterior thigh/groin pain with the utilization of rhBMP-2 in LLIF procedures, when compared with matched controls without rhBMP-2 exposure. This supports other studies demonstrating the deleterious inflammatory effects of rhBMP-2 around the nerves and validates the need for thorough irrigation of the operative site to remove any excess rhMBP-2 that could increase neurological complication rates.

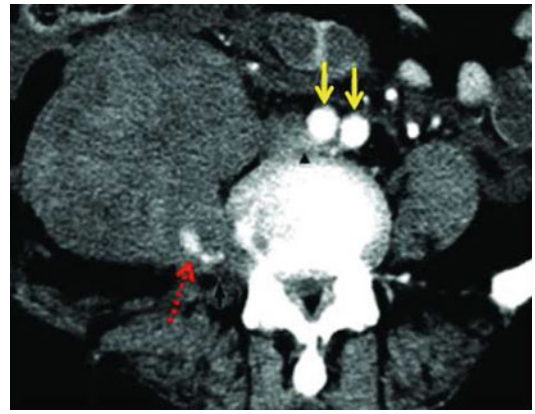


Fig. 20.36 Axial CT image after IV injection. The (*yellow solid arrows*) identify normal contrast in the great vessels anterior to the lumbar spine. The (*red dashed line*) identifies leakage or extravasation of contrast into the right psoas muscle resulting in hematoma

20.3.9 Wound Closure

Irrigation of the operative site will also allow careful evaluation of the operative site for any venous or arterial bleeding. After the cage is inserted and the operative bed is irrigated, the retractor can be closed slightly to release any tamponade effect the retractor blades may have on the psoas muscle. The initial hemostasis can be obtained with the bipolar cautery and augmented with a hemostatic agent like FloSeal or SurgiFlo. After the bipolar cautery is utilized to eliminate any brisk bleeding, there tends to be a small amount of general ooze from the disk space due to endplate bleeding and the psoas muscle. Hemostatic agent placement on the annuli and exposed cage can significantly slow down this ooze to prevent psoas hematoma formation. The hemostatic agent can also be placed moderately as the retractor is being removed, which can create a tamponade effect in the psoas muscle. If the psoas hematoma is large, it can result in ipsilateral radiculopathy due to compression or irritation of the lumbar plexus. Additionally, bleeding from a segmental artery injury can cause significant morbidity if unrecognized (Fig. 20.36).

Once each operative level is irrigated and hemostasis is obtained, attention should be directed toward wound closure. When closing the lateral incision, an attempt to close each individual layer, particularly the transversalis fascia, should be attempted to prevent a true abdominal hernia. If small incisions are made for each surgical level, transversalis fascia closure may be all that is required. Care should be taken not to entrap the subcostal, ilioinguinal, or iliohypogastric nerves at any level of the closure to prevent neuralgia or abdominal paresis.

20.4 Outcomes

Multiple studies have evaluated the utility of the LLIF technique in the treatment of adult spinal deformity. The overall radiographic and clinical outcome data are very promising with a lower complication profile when compared to traditional open approaches.

Tormenti and colleagues reported their retrospective review of eight cases performed with LLIF combined with open posterior fixation and compared this cohort with four cases who underwent posterior-only open surgery. The mean preoperative and postoperative coronal Cobb angles were 39° and 13°, respectively, in the LLIF group and 19° and 11°, respectively, in the posterior-only group. One case of cecal perforation was reported during the LLIF approach in this series. The investigators also reported six cases of lower

extremity sensory dysesthesias as well as two cases of lower extremity motor dysfunction postoperatively after the lateral approach. In most cases, these neurological issues resolved over several months. The investigators also reported one case of infection and meningitis, one case of ileus, one case of pleural effusion, and one patient who had a post-op pulmonary embolus (PE) [30].

Anand and colleagues reported on 28 patients treated with three or more levels of minimally invasive lateral transpsoas interbody fusion (LIF) and percutaneous pedicle screw (PPS) fixation, with a mean age of 67.7 years and mean follow-up time of 22 months. The mean intraoperative blood loss was of 500 mL for both stages, and operative times were 500 min. One-year visual analogue scale (VAS), treatment intensity scale, Short-Form 36 Health Survey, and ODI scores were statistically better preoperative values. The mean coronal Cobb angles were 22° preoperatively and 7.5° postoperatively, but sagittal balance correction was not reported. All patients had a solid fusion assessed by plain radiographs at 1 year. Complications were noted in 23 patients, the most of which was transient thigh dysesthesia (17/23) attributed to the LIF approach. Additionally, there were two transient quadriceps palsies, one retrocapsular renal hematoma, and one cerebellar hemorrhage in this cohort [28].

Dakwar and colleagues retrospectively reviewed 25 adult patients with degenerative scoliosis who underwent anterior reconstruction with LLIF at three or more levels with a mean follow-up of 11 months. The mean intraoperative blood loss was 53 mL per level, with a mean length of stay of 6.2 days. There was a significant improvement in radiographic (thoracolumbar coronal Cobb angle) and clinical (VAS and ODI) outcomes. Reported perioperative complications included one patient with rhabdomyolysis requiring temporary hemodialysis, one with implant subsidence, and one with hardware failure. Additionally, three patients (12%) experienced transient postoperative anterior thigh numbness in the distribution of the anterior femoral cutaneous nerve after the LIF procedure [29].

Wang and Mummaneni retrospectively reviewed 23 patients with thoracolumbar deformity treated with minimally invasive techniques. The patient mean age was 64.4 years, with a mean follow-up of 13.4 months. The mean blood loss was 477 mL. Coronal Cobb angles improved from 31.4° preoperatively to 11.5° postoperatively. Lumbar lordosis improved from 37.4° preoperatively to 47.5° postoperatively. Solid fusion was reported at every interbody level in 16 patients. Of the seven cases that did not utilize interbody fusion at every level, two patients developed pseudarthrosis. Thigh numbness, pain, weakness, and dysesthesias, all lateralized on the side of the anterolateral approach, were seen in seven patients (30.4%). In all but one case, these symptoms resolved in the postoperative period. Other complications included one patient with postoperative atrial fibrillation, one case of pneumothorax requiring a chest tube, one with cerebrospinal fluid (CSF) leak, and one patient who needed reoperation for S1 screw pullout [31].

Isaacs and colleagues performed a prospective nonrandomized multicenter evaluation on 107 adult patients with deformity with a mean age of 68.4 years who were treated with stand-alone LLIF (24.3%) or LLIF with either open (hybrid) or percutaneous posterior pedicle screws (cMIS) (75.7%). The mean operative time was 177.9 min. A total of 62.5% of patients had less than 100 ml EBL and only 8.4% had greater than 300 ml EBL. The overall complication rate was 24.3%. Patients undergoing stand-alone or cMIS LLIF procedures had significantly lower complications (9% had one or more major complications) than those undergoing hybrid approaches (20.7% had one or more major complications). The most common major surgical complication was postoperative neurological deficits (persistent thigh dysesthesias, numbness, weakness, and pain, all lateralized to the LLIF side of the approach, were seen in seven patients). The authors did not report radiographic parameters, other than the average preoperative coronal Cobb angle which was 24.3° [70].

In 2010, Mundis and colleagues performed a literature review on minimally invasive lateral approaches for interbody fusion to treat degenerative spinal deformity. Both patient-centered outcomes and objective radiographic parameters showed significant improvement in most studies. Complications rates varied between studies, but major complications were low. Thigh dysesthesia

was the most commonly reported complication associated with LLIF, but in most cases, symptoms were transient. The investigators concluded that the minimally invasive lateral approach was a safe and effective surgical strategy for treating adult spinal deformity [76].

Acosta et al. retrospectively evaluated the changes in the coronal and sagittal plane utilizing the LLIF technique in the treatment of degenerative lumbar disease in 36 patients. Eight patients had degenerative scoliosis whose mean regional lumbar coronal Cobb angles improved significantly from 21.4° preoperatively to 9.7° postoperatively. The mean global coronal alignment was 19.1 mm preoperatively and 12.5 mm postoperatively ($p<0.05$). In the sagittal plane, the mean segmental Cobb angle measured −5.3° preoperatively and −8.2° postoperatively ($P<0.0001$). The mean preoperative and postoperative regional lumbar lordosis was 42.1° and 46.2°, respectively, ($p>0.05$). The mean global sagittal alignment was 41.5 mm preoperatively and 42.4 mm postoperatively ($p=0.7$). The postoperative ODI and VAS scores improved significantly. However, fusion status was not reported. This study demonstrates the limitations the LLIF technique has regarding global sagittal correction [38].

In another study, Anand et al. reviewed 71 patients who underwent MIS correction of two or more levels for spinal deformity. There were 54 patients treated for degenerative scoliosis, 11 for idiopathic scoliosis, and 6 for iatrogenic scoliosis. All patients underwent a combination of three MIS techniques: direct lateral interbody fusion (66 patients), axial lumbar interbody fusion [34], and posterior instrumentation [67]. Thirty-six patients were staged with direct lateral interbody fusion done first followed by the posterior instrumentation and fusion including axial lumbar interbody fusion done 3 days later. Mean age was 64 years (20–84 years). Mean follow-up was 39 months (24–60 month). Patients who had a one-stage same-day surgery had a mean blood loss of 412 mL and a mean OR time of 291 min. Patients with two-stage surgery had a mean blood loss of 314 mL and OR time of 183 min for the direct lateral interbody fusion and 357 mL and 243 min for the posterior instrumentation and axial lumbar interbody fusion. Mean hospital stay was 7.6 days (2–26 days). The mean preoperative Cobb angle was 24.7°(8.3–65°), which corrected to 9.5°(0.6–28.8°). Mean preoperative coronal balance was 25.5 mm, which corrected to 11 mm postoperatively. Mean preoperative sagittal balance was + 31.7 mm and corrected to + 10.7 mm. The mean preoperative lumbar apical vertebral translation was 24 mm and corrected to 12 mm. Fourteen patients had adverse events requiring intervention: four pseudarthrosis, four persistent stenosis, two wound dehiscence, one late wound infection, one osteomyelitis, one adjacent segment discitis, one proximal junctional kyphosis (PJK), one screw prominence, and one idiopathic cerebellar hemorrhage. The authors concluded that the combination of these three novel MIS techniques allowed comparable correction of adult spinal deformity, with low pseudarthrosis rates, with significant improvements in radiographic and functional outcomes, and with considerably lower morbidity and complication rates at early and long-term follow-up [77].

Caputo and colleagues evaluated radiographic parameters and complications with the use of the LLIF technique in the treatment of adult spinal deformity. Thirty consecutive patients were followed for an average of 14.3 months. Lateral interbody fusion was supplemented with posterior instrumentation. Plain radiographs were obtained on all patients preoperatively, postoperatively, and at the most recent follow-up, and measurements of coronal Cobb angle, apical vertebral translation, segmental lordosis, global lordosis, disc height, neuroforaminal height, and neuroforaminal width were made at each time point. CT scans were obtained for all patients 1 year after surgery to evaluate for fusion. There was significant improvement in multiple radiographic parameters from preoperative to postoperative. There was improvement in coronal Cobb angle (72.3%), apical vertebral translation (59.7%), neuroforaminal height (80.3%), neuroforaminal width (7.4%), and disc height (116.7%). Segmental lordosis at L4–L5 increased 14.1% and global lordosis increased 11.5%.

There was no significant loss of correction from postoperative to the most recent follow-up. There was an 11.8% pseudoarthrosis rate at levels treated with LLIF. Complications included lateral incisional hernia ($n=1$), rupture of anterior longitudinal ligament (2), wound breakdown (2), cardiac instability (1), pedicle fracture (1), and nonunion requiring revision (1). The authors concluded that LLIF significantly improves coronal plane deformity in patients with adult degenerative scoliosis. In their patient population, they found that LLIF had the ability to correct sagittal plane deformity, although it was most effective at lower lumbar levels [69].

More recently, Uribe in collaboration with the ISSG analyze matched patient cohorts in an attempt to isolate the impact of approach (cMIS, HYB, and Open) on adverse events. Patients were queried from two multicenter databases for those with ASD treated via surgery and at least 1 year of follow-up. There were 280 patients who had undergone circumferential minimally invasive surgery or a hybrid procedure (cMIS and HYB; $n=85$) or open surgery (OPEN; $n=195$). Patients were divided into three separate groups based on the approach performed and were propensity matched for age, preoperative sagittal vertebral axis (SVA), number of levels fused posteriorly, and lumbar coronal Cobb angle (CCA) in an attempt to neutralize these patient variables and to make conclusions based on the approach alone. Inclusion criteria for both databases were similar, and inclusion criteria for this study consisted of an age >45 years, CCA >20, three or more levels of fusion, and minimum of 1 year of follow-up. Patients in the OPEN group with a thoracic CCA >75° were excluded to better match the patient populations. Sixty matched patients were available for analysis (cMIS = 20, HYB = 20, OPEN = 20). Blood loss was less in the MIS group when compared to the HYB and OPEN groups, but a significant difference was only found between the MIS and OPEN groups (669 vs 2322 ml, $p=0.001$). The MIS and HYB groups had more fused interbody levels than the OPEN group (4.5 and 4.1 vs. 1.6, respectively; $p<0.001$). The OPEN group had less operative time than either the MIS or HYB group, but it was only statistically different from the HYB group (367 vs 665 min, $p<0.001$). There was no significant difference in the duration of hospital stay among the groups. In patients with complete data, the overall complication rate was 45.5% (25/55). There was no significant difference in total complication rate among the cMIS, HYB, and OPEN (30%, 47%, and 63%, respectively; $p=0.147$). No intraoperative complications were reported for the MIS group, 5.3% for the HYB group, and 25% for the OPEN group ($p<0.03$). At least one postoperative complication occurred in 30%, 47%, and 50% of the MIS, HYB, and OPEN groups, respectively, ($p=0.40$). One major complication occurred in 30%, 47%, and 63% ($p=0.147$) of the MIS, HYB, and OPEN groups, respectively. All patient had significant improvement in both the Oswestry Disability Index (ODI) and Visual Analog Scale (VAS) scores after surgery ($p<0.001$), although the cMIS group did not have significant improvement in leg pain. Complications had no impact on ODI scores. As the invasiveness of the approach decreased, so did the intraoperative complication rate. The authors concluded that their data suggests that the surgical approach may impact complications, and if the goals of ASD surgery can be achieved, consideration should be given to less invasive techniques [78].

Park in collaboration with the International Spine Study Group (ISSG) most recently reported on the comparison of the hybrid (HYB) surgical approach, involving minimally invasive lateral interbody fusion with open posterior pedicle screws, to the circumferential MIS (cMIS) approach to treat ASD. In a retrospective, multicenter study, 105 patients with ASD who were treated with MIS techniques were analyzed. Inclusion criteria were age >45 years and coronal Cobb angle >20°, with a minimum of a 1-year follow-up. Patients were stratified into two groups: HYB ($n=62$) and cMIS ($n=43$). There was no difference in mean age (60.7 vs. 61.0 years, $p=0.910$) and number of interbody fusions (3.6 vs. 4.0 levels, $p=0.086$) in the HYB vs. cMIS groups, respectively. Posterior fusion involved a mean of 6.9 levels in the HYB group and a mean of 5.1 levels in the cMIS group

($p = 0.003$). The mean follow-up was 31.3 months for the HYB group and 38.3 months for the cMIS group. There was no significant difference between groups with regard to ODI or VAS scores. For the HYB group, the lumbar coronal Cobb angle decreased by 13.5°, lumbar lordosis (LL) increased by 8.2°, sagittal vertical axis (SVA) decreased by 2.2 mm, and LL–pelvic incidence (LL-PI) mismatch decreased by 8.6°. For the cMIS group, the lumbar coronal Cobb angle decreased by 10.3°, LL improved by 3.0°, SVA increased by 2.1 mm, and LL-PI decreased by 2.2°. There were no significant differences in these radiographic parameters between the two groups. However, the complication rate was higher in the HYB vs. cMIS group (55 % vs. 33 %, respectively; $p = 0.024$). The authors highlighted that while there was no significant difference in the degree of radiographic correction between the groups, the HYB group had greater absolute improvement in the degree of lumbar coronal Cobb angle correction, increased LL, decreased SVA, and decreased LL-PI. Although the complication rate was higher with the HYB approach, both approaches resulted in significant clinical improvement, as evidenced by decreased ODI and VAS pain scores [79].

The overall outcomes data are very promising with the LLIF technique in the treatment of adult spinal deformity. Radiographic parameters have been shown to significantly improve, but more importantly the clinical outcomes data demonstrate significant improvements with a lower complication profile compared to traditional open approaches.

Conclusion

Although multiple studies have demonstrated significant improvements in both radiographic and clinical outcomes when utilizing the lumbar lateral interbody fusion (LLIF) technique in the treatment of adult spinal deformity (ASD), not all patients with spinal deformity can be managed with this or other MIS techniques. The LLIF technique does have limitations, particularly global sagittal correction, and appropriate patient selection for the utilization of this approach is critical to optimize successful patient outcomes in the treatment of adult deformity. The minimally invasive spinal deformity surgery (MISDEF) algorithm can be utilized to assist surgeons in selecting the appropriate surgical approach for spinal deformity, which can often be complex. A thorough history, physical exam, and evaluation of the preoperative imaging are imperative to ensure there are no contraindications to performing the LLIF approach and the patient's radiographic measurements align with the MISDEF Class I and II parameters.

The transpsoas lateral lumbar interbody fusion (LLIF) surgical approach can be more complicated when utilized for deformity correction in the scoliotic spine due to the associated coronal and rotational deformities. Standardizing the technique from patient positioning to closing the wound can optimize radiographic and clinical outcomes. Proper patient positioning and intraoperative fluoroscopic x-rays are critical for a successful outcome. Approaching the deformity from the concavity can facilitate access to multiple surgical levels through a smaller skin incision, while allowing for a more comprehensive neuroforaminal decompression and soft-tissue and bridging osteophyte release. The most caudal and cranial lumbar levels are uncovered in the concavity of the curve and the most accessible prior to any deformity correction. Instrument these levels first prior to the apical levels of the curve. Utilizing a standardized technique for disk preparation and contralateral annular release can maximize coronal and rotational deformity correction. Placing a wide lordotic cage in the anterior 1/3 of the disk space that spans the ring apophysis can facilitate maximal lordosis correction and prevent subsidence. With repetition and experience, the surgeon's technique can be refined and evolved, improving radiographic and clinical outcomes while decreasing rates of complications.

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Neoplasia

21

Hsuan-Kan Chang and Jau-Ching Wu

21.1 Introduction

Spinal tumors basically can be categorized according to their primary or metastatic origins. Furthermore, these neoplasms also can be classified according to their anatomical locations, such as extradural, intradural-extramedullary, and intramedullary.

Primary tumors of the vertebral column are relatively rare. The overall prevalence in the United States was estimated at 2.5–8.5 per 100,000 persons per year [7]. Overall, primary tumors of the vertebral column only account for less than 10 % of all spinal tumors, much less than metastatic tumors [66]. The total new cases of primary spinal tumors are estimated to be 7,500 patients per year in the United States.

There are both benign and malignant primary spinal tumors based on histology features. Primary benign tumors of the spine commonly include aneurysmal bone cyst (ABC), hemangioma, osteoid osteoma, osteoblastoma, osteochondroma, chondroblastoma, and giant cell tumors. The most common primary benign tumor of the spine in adults is hemangioma, which has accounted for more than 10 % in autopsy studies [3, 21, 39]. On the other hand, the differential diagnosis of primary malignant spinal tumors includes chondrosarcoma, osteosarcoma, Ewing's sarcoma, and plasmacytoma (i.e., multiple myeloma). Among them, the most common primary malignancy of the spine is multiple myeloma and together with its soft-tissue form, plasmacytoma, accounted for up to 26 % of primary malignant spinal tumors in a long-term epidemiologic survey [33].

Spine vertebra accounts for the most common osseous site of metastasis from malignancy. Up to 90,000 new cases of spinal metastases occur in the United States annually [7], much more common than primary vertebral neoplasms. Furthermore, over 70 % of cancer patients had spinal metastasis [10]. Spinal cord compression caused by metastatic tumors occurs in 5–14 % of patients with cancer. These metastatic compressions could result in significant morbidity or neurological complications, including pain, immobility, and cauda equina syndrome [12, 29, 32]. The most common cancers related to metastasis involving the spinal column are lung, breast, prostate, renal cell, and gastrointestinal cancers [32]. Among these lesions, thoracic spine and the thoracolumbar spine junction are the most common sites of metastasis, with cervical spine being the least [75].

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21.2 Clinical Features

In patients with spinal tumors, the most frequent symptoms upon presentation are pain (85–95 %) and lower extremity weakness [76, 77]. The pain is usually non-relenting, characteristically worse at night, and not relieved after rest or lying down. The weakness is found in approximately 40 % of patients and usually develops insidiously within months or in some cases years after the onset of pain. Sometimes there also may be sensation loss, caused by neural compression. Temperature and vibration sensation and proprioception may be lost at first, followed by a loss of light touch. Other possible clinical manifestations include urine and stool incontinence, orthostatic hypotension, and sexual impotence due to autonomic dysfunction.

Upon neurological examination, spinal cord compression by the tumor mass in the thoracic and upper lumbar spine may present myelopathic signs, such as positive Hoffman sign, spastic weakness plus hyperreflexia in the lower extremities, upgoing Babinski signs bilaterally, and unstable gait. In cases of severe spinal cord compression, paraplegia with a sensory level is often present. In such cases, spinal cord compression syndromes are not uncommon, including anterior cord, Brown-Sequard, and cauda equina syndromes.

21.3 Diagnosis

Common diagnostic tools for spinal tumors are plain radiographs, radioisotope bone scans, computed tomography (CT) scanning, and magnetic resonance imaging (MRI). Angiography might be considered in cases of vascular lesion, like aneurysmal bone cyst and hemangioma, lesions with rich blood supply, or tumors with encasement of major vessels. It is a useful tool for demonstrating the vascular anatomy, including anterior spinal artery and artery of Adamkiewicz, which might be a critical feeding artery of the spinal tumor. Understanding the vascular supply or involvement could be invaluable for surgical planning and even possible preoperative tumor vessel embolization [47, 63, 68].

Plain radiographs are usually sufficient to demonstrate osteolytic or osteoblastic neoplasms of the spine. However, small or soft-tissue tumors with little invasion of the bony vertebra column could cause very subtle bony destruction and thus be missed by plain radiographs. It has been reported that bony destruction might not be present until there is nearly 50 % loss of trabecular mineralization [53]. In patients without osteopenia or osteoporosis, vertebral compression fracture could indicate extensive pathologic bone erosion and oncological problems.

Radioisotope bone scan is a nuclear medicine exam and a sensitive test for detecting bony breakdown resulting from tumor involvement [78]. Although the radioisotope bone scan has high sensitivity, its specificity is reportedly low. Not only neoplasms but also many other medical conditions, including infection, inflammation, and traumatic fracture, could yield false-positive results. Therefore, it is usually used for screening or follow-up after treatment.

CT is a rapid and useful tool in the assessment of spinal neoplasms, particularly those involving the bony vertebral column. The extent of osseous erosion caused by tumor, as well as the surrounding anatomy of vertebral columns, end plates, and vasculature, can be assessed by CT scans of the spine [32]. Although the image quality of soft tissue may not be comparably high as that seen using MRI, CT is definitely superior in the evaluation of bony structures and thus essential to aid surgical planning and oncological staging. The reformatted coronal and sagittal images of multidetector CT scans frequently provide useful information in preoperative planning of instrumentation and fixation (Fig. 21.1). In the past decade, post-myelogram CT has become less frequently used due to its invasiveness and technical dependence. The necessity of post-myelogram CT has been largely replaced by MRI in recent years.

MRI is now considered as the gold standard radiological image modality for spine tumors. Infection, inflammation, and neoplasia are usually clearly distinguished using modern MRI techniques. Moreover, MRI can also assist in differential diagnosis of pathologies of the neoplasm. MRI is particularly irreplaceable for

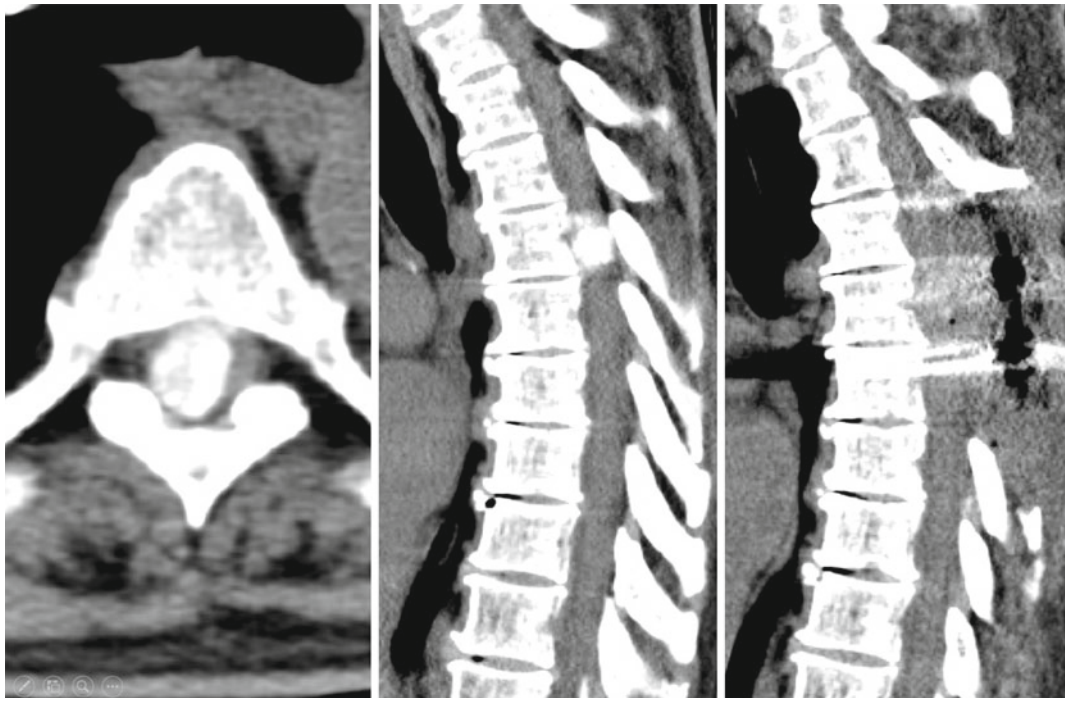


Fig. 21.1 Computed tomography (CT) of a thoracic spine psammomatous meningioma. *Left*: pre-operative axial view, the tumor with high density, indicating calcification, was located ventral-lateral to the spinal cord; *middle*: pre-operative sagittal view; *right*: post-operative sagittal view, the tumor was completely evacuated

providing detailed images of the soft-tissue and neural structures. Prior to the operation, spinal cord compression and tumor extent can be clearly depicted on magnetic resonance (MR) images. After surgery, MRI also provides important information to evaluate the extent of resection, degree of decompression of the neural tissue, and recurrence of the tumor. The image quality and resolution of MR images are superior to that of CT in terms of soft-tissue differentiation. Nevertheless, CT scans yield excellent evaluation of osseous tissue as well as vasculatures. Therefore, MRI and CT should be complementary to each other for not only preoperative planning but also postoperative follow-up [78]. The authors recommend obtaining both images for patients' assessment and surgical planning.

Other supplementary image examinations, such as positron emission tomography (PET) and CT of the chest/abdomen/pelvis, would help evaluate the tumor metastasis throughout the whole body [32]. In addition to image examinations, a histopathologic biopsy is essential for primary spine tumors [32]. The histopathology of the spinal tumor is an important guide in the determination of the treatment strategy and surgical planning—which we discuss in following paragraphs. Percutaneous CT-guided biopsy of the spinal tumor is frequently performed for tissue diagnosis prior to the surgery [78]. The overall diagnostic accuracy can reach 90 %, and biopsy of lytic lesions can yield an accurate diagnosis in 93 % of cases [43]. In suspected malignant lesions after image evaluations, the biopsy tract should be marked, and thus the tract can be removed during surgery for definite complete tumor resection [32].

21.4 Primary Vertebral Tumor

Lateral approaches to the thoracolumbar spine have been well described and commonly exerted for primary spinal tumors. Many of these typical

primary tumors, including aneurysmal bone cyst, hemangioma, giant cell tumor, neurofibroma, meningioma, plasmacytoma/multiple myeloma, and osteosarcoma, have been reported to be operated on through a minimally invasive surgery (MIS) lateral approach in the thoracic and lumbar spine areas [15, 61, 75].

21.4.1 Aneurysmal Bone Cyst

The annual incidence of aneurysm bone cysts (ABC) is 0.14–0.32 per 100,000 people [6, 66]. It has been estimated that ABCs may account for up to 10–20 % of all primary spinal tumors [22]. Typically, these ABCs are usually found in patients younger than 20 years old, with a median age of 13 years [41].

Histologically, ABCs are blood-filled cyst cavities with thin cortical septations [20]. Therefore, CT scans and MRI would demonstrate septa and fluid-fluid levels within the cyst cavity, which indicate multiple layers of blood product from old hemorrhages [27, 28, 66] (Fig. 21.2). The thoracic spine is the most common site of occurrence and the posterior element is usually affected, although the vertebral body may also be affected [36, 58].

Traditionally, ABCs are treated with surgery (curettage, intralesional resection, or en bloc resection), selective arterial embolization (SAE) alone, or preoperative embolization plus surgery [6, 36]. There has been one multicenter study that compared the three kinds of treatment strategies and demonstrated no significant differences on local recurrence and survival between all these treatments. The study therefore concluded that spinal ABCs can be treated effectively with intralesional resection, en bloc resection, or SAE [6]. In general, preoperative embolization is considered effective in decreasing intraoperative bleeding during intralesional resection surgery.

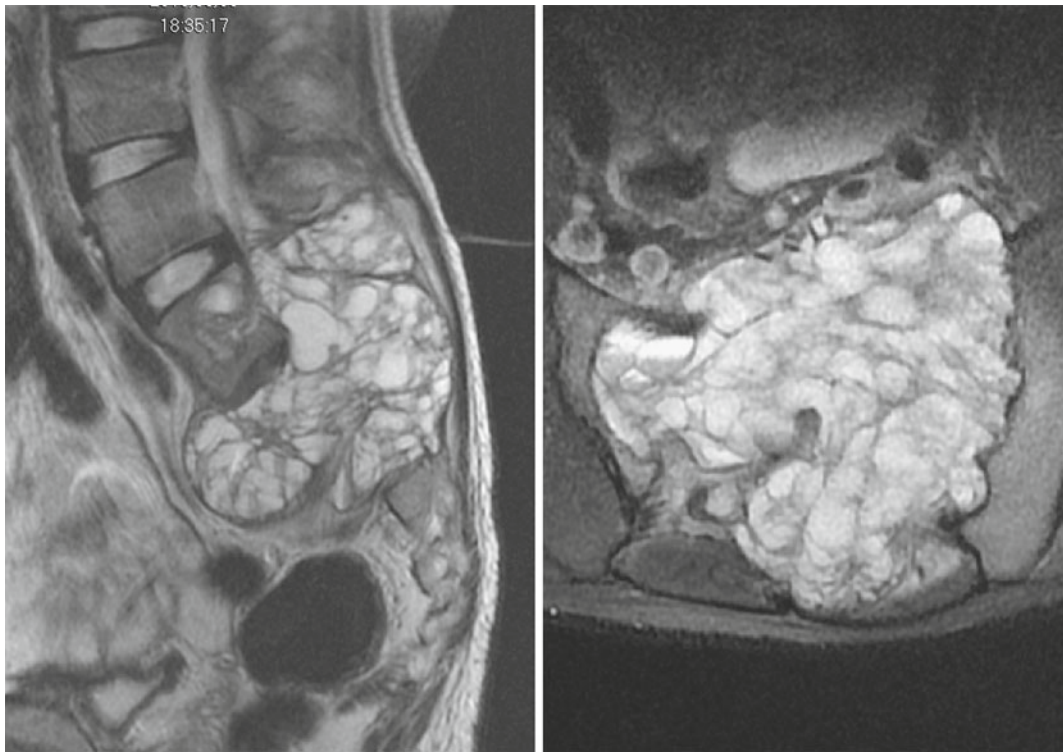


Fig. 21.2 Sacrum aneurysmal bone cyst, septa and fluid-fluid level within the cyst cavity. *Left*: sagittal T2-weighted magnetic resonance image (MRI); *right*: axial T2-weighted MRI

21.4.2 Hemangioma

Hemangioma is the most common primary benign tumor of the spine in adults. Hemangiomas accounted for more than 10% of primary spine tumors reported in autopsy studies [3, 21, 39]. However, most of these hemangiomas were asymptomatic and often incidentally discovered via examination for other purposes. They were usually solitary and found within the vertebral body [66].

The histologic features of hemangioma are aggregation of abnormal small vessel channels within bony trabeculae, and there may be also bony erosions [20]. On CT scans, hemangiomas usually demonstrate typically thickened trabeculae on both the axial and sagittal views. Therefore, these lesions earned the pathognomonic sign of "honeycomb" or "polka" [50]. There is usually high signal intensity on both T1- and T2-weighted MR images. A combination of both CT and MRI is common for the diagnosis of hemangiomas.

Although most hemangiomas are asymptomatic, they can cause pain, spinal cord compression, hemorrhage, or pathological fracture due to expansion of the tumor [21]. This phenomenon has also been associated with pregnancy [8].

Painful hemangioma or pathologic fracture without neurological deficit and cord compression can be effectively managed by vertebroplasty or kyphoplasty [1]. Surgery is usually reserved for cases of progressive neurologic deficits or spinal cord compression syndrome. Angiography before surgery may be a choice for evaluation of tumor vascularity and possible preoperative embolization to reduce bleeding during surgery [1, 21].

21.4.3 Osteosarcoma

Osteosarcoma is ranked as the most common primary bone malignancy. Osteosarcoma of the spine includes primary and metastatic malignancies and secondary malignancy which occurs as a result of previous radiation therapy or Paget's disease [2]. Osteosarcoma has a bimodal age distribution. The first peak occurs during the 10–14-year-old age span, which usually affects long bones. The second peak occurs in those older than 65 years old and is frequently associated with Paget's disease [55]. It is reported that only 1–2% of osteosarcoma occurs in the spine and mainly involves the vertebral body [50, 67].

The major presentation of spine osteosarcoma is pain and spinal cord compression resulting from pathologic fracture or tumor invasion into the spinal canal [78].

In histopathological examination, osteosarcoma has typical spindle cells with nuclear pleomorphism [20]. Osteoid or bone production could also be found within the tumor. On CT scans, osteosarcoma may demonstrate lytic and destructive lesions with matrix mineralization. Using MRI, osteosarcoma can demonstrate a hypo-intense signal in T1-weighted images and a hyperintense signal in T2-weighted images [65]. Moreover, contrast-enhanced MR images may provide details about surrounding soft-tissue extension and the degree of spinal cord compression [78].

Management of osteosarcoma involves both surgery and chemotherapy. Ideally, en bloc resection of the malignancy provides the optimal tumor control, while subtotal resection is usually associated with tumor recurrence as well as metastasis. Due to the difficulty of en bloc resection in spinal osteosarcoma, traditionally the prognosis of osteosarcoma has been poor. However, with the updated multimodality treatment strategies combining neoadjuvant chemotherapy, adjuvant chemotherapy, surgery, and radiotherapy, the long-term survival rate from osteosarcoma has substantially improved [18, 19].

21.4.4 Giant Cell Tumor

Giant cell tumor (GCT) mainly occurs in the sacrum and is the most common primary benign tumor of the sacrum, with occasional involvement of other spinal segments [14, 31, 75]. Generally, GCTs are diagnosed at the ages of 30–50 years, with a slight female predominance [64, 65, 69].

Common presentations of GCTs are local pain and neurologic deficits caused by compression of neural elements. Large GCTs can cause paraparesis, sensory impairment, and cauda equina syndrome due to spinal cord or nerve root compression.

On histological examination, GCTs contain multinucleated giant cells originating from osteoclasts in a spindle-cell stroma. The stromal cells may demonstrate mitotic activity, which is the proliferative component of the tumor. Using MRI, GCTs are usually hypo-intense in T1- and T2-weighted images with intraspinal extension and with occasional areas of hemorrhage. Also, heterogeneous gadolinium enhancement is often demonstrated [44, 65]. In general, GCTs usually are large osteolytic lesions that destroy the bony cortex with surrounding tissue extension [44].

Although GCTs are classified as benign tumors, their behavior is sometimes locally aggressive. Therefore, wide en bloc resection is curative for GCTs, while intralesional resection may prompt local tumor recurrence either with or without adjuvant radiotherapy [40]. Preoperative embolization may decrease intraoperative blood loss due to the abundant vascularity in these GCTs. Furthermore, postradiation sarcoma has been observed in 11 % of patients who received radiation for primary or recurrent GCTs [40].

21.4.5 Plasmacytoma and Multiple Myeloma

Multiple myeloma (MM), or so-called plasmacytoma, is the most common primary tumor involving the vertebral column. Multiple myeloma is a lymphoproliferative neoplasm with systemic involvement including the hematopoietic, renal, and bony systems. Plasmacytoma more specifically and frequently refers to the soft-tissue form and a solitary lesion [4]. These tumors commonly affect older patients in their 60s and have a male predominance. The annual incidence of multiple myeloma is about 0.5–0.7 new patients per million people [17, 38].

On CT scans, the typical image findings of multiple myeloma and/or plasmacytoma are diffuse osteolytic and have characteristic "punched-out" lesions within single or multiple vertebrae. Commonly MM or plasmacytoma involves mainly the anterior column, and sometimes MM might not be diagnosed until symptomatic. Diffuse osteoporosis or multiple compression fractures of the vertebral bodies are not uncommon in patients with MM [65].

In histological examination, cells of MM originate from plasma B cells with blue or pink cytoplasm. Cytologic atypia and binucleated cells are the characteristic features of pathology that can be observed. Bone marrow examination generally shows both normal and atypical plasma cells increasing [20, 65].

As MMs are usually quite radiosensitive, radiotherapy is often recommended as the initial treatment alone [35]. Vertebroplasty and kyphoplasty are useful in pain reduction and restoration of spinal alignment after pathologic fracture of the vertebral bodies [45, 79]. Surgery of en bloc spondylectomy plus instrumentation fixation is reserved for patients with spinal canal invasion or progressive neurologic deficits and/or spinal instability.

21.4.6 Meningioma

Meningioma comprises nearly 25 % of intracranial tumors and is one of the most common benign brain tumors. However, meningioma originating from the spinal region is remarkably less than that of intracranial tumors and accounts for about 12 % of all meningioma. Among all the intradural spinal tumors, approximately 25–45 % were meningioma, and the annual incidence of spinal meningioma is estimated to be 0.5–2 per 100,000 persons, with a strong female predominance. The peak age of occurrence of meningioma is between the 60 and 80 years of age. The most common site of involvement is the thoracic spine, followed by the cervical then lumbar spine [25, 71].

Meningioma tumors are benign and slow-growing. From the aspect of histology, they are considered to be derived from arachnoid cells, although this is not fully understood [71]. In terms of spinal meningioma, MRI evaluation is the choice of diagnostic tools. MRI provides excellent tumor localization, tumor-neural structure relationship, and soft-tissue anatomy, and further information about the tumor itself can also be depicted preoperatively.

In a review of the literature, the recurrence rate of meningioma ranged from 0 to 14.7 %. The predictor of tumor recurrence includes the invasion of the pia mater, the Simpson's resection grade, and the histological grade of the tumor

[34, 62, 71]. Primary total resection of meningioma tumors is the standard of treatment (Fig. 21.3). Simpson grade 1 resection may not be necessary in pathology grade 1 meningioma. However, it is crucial to achieve Simpson grade 1 resection in atypical or high-grade meningioma to decrease the rate of recurrence [51, 71]. In a long-term follow-up study, a rate of up to 32% recurrence of meningioma was observed in Simpson grade 2 resection after a mean follow-up of 12.2 years, while no recurrence was identified in Simpson grade 1 resection [51]. Therefore, the extent of resection is highly correlated to the rate of recurrence of meningioma.

21.4.7 Nerve Sheath Tumor

The nerve sheath tumor (NST), like neuroma or neurofibroma, is the most common spinal tumor, comprising one-third of primary spinal tumors [30]. NSTs are similarly distributed between both genders [15]. The most commonly diagnosed age of NST was in the patients' fifth decade [42]. According to its anatomical location, NSTs can be divided into intradural-extramedullary, extradural, or dumbbell type, which has both intradural and extradural parts [57] (Fig. 21.4). These tumors are believed to originate from Schwann cell progenitors at the nerve root [30]. Most patients with a NST present with pain and paresthesia. However, there are patients who occasionally present with motor deficits if the tumor mass is large enough to cause compression of the spinal cord [30].

Complete resection of a NST remains the gold standard management, despite the fact that it is not always feasible [13, 15, 30]. Traditional surgical approaches to NSTs of the thoracic spine include thoracotomy, (video-assisted) thoracoscopy, costotransversectomy, or a combination of the above. On the other hand, NSTs of the lumbar spine can be resected through posterior laminectomy or a posterolateral approach with partial or

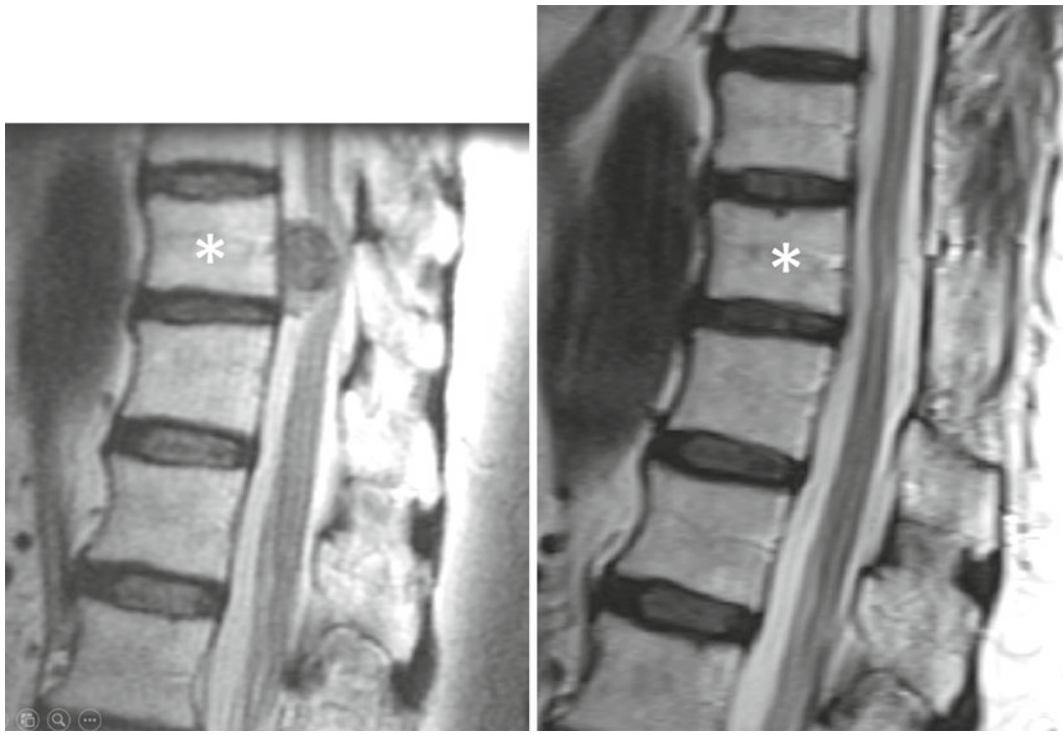


Fig. 21.3 T2-weighted magnetic resonance image (MRI) of T-11 spine metaplastic (ossified) meningioma. *Left*: pre-operative sagittal view, the tumor was located at ventral side of the spinal cord; *right*: post-operative sagittal view, tumor was totally removed. *vertebral body of T-11

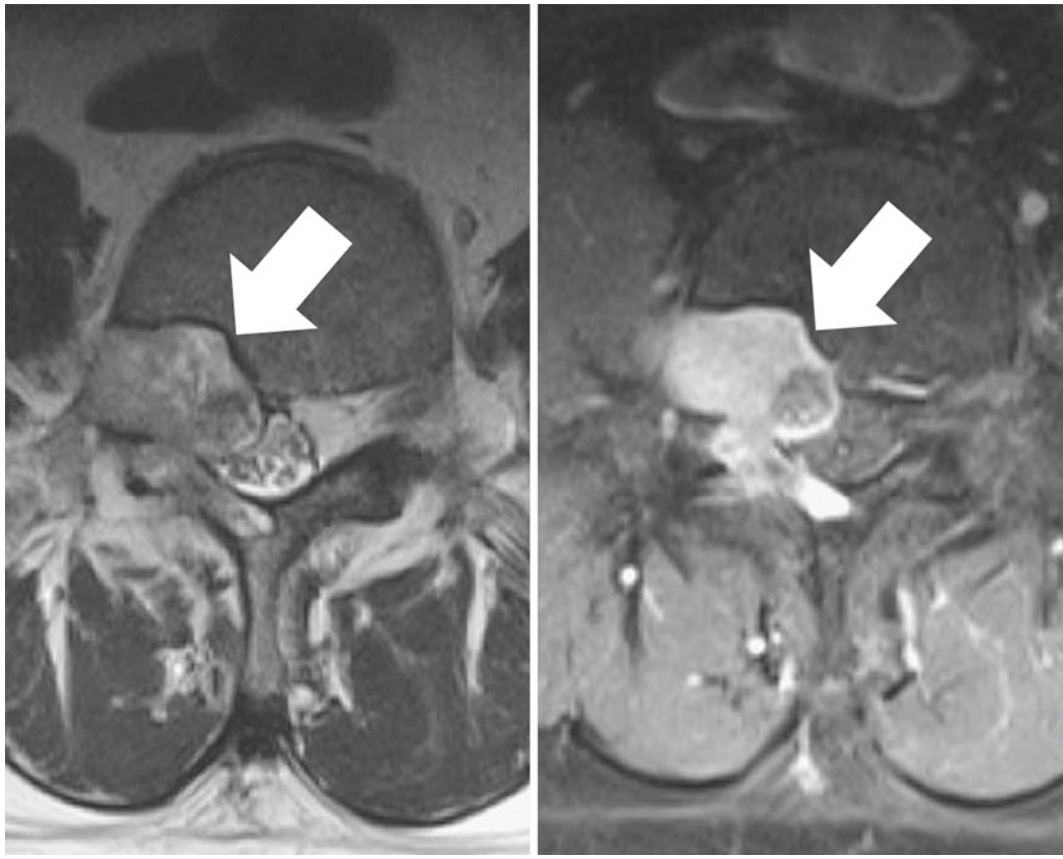


Fig. 21.4 Magnetic resonance image (MRI) of lumbar spine neurofibroma. *left*: T2-weighted axial view with contrast; *right*: T1-weighted axial view with contrast. *Arrow indicated tumor*

complete facetectomy, or lateral transpsoas approaches. Like resection of every other kind of tumor, instrumented fusion might be needed if the surgical approach compromises spinal stability, such as facetectomy [15].

21.5 Surgical Treatment for Primary and Metastatic Spine Tumors

Surgical treatment for spine tumors ranges from vertebroplasty [16], open anterior transthoracic, thoracotomy or retroperitoneal approaches [23, 26], an open posterior approach (transpedicular, costotransversectomy), a thoracoscopy-combined approach [26], and minimally invasive approaches [52, 80].

21.5.1 Open Surgery

The indication of traditional open surgery for thoracic and/or lumbar spine tumors includes medical-intractable pain, spinal cord compression, and instability [32]. The goal of an operation is to achieve complete tumor removal, local tumor control, and eventually disease control. The treatment strategy is mainly dependent on tumor histology. Each differential diagnosis of a primary malignant tumor, primary benign tumor, or metastatic tumor, or of spinal osseous tumors has different treatment strategies and goals.

For primary malignant vertebral tumors, the standard operative procedure of choice is en bloc resection plus adjuvant radiotherapy for best cure [11, 32]. On the other hand, intralesional resection plus radiotherapy may be sufficient for pri-

mary benign tumors [24, 32]. Many studies have demonstrated that en bloc spondylectomy provides a higher rate of tumor control, a lower rate of recurrence, and a longer term of disease-free survival for primary malignant vertebral tumors [5, 9, 11, 49, 70, 72–74]. Boriani et al. reported a lower recurrence rate (22.4 %) following en bloc resection compared to non-en bloc resection (100 %) for chondrosarcoma [5]. In a study by Talac et al., a significant lower recurrence rate (11 %) following "en bloc resection with negative margin" was noted, compared to "piecemeal resection with negative margin" (33 %) and "resection with positive margin" (70 %) for primary sarcoma [73]. Sciubba et al. published a study that Ewing's sarcoma and osteogenic sarcoma had improved rates of local tumor control after en bloc resection [70]. Furthermore, Ozaki et al. reported significantly better survival rates in patients with wide resection than those who had non-wide excision (biopsy or intralesional) for spine osteosarcoma [56].

The technique of en bloc resection of these spinal tumors can be challenging and is sometimes only achievable with sacrifice of some neural tissue. Therefore, en bloc spondylectomy usually involves experienced orthopedic or neurological surgeons, and it is not uncommon to combine both anterior and posterior/lateral approaches. There are major perioperative complications, such as spinal cord injury, unintended durotomy, and vascular injury to aorta and vena cava. The complex operation often results in spine instability that requires reconstruction and instrumented fusion of the vertebral column.

For metastatic tumors of the spine, surgical management can be effective in the relief of symptoms and in the improvement of life quality. Surgical decompression or evacuation of the tumor mass could provide better pain control, regain or maintain mobility, and offer improved sphincter control [29]. For these metastatic tumors of the spine, the surgical goal is mainly palliative and is better reserved for patients whose life expectancy is considered more than 3 months [10]. Although the final outcome depends on the status of the primary oncological disease, surgery is often very effective to relieve intractable pain, spinal instability, or neurologic compromise.

Surgical strategies to manage spinal osseous metastatic tumors range from intratumoral resection to en bloc resection. The various approaches include direct posterior decompression with or without posterolateral fusion, costotransversectomy with corpectomy and placement of interbody support and bone graft with posterolateral fusion, thoracotomy with corpectomy and cage reconstruction, retroperitoneal approaches, and vertebroplasty/kyphoplasty [32]. In a landmark study by Patchell et al., direct decompressive surgery plus postoperative radiotherapy was superior to treatment with radiotherapy alone for patients with spinal cord compression caused by metastatic cancer. Direct decompressive surgery provided improvement in ambulation, greater pain control, and less corticosteroid use [60].

The optimal paradigm of treatment for these spinal tumors remains uncertain. Cloyd et al. published meta-analysis and a systemic review of the present literature focusing on the prognosis of primary and metastatic spine tumors after treatment. The median time to recurrence was 113 months for the primary tumors and 24 months for the metastatic tumors. Disease-free survival rates at 1, 5, and 10 years were 92.6 %, 63.2 %, and 43.9 %, respectively, for the primary tumors, whereas the rates were 61.8 %, 37.5 %, and 0 %, respectively, for the metastatic tumors [11]. Furthermore, this review study also pointed out the risk factors of tumor recurrence, such as old age, male sex, previous metastatic tumors, and osteosarcomas. Patients with the aforementioned characteristics were significantly associated with tumor recurrence [11].

21.5.2 MIS Lateral Approach

Minimally invasive surgery (MIS) has been an emerging option in the management of degenerative spinal diseases to reduce postoperative comorbidities. There has also been more application of MIS in the management of oncological disorders of the spine, particularly in the thoracolumbar spine. Traditionally, open surgery

for spinal tumors has been divided into anteriorly based or posteriorly based approaches, which are associated with different morbidities. Posterior approach-related morbidities include extended soft-tissue dissection resulting in excessive blood loss, a limited window to ventral lesions and constraints on vertebral body reconstruction and kyphotic correction. Anterior approach-related morbidities include a large incision for conventional thoracotomy, entry to the chest cavity, and pulmonary complications (such as atelectasis, pneumo- or hemothorax, pleural effusion). Also, most of spine surgeons are unfamiliar thoracoscope-combined techniques. On the other hand, the MIS lateral approach has been developed in order to reduce the abovementioned approach-related morbidities. For example, the MIS lateral approach to the thoracic and lumbar spine can minimize muscle destruction, blood loss, wound pain, and hospital stay, whereas it can still achieve complete tumor removal and reconstruction of spinal stability [75]. The advancement of tubular and expandable retractors, specialized instruments, and fiber-optic illuminations has helped the MIS lateral approach to prevail [59].

There are also disadvantages regarding MIS lateral approaches. Inevitably, the MIS lateral approach to the thoracic or lumbar spine requires a long working distance with a narrow visual window and depends on fluoroscopic guidance. There is a steep learning curve and requires experienced operators. Due to the limited space, multiple segments of lesions are difficult to operate on within a single approach. Most of the reports on MIS lateral approaches have so far dealt with only three vertebral bodies [15, 37, 46, 61, 75]. Moreover, posterior transpedicular percutaneous screw fixation is frequently necessary to stabilize the vertebral column. Separate posterior skin incisions are therefore needed. Occasionally, there are severe adhesions and inflammatory infiltrations caused by metastatic spinal tumors, and thus the tissue dissection may be difficult and hazardous [59]. Therefore, the MIS lateral approach may not be feasible for all types and anatomic locations of spinal tumors. Vertebral body tumors and ventral and lateral lesions of intradural tumors are more favorably approached by the MIS lateral approach. Primarily posterior column or pedicle-based tumors may be better operated on via posterior or transforaminal approaches. Most experts also recommend posterior-based approaches for tumors in the high thoracic region (T1-4) due to the anatomic restriction of mediastinum and axilla [59, 75].

Application of the MIS lateral approach on spinal tumors is relatively new and there are scarce reports in the literature. The tumor pathologies most commonly reported using the MIS lateral approach included neurofibroma [15, 75], meningioma [75], plasmacytoma and multiple myeloma [61, 75], hemangioma [75], osteosarcoma [75], giant cell tumor [75], aneurysmal bone cyst [61], and mostly metastatic tumors [37, 46, 48, 59, 61, 75]. There was one case report of extradural foraminal spinal neurofibromas that was dealt with by the MIS lateral (retroperitoneal/retropleural) approach for tumor resection in three patients [15]. An expandable tube retractor (MaXcess, NuVasive, San Diego, CA, USA) was used. All three patients had successful tumor resection with complete resolution of their pain and motor deficits. Complete resection of the neurofibromas was noted in two patients and a tiny residual in the third patient. No instrumentation was needed due to no removal of bone or critical ligamentous structures. There also was no instability in postoperative radiographic follow-ups. The earliest case series in the literature was reported by Kossmann et al. in 2001, which included six metastatic tumors using the SynFrame (Stratec Medical, Oberdorf, Switzerland) retractor system [37] via a mini-open transthoracic route for thoracic lesion or mini-open retroperitoneal route for a lumbar lesion. No intra- or postoperative complications related to the minimal access developed, and there were no vascular or visceral complications. However, no midterm or long-term result was recognized in this case series. There was another case series reported in 2008 that described 37 patients who underwent the MIS lateral approach for a T or L spine traumatic burst fracture or vertebral body tumor [61]. Single-level corpectomy

for the tumor was done in 11 patients through transthoracic (T5–T11), transthoracic transdiaphragmatic (T12–L2), or retroperitoneal mini-open approaches (L3–4). A SynFrame (Stratec Medical, Oberdorf, Switzerland) table-mounted retractor was used. Most of these cases were metastatic malignancies, such as the breast, liver, renal, and lung carcinoma. Besides metastasis, there were two cases of multiple myeloma and one case of ABC. Nine out of the 11 tumor patients were stabilized with posterior fixation. The remaining two tumor patients were reconstructed with only intervertebral cages because the posterior element was not involved. As a result, construct stability was achieved in all patients in postoperative radiographic follow-ups at 6 months, and no patient needed reoperation. Clinically, minimal pain was observed at the postoperative 24-month follow-up, and improvement with no neurological deterioration was noted in most patients. Six perioperative complications from the anterior approach developed out of 37 cases, including unintended durotomy, pneumothroax, transient paralytic ileus, persistent or transient ilioinguinal hypesthesia, and superficial wound infection. However, no long-term tumor results were reported in this literature.

One case series reported five compression fractures with painful kyphosis caused by osteoporosis or metastatic malignancy (not specified) which were evacuated via the extreme lateral interbody fusion (XLIF, NuVasive, San Diego, CA, USA) approach in the T or T-L spine. Single-level corpectomy with two adjacent diskectomy was performed in all five cases. All four patients went on to develop radiographic evidence of solid fusion, except one patient who died from widely metastatic cancer 2 months following her surgery. As well, no long-term tumor-related results were recognized in this literature [46]. By far the largest case series of the MIS lateral approach for spine tumors was reported by Uribe et al. [75]. Twenty-one consecutive patients were operated on for T spine tumors with various pathologies, including neurofibroma, meningioma, plasmacytoma, hemangioma, osteosarcoma, giant cell tumor, and metastatic tumor, via the XLIF (NuVasive, San Diego, CA, USA) approach. Either a mini-open transthoracic or retropleural approach was adopted. Primary tumors occurred in 76 % of the patients and secondary (metatstatic) in only 24 % of the patients. The surgical indications included pain, instability, spinal cord compression, and neurologic deficit. The degree of resection was based on tumor histology. Subtotal resection of metastatic tumors was not considered a failure. Mean operative time was 117 min (40–284 min). Mean blood loss was 291 mL (25–1,650 mL). Average hospital stay was 2.9 days. Of the 21 patients, 5 had improvement of neurological deficit, and the rest without neurological deficit remained stable. Postoperative improvement of visual analogue scales (VAS) and Oswestry disability index (ODI) were demonstrated. There were no intraoperative complications. Only one perioperative complication, pneumonia, developed in one patient, and there was no postoperative pneumothorax in all patients. After a mean follow-up period of 21 months (range, 6–24 months), two patients had residual tumor (multiple myeloma and meningioma), and two patients died at 6 and 12 months (respectively) postoperatively due to their metastatic cancer.

The development of MIS approaches to the thoracolumbar spine aimed to alleviate the significant approach-related morbidities in conventional open surgery. Apparently, this is the trend of spine surgery development, since MIS approaches allow less muscle and soft-tissue destruction, reduce blood loss, minimize postoperative pain, shorten hospital stays, and facilitate early mobilization [54]. To date, the MIS lateral approach appears to be safe and effective for thoracic or lumbar spinal tumors with all the benefits mentioned above [59]. Although there has been less data on long-term local tumor control and a lack of strong evidence compared to traditional open surgery, the MIS approaches would likely prevail along with the advancement of technology. In the near future, more evidence of MIS lateral approaches would likely demonstrate that it is a viable and effective option for treating spinal tumors in the thoracolumbar spine.

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Minimally Invasive Lateral Spine Surgery in Trauma

22

Joseph Pyun, Tristan Weir, Kelley Banagan, and Steven C. Ludwig

22.1 Introduction

Thoracolumbar trauma patients present unique challenges to the spine surgeon, whose goals are to prevent primary or secondary neurological injury, enhance neurological recovery, stabilize the spine to promote early mobilization, and minimize surgical morbidity. Minimally invasive surgery (MIS) has become a key tool in the spine surgeon's armamentarium in the treatment of these potentially fragile patients, as it affords an alternative to traditional open procedures and their associated increased blood loss and infection rates [1, 2]. Specifically, lateral minimally invasive spine surgery (MISS) has recently become a treatment option in this patient population. The development of minimally invasive techniques potentially allows surgeons to better treat spine trauma patients by providing early decompression or stabilization while minimizing the morbidity of surgery. In this chapter, the epidemiology of thoracolumbar spinal cord injuries will be discussed, followed by the indications for the use of lateral MISS procedures versus the conventional open anterior approaches. The surgical technique for lateral MISS will be outlined, as well as the pros and cons of this approach. Finally, a case example will detail the use of lateral MISS in clinical practice.

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22.2 Epidemiology of Thoracolumbar Spinal Cord Injuries (SCI) in Trauma

Thoracolumbar spinal injuries are relatively common with an incidence of 150,000–160,000 fractures per year, 10 % representing major injuries [3, 4]. Ninety percent of all thoracic and lumbar fractures occur at the thoracolumbar junction, and 10–20 % of those fractures are burst fractures [5]. Burst fractures occur most commonly in men during their second or third decade of life and often result from high energy trauma, such as motor vehicle accidents or falls from height [6]. Thoracolumbar injuries often result in significant incurred costs to the individual and society, including the cost of treatment and lost productivity. The incidence of neurologic injury for these cases ranges from 10 to 75 %, and those sustaining incomplete neurologic injuries have some potential for functional recovery [7]. Approximately 19.4 % of burst fractures are associated with a neurologic deficit, especially in those fractures with more than 33 % spinal canal

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narrowing [8]. The level of spinal cord injury also correlates with the likelihood of recovery. Injuries at the level of the cauda equina are most likely to recover, followed by the conus medullaris and the spinal cord, respectfully [7]. The goals of treatment for thoracolumbar spinal injuries are to prevent neurologic deterioration, enhance neurologic recovery, stabilize the fracture to facilitate rehabilitation, and prevent late pain and deformity.

22.3 Indications for the Anterior Approach

Several factors should be considered when choosing the optimal approach for treating thoracolumbar fractures, including the bony and/or ligamentous injury pattern, neurologic status, experience of the treating team, medical comorbidities, body habitus, baseline level of function, prior history of radiation or surgery, and the condition of the soft tissues. Relative indications for an anterior approach include severe vertebral body comminution, incomplete neurologic deficit, and secondary neural compression following posterior realignment and stabilization for a fracture dislocation associated with a burst fracture. In a study by Sasso et al., 91 % of patients with incomplete injuries improved at least one modified Frankel grade, and 95 % appeared to achieve stable arthrodesis after anterior decompression and reconstruction [9]. Compared to posterior or lateral decompression, anterior decompression for thoracolumbar spine fractures with incomplete neurologic deficits resulted in a higher rate of neurologic improvement and recovery of bowel and bladder control [10]. There is evidence to suggest that an anterior approach for incomplete injuries results in better neurologic recovery compared to a posterior approach due to enhanced visualization and the ability to perform a better decompression [11]. Esses et al. found canal compromise improved from 44.5 to 16.5 % compared to 58 to 4 % when treated with posterior distraction versus anterior decompression and instrumentation, respectively [12]. Studies have also confirmed the ability to achieve and maintain correction of posttraumatic kyphosis with an anterior approach [9, 12, 13]. Additionally, biomechanical studies have shown that an anterior corpectomy with instrumentation is superior to posterior treatment for thoracolumbar burst fractures [14–16]. McCormack et al. developed the load-sharing score, which was intended to identify fractures that would benefit from anterior column reconstruction due to the severity of injury. This score has been validated and bases its scoring on the proportion of vertebral body comminution, displacement of fragments, and degree of kyphotic correction [17].

22.4 Complications Associated with the Open Anterior and Posterior Approaches

The anterior approach has potentially significant complications despite the success of this technique. This approach is associated with a complication rate ranging from 17 to 31 %, including pneumonia, pulmonary embolism, thoracic duct injury, sympathectomy, retrograde ejaculation, pneumothorax, atelectasis, bone graft pain, meralgia paresthetica, neurological worsening, instrumentation failure, graft dislodgement, dural tears, wound infections, stroke, bleeding from the great vessels, visceral injury, postoperative hernia, diaphragm injury, infection, post-thoracotomy pain syndrome, and deep venous thrombosis [18–24]. Due to the injury pattern that can occur at the thoracolumbar junction, certain fractures may necessitate both posterior and anterior approaches. The obvious advantage of this method is that all the surgical goals can theoretically be accomplished, but the morbidity of a more invasive procedure is a drawback. Indications for a circumferential approach include posterior stabilization following an anterior decompression and fusion, anterior column support following a posterior stabilization procedure, and the need for additional support and a fusion bed in the treatment of osteoporotic fractures, circumferential decompression, and ankylosing disease. A combined anterior-posterior approach has an unsurprisingly low pseudarthrosis rate but has high complication (16–50 %) and mortality (9 %) rates [20, 25]. Thoracotomy and retro-

peritoneal approaches carry significant morbidities, as well. Due to the complications outlined above, surgeons have sought less invasive surgical options that achieve the same operative goals, but with lower morbidity [26–33].

22.5 Benefits of the Lateral MISS Approach

MISS can be defined as a set of surgical techniques and principles that emphasize soft tissue preservation, while maintaining the principles of fixation, decompression, and correction. Indications for MISS in thoracolumbar trauma include burst fractures, distraction injuries, fracture-dislocations, osteoporosis, and unstable sacral fractures requiring lumbopelvic fixation. MISS lacks long-term evidence to support its use, but several case reports offer evidence to support its utility in thoracolumbar and lumbar trauma [34, 35]. The role of minimally invasive posterior stabilization in the treatment of thoracolumbar fractures has also been supported by several studies [36–41]. Although MISS techniques appear to offer considerable advantages over conventional open surgery, such as less blood loss and lower infection rates [1, 2], long-term data is needed to validate its superiority.

The minimally invasive lateral approach to the spine has been utilized by surgeons to access both the disk space and the vertebral body for a variety of lumbar degenerative conditions. With the development of surgical tools for the lateral technique, the creation of a safe surgical working zone allows the surgeon to target a specific vertebral body fracture, decompress the spinal canal, place a structural device with bone graft, and safely place instrumentation to stabilize the spine.

22.6 Lateral MISS Techniques

Smith et al. illustrated the mini-open, lateral approach for the treatment of thoracolumbar trauma [2]. The approach for L2–L5 injuries is the same as the standard retroperitoneal, transpsoas approach outlined by Ozgur et al. [42], but more care is taken to avoid excessive lateral flexion by using less table break and avoiding the use of a bump under the contralateral flank. Additionally, a slightly larger incision allows for greater visualization and a larger work area for the corpectomy. A lateral transpleural approach was used for T5–T11 and was accomplished with ipsilateral lung deflation. A retroperitoneal approach was used for treating T12–L1 injuries by creating a plane between the parietal pleura and the ribs, retracting the pleura and diaphragm anteriorly. The twelfth rib and iliac crest limit the exposure of the upper and lower lumbar spine, respectively [42]. The lateral approach requires sequential tubular dilation, docking an expandable retractor on the anterior column to allow for a safe ventral working zone, performing diskectomies adjacent to the fracture, coagulating and ligating the segmental vessels, and, lastly, performing a corpectomy at the fractured vertebra (Fig. 22.1) [2].

After performing the corpectomy, there are several options to reconstruct the anterior column. These options include using a structural allograft, autograft, or a static or expandable cage. The expandable cage technology facilitates the reconstruction of the corpectomy defect produced through the MISS lateral approach. After reconstructing the anterior column, supplemental fixation can be performed with anterolateral plating or posterior percutaneous transpedicular screws.

Smith et al. [2] investigated the use of MISS lateral techniques in the treatment of thoracolumbar fractures. The study included 52 patients with thoracolumbar fractures that were treated with mini-open, lateral corpectomies with anterolateral plating or percutaneous transpedicular screws to supplement fixation. The median operative time was 128 min compared to 210–617 min for open surgery [22, 43]. The lateral MISS approach had significantly lower blood loss of 300 ml compared to 2–3 l in open surgery [43, 44]. This study showed an acceptable complication rate of 15 % versus literature values that vary widely for open procedures [45]. The median length of stay in the hospital was 4 days compared to the reported 10–35 days for open surgery [5, 46]. There was no significant difference in outcome between the anterolateral plating and

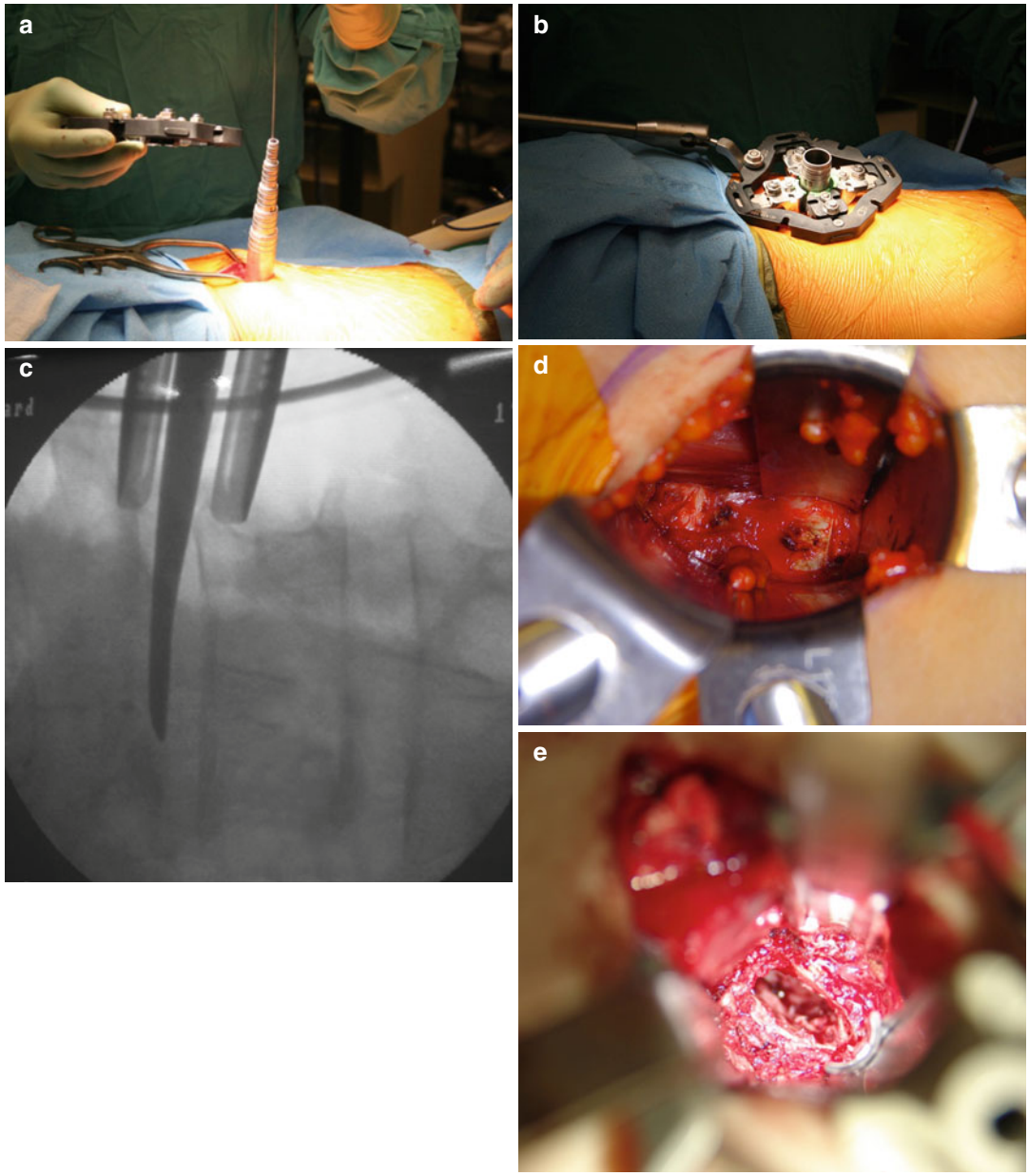


Fig. 22.1 Sequential tubular dilation (**a**), docking of expandable retractor (**b**), intraoperative AP fluoroscopic image with the docked retractor and Cobb elevator in the disk space (**c**), intraoperative view of the working zone (**d**), and magnified view of the working zone after diskectomy (**e**)

percutaneous posterior screw groups. Given the results of this study, lateral MISS appears to be a viable option for traumatic spine injuries, especially because these patients may be suffering from concomitant injuries that make them unfit for a larger, open procedure.

22.7 Pros of the Lateral MISS Approach

There is limited data regarding lateral MISS approaches for thoracolumbar spine trauma [5, 21, 47–49]. The lateral approach can be utilized

throughout the thoracolumbar spine with the exception of L5–S1, which is obstructed by the iliac wing. The most common levels for the lateral approach are L2 to L4, which lack the anatomical difficulties of the thoracic spine and lumbosacral junction [23]. In addition to the aforementioned advantages of MISS for thoracolumbar trauma, the lateral approach also has unique benefits. Lateral MISS allows for the placement of the interbody structural support on the strongest part of the end plate, the apophyseal rim. The greatest diameter of the vertebral end plate is in the coronal plane, and a lateral approach allows for utilization of this bony morphology [23]. Additionally, the lateral approach obviates the need to mobilize the great vessels when performing the corpectomy and placing the interbody support. A lower frequency of postoperative ileus can be attributed to less manipulation of the abdominal contents [34]. The lower likelihood of injuring the superior hypogastric plexus also makes retrograde ejaculation less likely [42]. Finally, operative time and estimated blood loss are significantly lower with the lateral MISS approach [38].

Minimally invasive and open short-segment fixations demonstrate no significant differences in outcomes or loss of deformity correction. The vast majority of the patients in the Smith et al. study maintained or improved their neurologic status at 24 months of follow-up. These results are consistent with the literature regarding neurologic status following corpectomy for traumatic injuries of the spine [50, 51]. Additionally, biomechanical studies have demonstrated the superiority of direct anterior reconstruction over posterior fixation alone [26, 29, 30, 32, 52].

22.8 Cons of the Lateral MISS Approach

Despite the reported success of the lateral MISS approach, disadvantages of using this technique include a steep learning curve, reliance on imaging and nerve monitoring, increased cost, potentially difficult management of intraoperative complications, decreased visualization, and potential neurovascular injury [26, 29, 30, 32, 52]. Specifically, this approach poses a risk of injury to the sympathetic chain, genitofemoral nerve, segmental arteries, and ureter, as these structures all lie in close proximity to the dissection path [2, 42, 53]. The most common complication associated with the lateral approach, however, is transient thigh numbness, pain, or weakness, the incidence of which ranges from 1 to 60 % [54]. This could result from the dissection through the psoas major, causing trauma to the muscle and potential injury to the lumbar plexus and genitofemoral nerve [42]. There is an increased risk of damaging the intervertebral nerves when working distally, where the nerves travel anteriorly over the intervertebral disk [55]. As this approach involves the abdominal wall, it is no surprise that a case report describes an incisional hernia after undergoing a lateral MISS procedure. To avoid hernias, the authors recommended making the incision as posteriorly as possible and using blunt dissection [56]. While lateral MISS does have its drawbacks, the morbidity is generally less than a patient would experience with an open procedure.

22.9 Case Example: A 22-Year-Old Male with Thoracolumbar Injury with Incomplete Neurological Deficit

A 22-year-old male, who was involved in a high-speed motor vehicle collision, sustained multiple injuries including a subarachnoid hemorrhage, bilateral hemopneumothoraces, an open right femur fracture, and bilateral humerus fractures. He presented with incomplete neurological deficits of his lower extremities, with the right proximal muscle groups having a higher motor score. The patient was found to have a noncontiguous spine injury. Imaging revealed an L3 burst fracture (Figs. 22.2 and 22.3) with posterior ligamentous complex (PLC) disruption, as well as a T12–L1 osseoligamentous flexion-distraction injury (Fig. 22.4). Based on his physical exam findings and imaging, it was determined that his incomplete neurological deficit was due

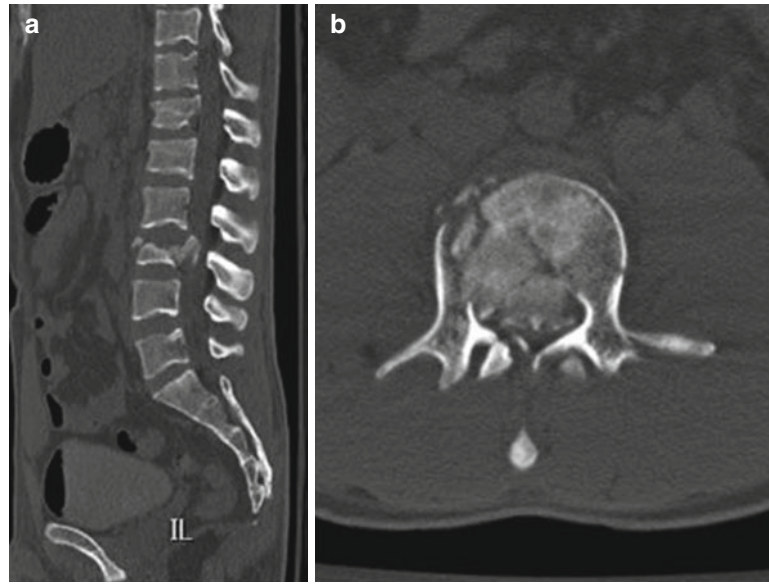


Fig. 22.2 Sagittal (**a**) and axial (**b**) computed tomography scans demonstrating a comminuted L3 burst fracture with greater than 50 % loss of height, retropulsion, and severe canal stenosis

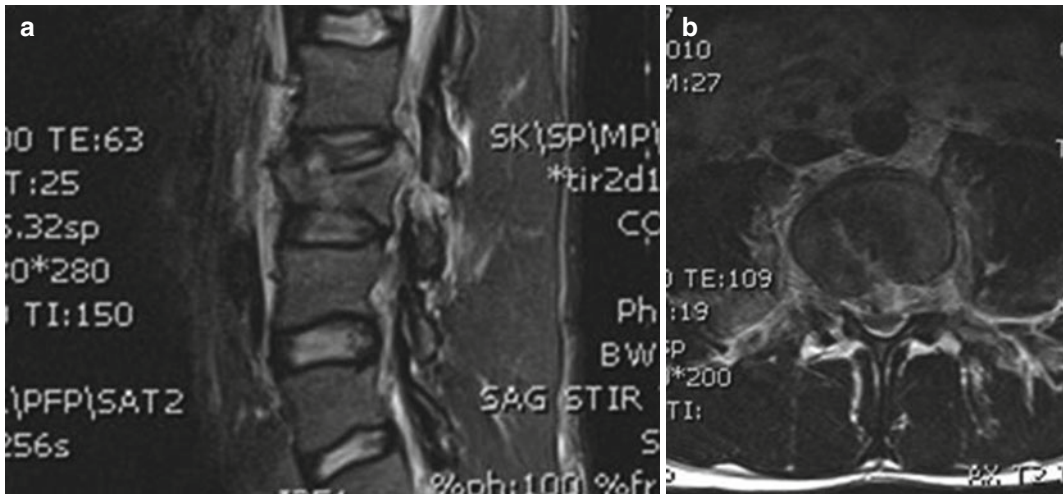


Fig. 22.3 Sagittal (**a**) and axial (**b**) T2 magnetic resonance imaging scans demonstrating a L3 burst fracture with greater than 50 % loss of height, retropulsion, severe canal stenosis, and poster ligamentous complex injury

to the L3 burst fracture, with associated 90 % canal compromise. Despite this finding, both injuries required stabilization. The surgeon performed a posterior MIS T11–L4 instrumentation with facet joint fusions followed by a mini-open lateral L3 corpectomy with placement of an expandable cage and local bone graft from the corpectomy site (Figs. 22.5). Postoperatively, the patient regained normal neurological function.

Conclusion

Thoracolumbar trauma patients are a vulnerable subset of patients who are often under significant duress due to multiple injuries. The goals of surgical treatment of these patients include prevention of primary or secondary neurological injury, enhancement of neurological recovery, and stabilization of the spine to promote early mobilization. The challenge of

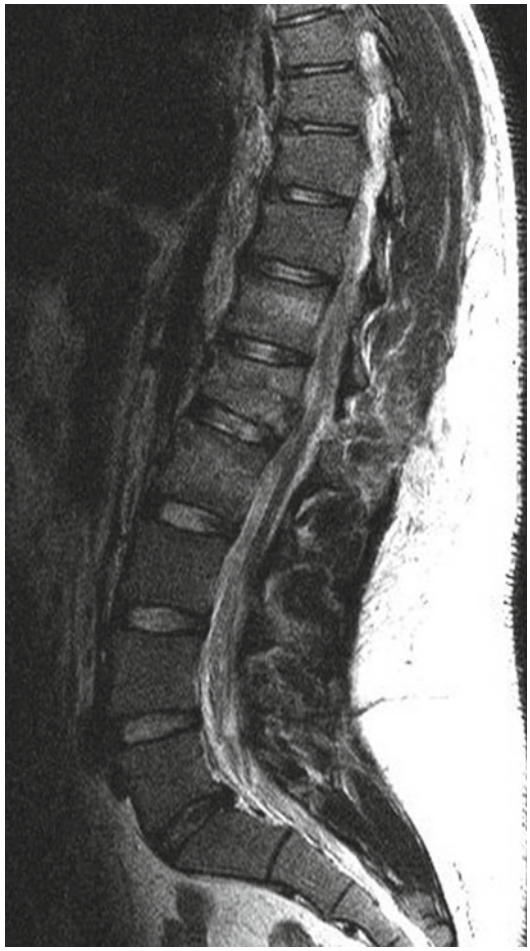


Fig. 22.4 Sagittal magnetic resonance imaging scans showing a T12–L1 osseoligamentous flexion-distraction injury (*arrows*)

minimizing the morbidity of treatment has provided an impetus for the implementation and development of MISS. The lateral MISS approach enables the surgeon to combine the benefits of an anterior approach with less morbid techniques. This is significant in light of the proven benefits of anterior decompression when compared to posterior distraction in the treatment of certain thoracolumbar injuries, including the potential for improved direct decompression to increase the likelihood of neurologic recovery and improved kyphotic correction. There is an additional advantage unique to the lateral MISS approach which includes the ability to place an interbody supportive device on the apophyseal rim. A disadvantage of MISS is the potentially steep learning curve which may initially lead to longer operative times and a higher rate of complications. As interest in the use of lateral MISS in the treatment of thoracolumbar trauma increases, novel techniques and improvements on current techniques will be developed. Further studies are needed to universally endorse this technique, but as illustrated in the case example, the lateral MISS approach may become a vital tool for spine surgeons in the treatment of thoracolumbar fractures.

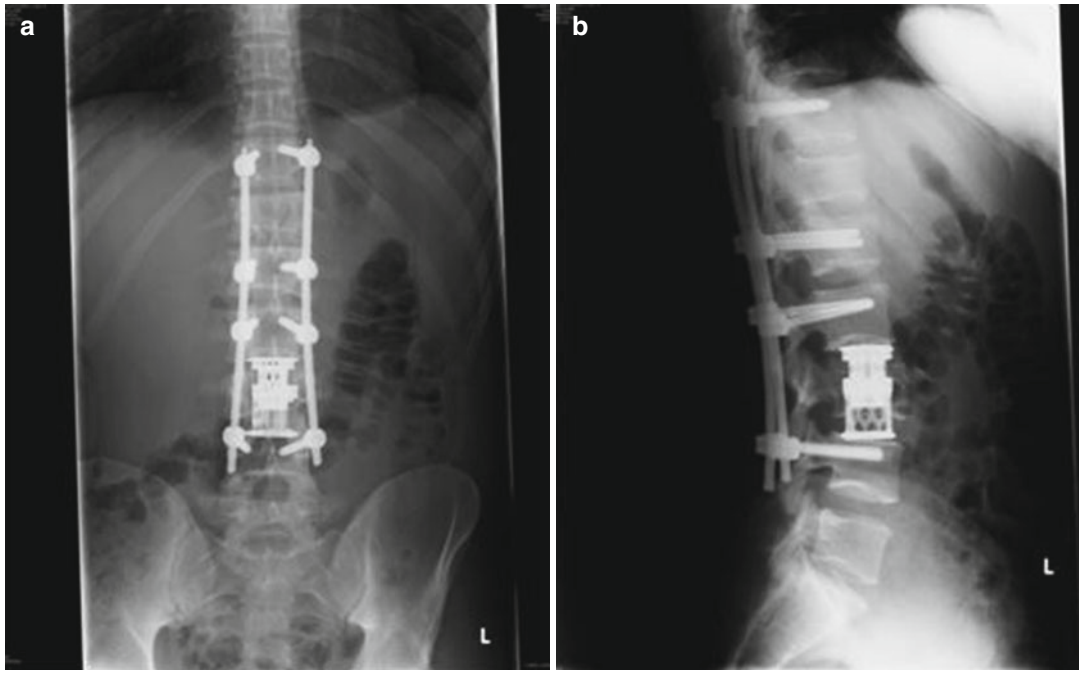


Fig. 22.5 Anteroposterior (**a**) and lateral (**b**) x-rays after mini-open lateral L3 corpectomy, titanium cage placement, and percutaneous transpedicular screw fixation from T11 to L4

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Lateral MIS Surgery for Spinal Column Infections

23

Li-min Rong and Lei He

23.1 Introduction

Spinal infections which fail conservative treatment or have neurologic compromise, spinal deformity or instability, demand surgical intervention. The basic principles of surgery for spinal infections include removal of the lesion, drainage of abscesses, nerve decompression, and correction of deformities. On this basis, meticulous planning, proper implant choice, and appropriate long-term antibiotics are necessary. The surgical approach is largely dependent on the extent and location of the infection, spinal destruction, neurologic deficits, health status, and comorbidity of the patient. Since vertebral body and end plate are most commonly involved in cases with spinal infections such as tuberculosis or discitis, anterior debridement is mostly used. When it becomes extensively involved from anterior to posterior column, debridement via anterior-posterior combined approach is suggested to be performed. Drainage of abscesses and foci is mostly carried out by an anterior procedure, but recently, it has been reported via posterolateral or transpedicular approach. As it is known that adequate debridement and drainage leads to sufficient decompression of the neural structures, while deformity correction mainly relies on intraoperative distraction, internal fixation, and achievement of solid fusion in cases with spinal infections. Currently, radical resection of infected bone is commonplace. The use of bone graft and rigid internal fixation in infected area has also been accepted by most spine surgeons.

The infected spine is more inherently unstable than the typical degenerative spine, so instrumentation should be strongly considered. As a result, the use of internal fixation achieves instant stabilization of the spine, which prevents postoperative displacement, fracture or collapse of the bone graft, and kyphoscoliosis deformity. Patients with internal fixation can benefit from it because of early functional exercise and rehabilitation, especially for those with neurological impairment, and may maximize the improvement of neurological function as early as possible. As the previous studies reported, owing to a low incidence of complications related to internal fixation, it is safe and effective for the patients with spinal infections.

The traditional interbody fusion includes both anterior and posterior approaches. Among them, the posterior spinal fusion carried out initially. In 1911, Hibbs and Albee independently reported the posterior spinal fusion for the treatment of spinal tuberculosis. This procedure reduces the

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degree of kyphosis and shortens duration of recovery. Moreover, it is not difficult to operate and achieve solid fusion, so as to make sure the stabilization of the spine is accomplished.

Thereafter, Hodgson et al. recommended definitive debridement, grafting and arthrodesis at the same time for patients with spinal tuberculosis in 1960. This procedure also succeeds in the treatment of other spinal infection diseases. Anterior spinal fusion can complete kyphosis correction via anterior distraction. With the pressure of vertebral body given to the bone graft, it supports a favorable environment of bone growth. In addition, anterior bone graft can fill the bone defects and eliminate dead space. Since anterior columns are mostly involved in the spinal infection, anterior procedure can directly deal with the diseased region, complete definitive debridement of foci (including abscesses, granulation tissue, and caseous necrosis), and diseased vertebral. Due to the bone graft that located between adjacent anterior columns bears the main axial pressure, it easily achieves solid bony fusion.

In consideration of thoracolumbar infections, it mainly includes three procedures: anterior debridement and interbody fusion combined with internal fixation, posterior debridement and interbody fusion combined with internal fixation, anterior debridement and interbody fusion combined with posterior internal fixation. Benli et al. performed four different procedures in 76 cases with spinal tuberculosis respectively. It included anterior radical debridement with anterior fusion and anterior instrumentation, posterolateral drainage and posterior fusion, anterior drainage and anterior strut grafting, posterior instrumentation following anterior radical debridement. There were no significant differences in the four groups in terms of fusion rates, correction of kyphotic deformity, recurrence rate, and clinical result. All the patients had a solid fusion mass at the last controls. Reactivation was not seen.

However, posterior procedure leads to extensive dissection of paravertebral muscles, facet joint, and ligaments, which aggravates the instability of intervertebral structure. It will result in postoperative epidural adhesion owing to both the excessive distraction of dural sac or nerve root and intraspinal operation at the same time. As a result of tension in cases with kyphosis who accept posterior interbody fusion, the incidence of nonfusion or pseudarthrosis is relative high. Conversely, there is a potential risk that bone graft will turn into a sequestrum if it fails to eliminate and control the infections after anterior interbody fusion. In addition, such complications of anterior approach as visceral damage, large vessel bleeding, and sexual dysfunction have been reported. Surgeons attempting to use this surgical technique are challenged by the required technical skills, steep learning curve, and continued requirement for access surgeon.

Minimally invasive spine surgery, characterized by small incisions, less trauma, less postoperative pain, shorter hospital stays, and faster recovery, has achieved the same effect as conventional operations and developed rapidly in recent years. Ozgur reported a novel surgical approach and named it as extreme lateral interbody fusion (XLIF) in 2006, which was distinct from the posterior or anterior procedure. It has also been described as direct lateral lumbar interbody fusion (DLIF). This minimally invasive spinal approach allows retroperitoneal access for discectomy and graft placement with a low complication rate. It was first used in the treatment of degenerative disc disease, degenerative scoliosis, and artificial disc replacement. With the development and familiar with the technique, the minimally invasive lateral transpsoas retroperitoneal approach can be applied for the treatment of spinal infections.

23.2 Surgical Indications and Techniques

23.2.1 Indications and Contraindications

23.2.1.1 Indications

Lumbar infections with vertebral destruction and collapse, including spinal tuberculosis, nonspecific spinal infections such as acute/chronic suppurative infection, postoperative

infection of intervertebral space, particularly the following cases:

1. Neurological deficit or spinal cord compression
2. Formation of cold abscess, sequestrum, or sinus
3. Spinal instability or deformity
4. Disease progression despite adequate antibiotic treatment

23.2.1.2 Contraindication

1. Poor medical condition, such as anemia, hypoalbuminemia, and multiple organ dysfunction that cannot tolerate surgery
2. Active tuberculosis in other sites of the body
3. Serious vertebral destruction which involves beyond two levels
4. Focus of infection herniated to the spinal canal, which needs a posterior direct decompression
5. Previous history of retroperitoneal surgery

23.2.2 Technique

23.2.2.1 Preoperative Preparation

Diagnosis is confirmed through completing laboratory investigations and imaging studies, followed by preoperative anti-infection treatment. Intravenous antibiotics are administered for nonspecific spinal infections, while antituberculous treatment consisted of a triple (isoniazid, rifampin, and pyrazinamide) or quadruple chemotherapy (plus ethambutol) is given for 2 weeks for patients with spinal tuberculosis. It is imperative to monitor the inflammation parameters (i.e., ESR, CRP, and WBC) that close to normal or decrease obviously. Preoperative supportive therapies are given simultaneously to patients in order to improve the general state of health.

23.2.2.2 Operative Procedure

The debridement and interbody fusion can be performed via a minimally invasive lateral retroperitoneal transpsoas approach. Removal of infected intervertebral disc is accomplished with curettes and reamers from one side to the other. The disc spaces were carefully debrided of devitalized end plate, vertebra, sequestrum, caseous necrosis, and granulation, as far as possible the devitalized annulus fibrosus near the spinal canal. Then gently decorticate the remaining end plates and wash the wound with saline solution. The sequential trial implants were used to determine the size of autograft bone or cage required for structural support, followed by the reconstruction of anterior column with iliac bone, XLIF cage, and titanium mesh according to the bony defects.

The structural cages filled with cancellous bone are suitable to implant into the disc space for the case with erosion of the end plate. Since XLIF cage is larger than conventional cage, it can effectively restore the intervertebral foramen volume and disperse bearing stress with larger contact area, which provides a better fusion environment. Numerous published literatures have reported that using bone graft or implants has not been correlated with an increase in the risk of recurrent infection in the treatment of spinal infections, when foci of infection were completely removed. For the cases with serious bone destruction, it is recommend to fill with structural iliac crest autograft bone or the titanium mesh cage with morselized autograft iliac crest through the direct lateral retroperitoneal approach. Autograft bone is the most commonly used to restore intervertebral height and provide support for anterior column. The previous studies have demonstrated that the use of allograft bone also achieve a good clinical effect, which could avoid complications such as postoperative pain of bone harvesting area, fractures, etc. The mixed streptomycin or other sensitive antibiotics are often implanted into the infected disc space with bone grafts.

Internal fixation provides favorable postoperative stability of spine immediately, prevents bone graft or mesh from shifting or subsiding, and can be used for the correction and prevention of deformities. Lateral fixation can theoretically be performed using plates and screws through the same approach, when there may be enough residual healthy vertebral body to accommodate the screws, without changing the position and performing the posterior fixation, even the secondary surgery. It definitely reduces the operative time and trauma. If the strength of the remaining vertebral body is

insufficient, and the preoperative examination indicated instability of spine, the posterior percutaneous pedicle screw instrumentation is recommended. As the biomechanical study proved, it maximizes stability after lateral interbody cage placement. If the vertebral body is destructed severely, it suggests to cross the infected area and place instrumentation in the adjacent healthy vertebral body temporarily via posterior approach. The internal fixation will be taken out when the diseased segment achieves fusion.

23.2.2.3 Postoperative Treatment

The patient can sit up and turn over on the bed by himself/herself on the second day after the surgery. According to the pain relieving conditions of the incision, he/she can leave the bed and move about, wearing the waist brace during 2–5 days after the operation. The brace is supposed to be worn for about 3 months. Postoperative X-ray and CT scans are planned in order to evaluate the conditions of internal fixation and decompression. The patient is about to discharge in 1 week, and the radiologic evaluation should be performed at 1, 3, 6, and 12 months and every year postoperatively during the follow-up.

The inflammation parameters and hepatic-renal function needs continuous monitor postoperatively. Intravenous antibiotics are administered for 6 weeks, followed by oral antibiotics for at least 6 weeks, until the CRP is normal or near normal, the ESR is trending down, there is substantial clinical improvement, and imaging studies show evidence of fusion across the previously infected area. Considering the cases with tuberculosis, antituberculous treatment consisted of isoniazid, rifampin, pyrazinamide, and ethambutol is given to these patients for about 1 year. Intravenous levofloxacin in combination with the antitubercular agents is recommended to administered for 2 weeks postoperatively.

23.3 Clinical Outcomes

The direct lateral lumbar retroperitoneal approach has the advantage of excellent exposure for thorough debridement of infected disc from one side to the opposite, even the destructed annulus fibrosis beside the spinal canal or anterior border of vertebral body. It allows removal of the destructed end plates and partial vertebral body through the working channel, which is beneficial to the infected cases by debriding the necrotic tissues, relieving the nerve root compression, and reconstructing stability of lumbar spine at the same time. However, this minimally invasive approach can hardly remove the diseased intervertebral disc completely, especially the parts herniated into the spinal canal. The lesion of multiple segments seems to be difficult to deal with due to the limitation of the working channel. There is an increasing risk of approach-related neurological complications owing to the possibility of variation of the intrapsoas nerves when combined with larger abscess of psoas major.

Shepard et al. has reported a case of medically refractory discitis of L1–2 and L2–3 level in a patient with multiple comorbidities including hypertension and pulmonary embolism. Considering that his poor condition would likely not tolerate a two-level vertebrectomy with anterior reconstruction, they chose to proceed with a limited debridement via a minimally invasive lateral retroperitoneal transpsoas approach. The L1–2intradiscal abscess fluid culture postoperatively was negative for bacteria and mycobacterium tuberculosis. Repeat lumbar MRI showed a significant decrease in the size of the fluid collection. The patient was maintained in a thoracolumbar-sacral-orthosis (TLSO) brace postoperatively and continuous antibiotics. His symptoms relieved obviously, with ESR/CRP trending down to normal. At 11 months postoperatively, the patient was able to ambulate with a walker. He reported minimal back pain and plain films showed a slight kyphosis centered at the L1–L2 level. This case suggested that limited debridement via a minimally invasive lateral retroperitoneal transpsoas approach may be an effective alternative to aggressive debridement for patients with lumbar discitis/osteomyelitis who was otherwise a suboptimal surgical candidate.

A retrospective chart analysis by Madhavan et al. was performed for ten patients who had presented with lumbar discitis and osteomyelitis. They all had undergone debridement via the direct lateral retroperitoneal approach. The infection involved one disc and the adjacent vertebral body in nine cases (L2–3 in five cases, L3–4 in three cases, and L1–2 in one case), while one case involved two levels (L3–4 and L4–5). Structural iliac crest autograft bone was used for anterior column reconstruction in nine cases except in one patient with a large bony defect, in whom a titanium mesh cage with morselized autograft iliac crest was used. Eight patients underwent posterior pedicle screw instrumentation, two patients did not undergo posterior instrumentation, and one of these developed a kyphotic deformity that received a secondary posterior procedure. Average follow-up was 680 days. Infection was eradicated in all patients according to a history, physical examination, imaging studies, and laboratory parameters. One patient developed a painful neuroma at the iliac crest harvest site and one patient with a retroperitoneal hematoma. There were no approach-related neurological injuries or postoperative surgical site infection. The direct lateral approach for the surgical treatment of lumbar discitis and osteomyelitis allows for thorough debridement and spinal reconstruction without the need to mobilize the great vessels, which was considered as an alternative to the open anterior approach. The authors also recommend posterior instrumentation to prevent the development of kyphosis.

The author applied lateral lumbar retroperitoneal approach for the treatment of single segment discitis and lumbar tuberculosis, which has achieved satisfying outcomes. All the cases were performed this procedure combined with lateral screw-rod or posterior percutaneous pedicle screw fixation. During the follow-up, the postoperative symptoms and radiologic features, ESR and CRP, average pain scores of Japanese Orthopedic Association Assessment (JOA), Oswestry disability index (ODI), and visual analog scale (VAS) improved significantly, without any approach-related complications of vascular and neural injury. Debridement and bone grafting through the working channel indicated a definite therapeutic effect for the case with erosion of the end plate and disc, which has shown the advantage of minimally invasive surgery. For the cases with serious bone destruction, it is also feasible to remove the sequestrum and necrotic tissues under the working channel, while filling the void with structural iliac crest autograft bone or the titanium mesh cage with morselized autograft iliac crest. The midterm and long-term clinical outcomes and safety evaluation remain to be seen.

23.4 Complications

23.4.1 Approach-Related Complications

Approach-related complications include vascular, visceral, and neural injury. Since infection is always accompanied by retroperitoneal adhesion, it is recommended to distinguish cautiously the anatomic structures, particularly the chord structures, when the working channel is built. Moreover, the distorted anatomy makes it easier to plunge the dilators into the soft necrotic spinal column, which leads to neurological injury or bleeding from a segmental vessel. Use blunt dissection with fingers, and repair the damaged tissue once the injury occurs. Advance preparations should be made to carefully position the dilators and retractor. Fluoroscopy and neuromonitoring should be carefully set up to make sure the safety of the approach. Preoperative MRI and CT studies were significant to plan the surgical corridor. The injury of the lumbar plexus presents primarily as transient postoperative thigh pain or numbness as well as lower extremity muscle weakness, which can recover within 6 weeks without any intervention. The pharmacologic treatment combining NSAIDs, steroid, and neurotrophic drugs can promote recovery of neurological function.

23.4.2 Instrumentation-Related Complications

Instrumentation-related complications include subsidence and displacement of the implants (interbody fusion cage, titanium mesh cage, and bone grafts), loosening or breakage of internal fixation, delayed fusion or nonfusion, etc. Since instrumentation-related complications always lead to reoperation, surgeons should thoroughly debride the infected areas, take active part in anti-infection, and select appropriate implant based on the conditions of the debridement and spinal stability. It is significant to exhort the patients to wear brace during the upright posture postoperatively.

23.4.3 Infection-Related Complications

Infection-related complications include inadequately debridement, spread of infection, relapse, impaired wound healing, sinus formation, etc. In order to avoid these, surgeons should thoroughly remove the infection focus during the procedure and select the appropriate antibiotic depending upon the antibiotic susceptibility tests of the causative organism, following a combination drug regimen. It requires the sufficient anti-infective therapy, including at least 4–6 weeks intravenous antibiotics followed by subsequently 6-week oral antibiotics for nonspecific infection, while 1–2-week preoperation and approximately 1-year postoperation for tuberculosis.

23.5 Case Studies

23.5.1 Case 1

A 75-year-old man complained of low-back pain for 5 months. The pain was worse with movement and radiated into both side of the hip. Despite analgesics and physiotherapy, in the last 2 weeks, the symptoms had continued to get worse. He developed high fever and felt sick at the same time without night sweat. The antipyretics could relieve the symptoms to some extent. No significant abnormity was found in the physical examination except tenderness and percussion pain on the L2–3 spinal process and decreased range of motion. The pain score was shown as follows: VAS for backaches was 7 points while 0 for leg pain, 28 % for ODI, and18 for JOA, respectively. The patient presented with repeated fever with body temperature fluctuation in 38–39 °C. The blood samples revealed leukocytosis with an elevated blood sedimentation rate, as well as the C-reactive protein. Considering the possibility of spinal pyogenic infection, we treated with levofloxacin, which worked soon after prescription. The surgery was performed after the condition that temperature returning to normal. Firstly, we debrided paravertebral abscess, the disc space, and adjacent vertebral bodies of L2–3 via lateral lumbar retroperitoneal approach. Then the cages were inserted into the diseased disc space followed by lateral fixation through the same approach. *Streptococci* was found in the culture of the focus and the pathology report supported the diagnosis of purulent inflammation. With the 4-week intravenous antibiotics followed by subsequently 6-week oral antibiotics, the patient recovered well. VAS score of low-back pain decreased to 1 point, while no leg pain was reported. Blood samples revealed no abnormity when he discharged from hospital (Fig. 23.1).

23.5.2 Case 2

A 25-year-old woman presented with progressive low-back pain for 2 years and continued to get worse accompanied with limitation of activity. No fever or night sweats were detected. Considering the physical examination, tenderness and percussion pain around the L1–2 spinal process were reported, while the mobility of the lumbar spine was detected. VAS score for back pain was 7 points. Blood samples revealed neither leukocytosis nor abnormity in ESR and CRP. Considering the possibility of

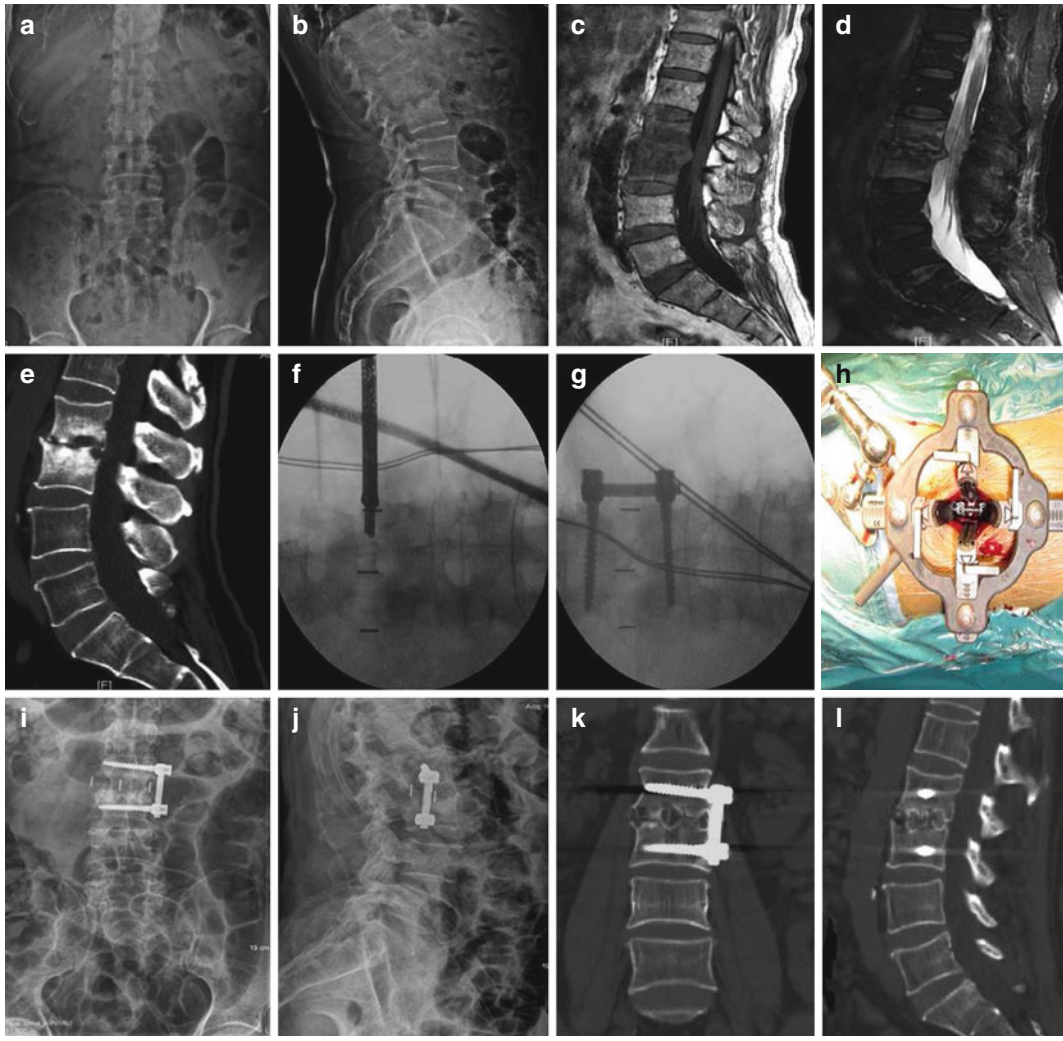


Fig. 23.1 (**a**, **b**) Preoperative plain film demonstrated a collapsed in L2–3 disc space with a loss of end plate; (**c**, **d**) preoperative MRI showed the destruction of L2–3 intervertebral disc and end plate with low signal intensity in T1-weighted images, but mixed signal intensity in T2-weighted images; (**e**) preoperative CT scan indicated partial destruction of the L2 and L3 vertebral body; (**f**) intraoperative X-ray showed the XLIF cage was inserted into L2–3 disc space through the working channel; (**g**) intraoperative X-ray showed the lateral screw-rod fixation; (**h**) the operation of lateral screw-rod fixation; (**i**, **j**) postoperative X-ray demonstrated the satisfactory position of the implants; (**k**, **l**) 2 years after surgery, the CT scan indicated solid bony fusion in L2–3 disc space

spinal tuberculosis, antituberculous treatment consisted of isoniazid, rifampin, pyrazinamide, and ethambutol is given to these patients for about 2 weeks. And then, we debrided psoas abscess and adjacent vertebral bodies of L1–2. Then the bone graft that harvested from the iliac crest was inserted into the diseased disc space followed by posterior percutaneous pedicle screw fixation. The pathology report supported the diagnosis of tuberculosis infection. With 2 weeks of continuous antituberculous treatment and intravenous levofloxacin, the patient recovered well and wore brace during the rehabilitation training. The VAS score of low-back pain decreased to 1 point 1 week after surgery. Blood samples revealed no abnormity when she discharged from hospital (Fig. 23.2).

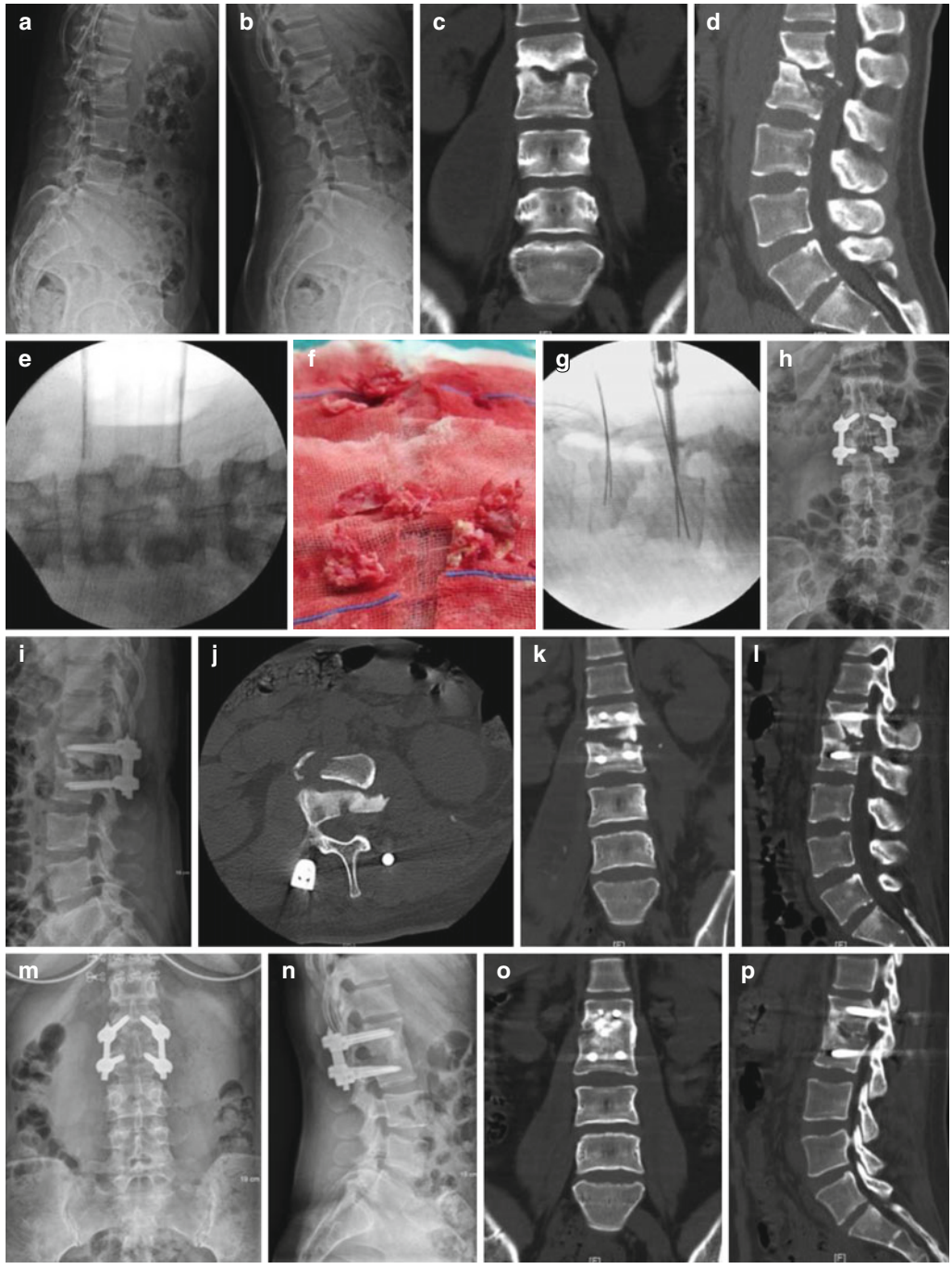


Fig. 23.2 (**a**, **b**) Preoperative dynamic X-ray demonstrated the instability and collapse of L1–2 intervertebral space with a loss of endplate; (**c**, **d**) preoperative CT scan showed the destruction of vertebral body and the giant psoas abscess on the right side; (**e**) intraoperative X-ray of the XLIF working channel; (**f**) lesions debrided from the L1–2 intervertebral space; (**g**) intraoperative lateral X-ray showed the position of posterior percutaneous pedicle screw fixation; (**h**, **i**) postoperative X-ray indicated the satisfactory position of the implants; (**j**) postoperative axial image of CT scan showed the bone graft; (**k**, **l**) postoperative CT scan demonstrated the decreased size of psoas abscess and satisfactory position of the bone graft; (**m**, **n**) 1 year after surgery, the X-ray demonstrated a solid bony fusion at L1–2 level, while the internal fixation were posited well; (**o**, **p**) 1 year after surgery, the CT scan indicated new bone formation peripherally around the structural graft in the previously infected disc space, while psoas abscess was eliminated thoroughly

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Adjacent Level Disease and Proximal Junctional Kyphosis

24

Matthew F. Gary and Michael Y. Wang

24.1 Introduction

Adjacent segment disease following lumbar spinal fusion refers to any symptomatic pathology occurring rostral or caudal to a previous fusion. The exact etiology of adjacent segment disease is controversial with evidence implicating increased biomechanical forces on the neighboring functional segmental unit as well as an intrinsic degenerative predisposition in this patient population [1–13]. The popularity of posterior instrumented spinal fusions over the last two decades and an aging population has significantly increased the incidence of adjacent segment disease. These patients can present with debilitating symptoms from stenosis, instability, and spinal imbalance. Surgical intervention traditionally consists of a revision posterior approach with extension of the instrumentation and decompression [14–16]. These surgeries are typically higher risk secondary to longer anesthetic durations, increased blood loss, an older patient population, and higher rate of cerebrospinal fluid leak (CSF) from scar tissue [17]. When adjacent segment disease includes proximal junctional kyphosis (PJK), disability arises from sagittal imbalance. A posterior only approach to correct this imbalance usually requires multiple osteotomies, again increasing the operative risk. Also, an open posterior approach has the potential to further disrupt and destabilize the new spinal levels rostral to the construct. Miwa et al. reported on their experience with posterior lumbar interbody fusions (PLIFs) to treat adjacent segment disease after a single level lumbar fusion and discovered that 44 % of these patients deteriorated again because of recurrent adjacent segment disease [15].

The use of a minimally invasive lateral interbody fusion for adjacent level disease and proximal junctional kyphosis affords the benefits of being a shorter duration surgery with less blood loss and almost no risk of spinal fluid leak (Fig. 24.1) [18–27]. Correction of sagittal imbalance can also be achieved utilizing lordotic cages.

24.2 Patient Selection

Patients who present with radiographic adjacent segment degeneration (adjacent segment disease) do not always necessitate reoperation. Only those who present with symptomatology such as neurological findings or axial pain are considered to have symptomatic adjacent segment disease. Presenting symptoms are the same as found in

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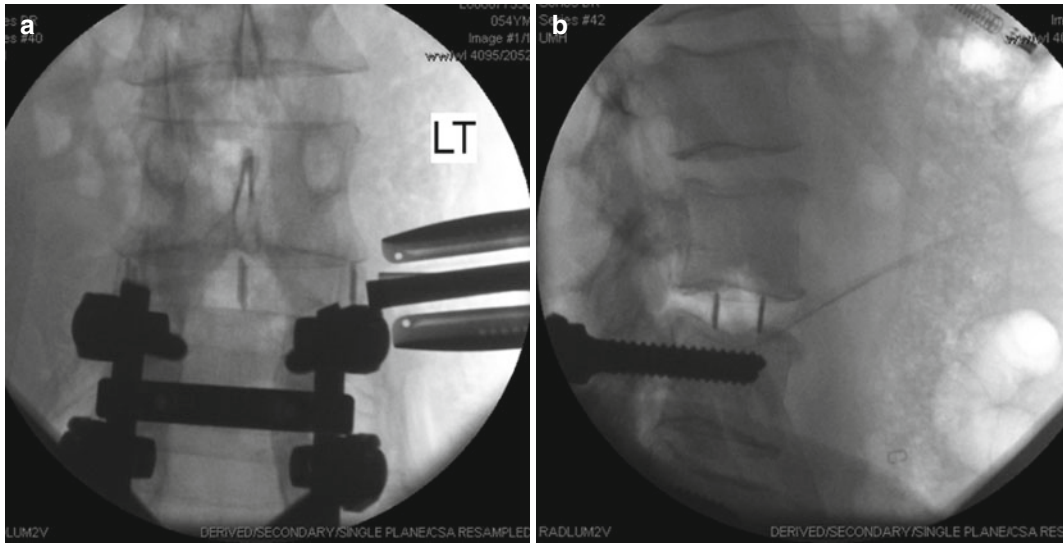


Fig. 24.1 (**a**) Intraoperative fluoroscopic images showing retractor placement at the adjacent level disk; (**b**) lateral fluoroscopic image showing excellent restoration of interbody height using a lateral cage

other degenerative processes of the lumbar spine and can include: radiculopathy, neurogenic claudication, weakness, and mechanical back pain. A thorough history and physical examination is used to determine if the patient's symptoms localize to the adjacent segments.

The initial work-up consists of plain radiographs: standing full spine and bending. These allow assessment of overall spinal balance and stability at adjacent segments. Given the increased forces exerted on adjacent segments, proximal junctional kyphosis can result from loss of disk height and progressive compression fractures of the vertebral body above or below the construct. A computed axial tomography (CT) scan can be obtained to assess the fusion mass at the previous operative site, as well as look for any hardware failure. Finally, a magnetic resonance image (MRI) is acquired to assess the neural elements. Occasionally, other studies are needed to enhance operative planning, such as electromyelography (EMG), bone densitometry (DEXA) scan, and diagnostic injections.

If the patient's symptomatology has been correlated with the adjacent pathology, an operative approach is tailored to the individual patient. The risk profiles of the lateral approach versus the posterior approach are inherently very different. The benefits and limitations of the lateral approach are discussed below. When deciding between the lateral approach and the more traditional posterior approach for adjacent segment disease, it is important to weigh the risks of each approach with the patient's overall goals and risk tolerance.

24.3 Benefits

The minimally invasive lateral approach has allowed for a direct route to the intervertebral disk without significant muscle dissection or blood loss. Patients with multiple medical comorbidities and the elderly can most benefit from this less invasive approach as operative time and hospital stay is significantly shortened [26]. There is also the added benefit to both the patient and the surgeon from not having to dissect through thick scar tissue to obtain decompression. Of note, the lateral approach relies upon an indirect decompression, which has been demonstrated to increase the neuroforamina by up to 57 % and area of the central canal by up to 143 % [28, 29]. This indirect decompression reduces the risk of a cerebrospinal fluid leak (CSF) and also avoids disrupting the posterior elements possibly preventing further adjacent segment degeneration (Fig. 24.2).

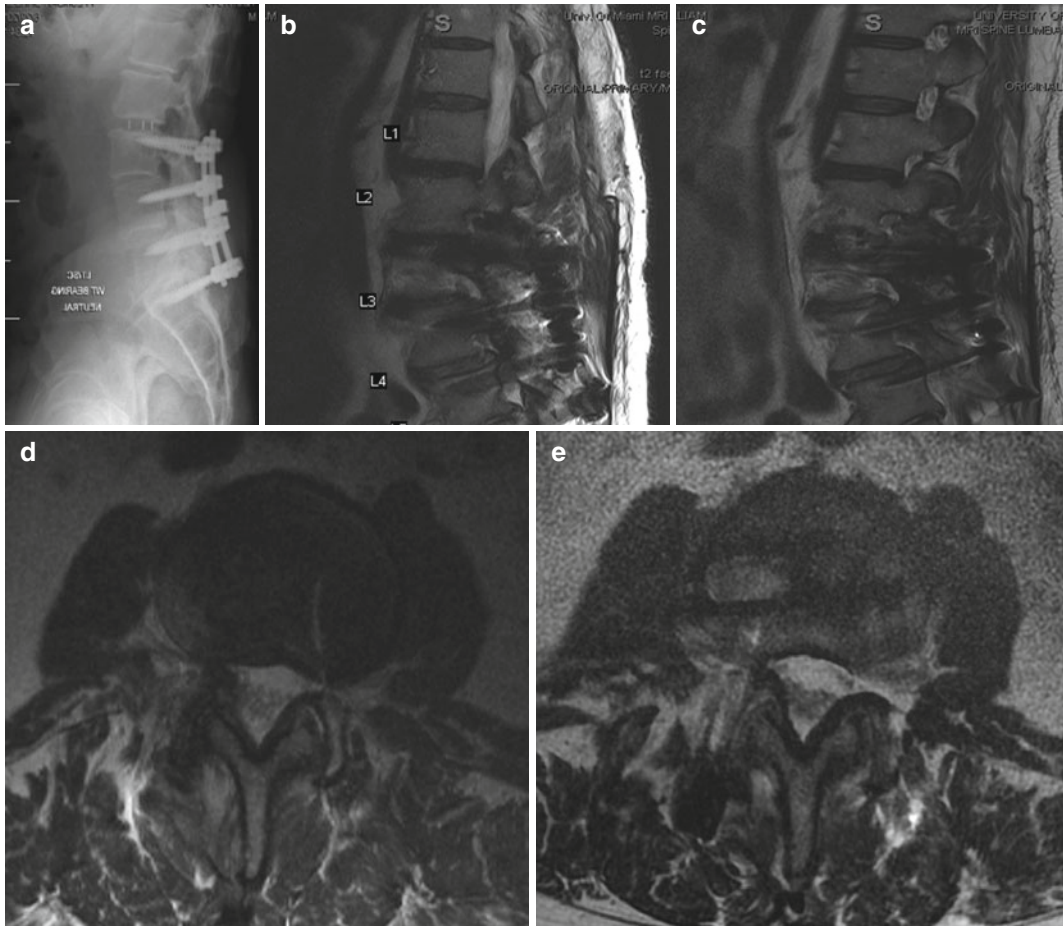


Fig. 24.2 Preoperative view showing a patient who successfully underwent an L3-S1 laminectomy with posterior instrumented fusion. (**a**) Parasagittal T2-weighted MRI image showing the neuroforamen (**b**) before and (**c**) after lateral interbody fusion. Axial T2-weighted MRI image at the adjacent treated level showing the spinal canal and lateral recesses (**d**) before and (**e**) after adjacent segment surgery

24.4 Limitations

As with any new technique, the lateral approach requires special training to become comfortable with the anatomy and nuances. Also, given the minimal opening, this technique is highly reliant upon fluoroscopy, increasing the patient and surgeon radiation exposure, especially during the early learning phase. Unfortunately, one of the more common locations for adjacent segment disease, L5/S1, is precluded from the lateral technique because of the iliac crest. Also, in some patients with a high crest, even L4/L5 is not accessible. One must evaluate the preoperative anterior-posterior (AP) imaging carefully to evaluate accessibility around the crest.

Previous abdominal surgery, while not an absolute contraindication to this technique, must be weighed carefully. Smaller abdominal surgeries can be avoided by entering on the contralateral side. However, larger abdominal or retroperitoneal surgeries with a high likelihood of scar tissue in the retroperitoneal space can significantly increase the risk of surgery especially if the vasculature is scarred down.

EMG monitoring has made this technique safer around the lumbar plexus. Occasionally, a patient will have a very anterior lumbar plexus as

evidenced by low stimulation thresholds with the dilators. In these instances, the lumbar plexus is swept posteriorly. Rarely, the plexus cannot be avoided and the procedure must be aborted. A meta-analysis of lumbar plexopathies following the lateral approach found that reporting of plexus injuries in the literature has been inconsistent with the incidence of motor weakness ranging from 0.7 to 33.6% [30]. There was a lack of consistency in the descriptions of lumbar plexopathies and a lack of diagnostic paradigms. The true incidence of plexus injury is unknown, and evolving techniques have likely diminished the incidence over time [31].

Dissecting through the psoas muscle can also lead to transient weakness in hip flexion and anterior thigh pain/numbness from tension on the genitofemoral nerve which lies on the surface of the psoas muscle [25]. Anatomic variants, which place the vasculature lateral relative to the vertebral body, should be excluded from the lateral approach if there is not enough room to safely perform the diskectomy and place a cage.

Finally, this technique relies upon an indirect decompression to relieve any neurological symptoms. Though rare, patients whose neurological symptoms are not relieved will still require a posterior decompression.

24.5 Surgical Technique

The lateral approach for adjacent segment pathology utilizes the same techniques described previously since the reoperation is across virgin tissue. Cages allowing for concomitant lateral screw placement must be carefully planned to avoid the adjacent screws. Supplementation with posterior instrumentation requires an open technique to attach on to the previous hardware. Wang et al. reported 21 consecutive cases of adjacent segment disease treated with a minimally invasive lateral interbody fusion without posterior instrumentation [27]. All of these patients had good fusion at last follow-up (Fig. 24.3).

Those patients with significant proximal junctional kyphosis require a more aggressively lordotic cage for restoring sagittal balance. By placing the retractor at the midpoint of the disk space, the soft tissue can be dissected anteriorly to expose the anterior longitudinal ligament (ALL). The ALL can then be opened which allows for placement of a hyperlordotic cage to correct positive sagittal balance [18, 19]. Then these patients are supplemented with posterior instrumentation and facetectomies; substantial sagittal restoration can be achieved.

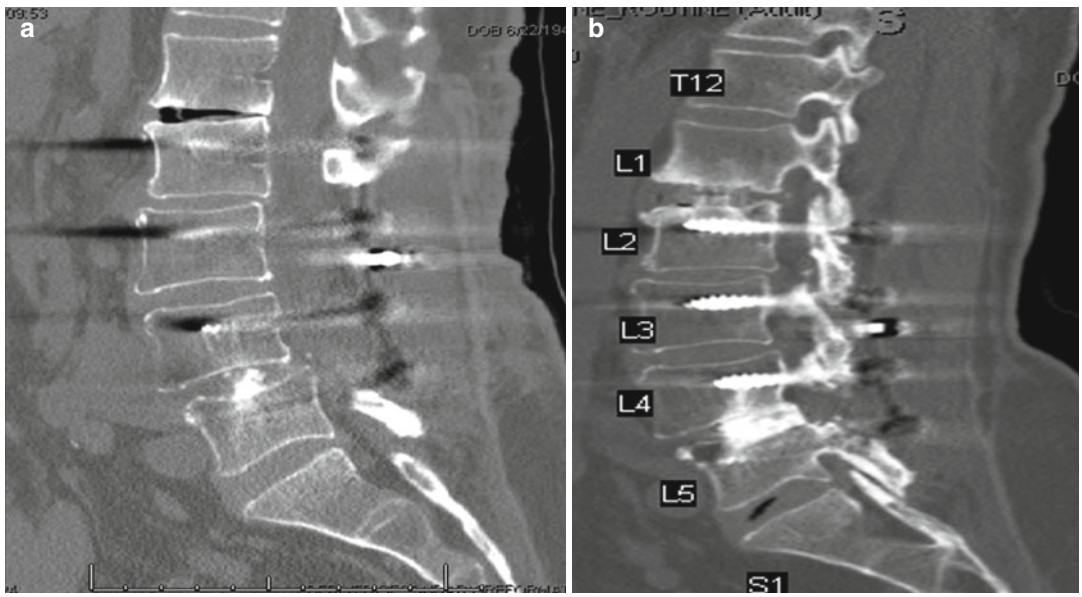


Fig. 24.3 (**a**) Preoperative and (**b**) postoperative sagitally reconstructed CT scan images showing increased interbody height and arthrodesis

24.6 Complication Avoidance

A thorough understanding of the risks unique to this approach and the best methods of complication avoidance are critical. The lateral approach requires entrance into the retroperitoneal space. As such, injury to the bowel is avoided by guiding the instruments to the disk space utilizing the two-finger technique to sweep away the abdominal contents as the dilators are directed to the disk space. Bowel injury can also be avoided by utilizing a mini-open technique for direct visualization of the peritoneum as the dilators are inserted.

Vascular injury can be avoided by carefully examining the relation of the vasculature to the disk space and psoas muscle on preoperative imaging. If there is not enough space to place a cage with a width of 18 mm, then the lateral approach is not an option. Also, entering on the left side is preferred if possible since it avoids the inferior vena cava, which is more vulnerable to injury and harder to repair than the aorta. Recognizing segmental branches and ligating them prior to incising the disk is critical to avoiding excessive blood loss.

The lumbar plexus is more posterior in the rostral lumbar spine. Since reoperation for adjacent segment disease is typically performed at the more rostral lumbar levels, injury to the plexus is much less likely. Techniques to even further lower this risk include shallow docking and an oblique lateral approach, which are discussed further in other chapters. Shallow docking can also be utilized, but frequently the psoas muscle is very thin at the upper lumbar regions.

24.7 Postoperative Care

Patients are generally sent home from the hospital in 1–3 days to ensure they can independently ambulate, void, eat, and pass flatus. In general, patients are placed in an external orthosis for up to 12 weeks, especially when there is no posterior supplementation. Strenuous activity and heavy lifting is avoided until fusion is documented.

The first follow-up visit at 6 weeks is to ensure proper wound healing and to evaluate on plain radiography that the alignment is stable. At the 3-month follow-up, dynamic radiographs or a CAT scan are obtained to ensure proper fusion has occurred. After the 6-month follow-up, the patient is usually followed as needed if symptoms have resolved.

At the level of T12/L1 or L1/L2, the thoracic cavity can also be entered. This engenders the risk of a pneumothorax. If the parietal pleura is encountered, care and attention must be taken to avoid a tension pneumothorax. The pleura can be stitched and repaired or a small chest tube inserted and managed in a very conservative manner.

Conclusions

There is a paucity of literature specifically evaluating the lateral interbody technique for adjacent segment disease. However, the benefits afforded by this technique, shorter length, reduced blood loss, lower CSF leak rate, and restoration of sagittal balance, are empirically very promising. Prospective studies evaluating the lateral approach versus posterior revision surgery for adjacent segment disease are needed to better delineate the benefits of this approach.

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Part V

Technical Nuances

25 Lateral Lumbar Interbody Fusion: A Review of the Current Clinical Outcomes of Different Supplemental Fixation Techniques

Fred Xavier, Brendon Walker, Tucker Callanan, Samuel Grinberg, Byung Jo Victor Yoon, Celeste Abjornson, and Frank P. Cammisa Jr.

25.1 Introduction

An average of 2 % of US workers are compensated for spinal disorders every year [1]. Back pain represents the second most common cause of visits to a physician but the most common one for reduced workforce among individuals younger than 45 years old [2–4]. Among the group of people who sought medical treatment, 78 % consulted their regular physicians, whereas 12 % rushed to the emergency room of a local healthcare facility. The financial burden of several hospital visits on the families and the overall society is enormous. In 2004, the direct annual medical costs were assumed to reach close to $ 200 billion [5].

The pathophysiology of low-back pain (LBP) is multifactorial. Disk degeneration is a leading cause of spinal instability and LBP. Senescence of the avascular nucleus pulposus with decreased transport of nutrients is thought to lead to degenerative disk diseases (DDD), intervertebral disk space narrowing, and osteophyte development. The intervertebral disk (IVD) loses its blood supply in the first decade of life [6, 7]. Moreover, aging and osteoporosis are also responsible for a substantial amount of axial bone mass loss resulting in osteoporosis-related fractures and spinal deformity [8–10]. The resulting pain and discomfort lead to disability and decreased quality of life. When conservative treatments fail to alleviate the recurrent symptoms, surgical procedures are advised.

Lumbar spinal interbody fusion surgeries have been performed for decades to treat patients with intractable LBP syndromes due to spinal instability, spondylosis, or spinal deformities [11]. Initially, bone autografts were harvested from the patient's body to fill the intervertebral disk space and restore the anatomical curvature while providing mechanical stability until bony fusion. Complications inherent to the bone graft biomechanics and the donor site morbidities have led to advanced research in biomaterials and the genesis of various alternatives such as allografts, metal cages, and poly-ether-ether-ketone (PEEK) cages [12–14]. More importantly, to achieve the optimal access to the anterior spinal column, several fixation techniques were developed over the years based on surgical approaches. This concept, with the primary goal of minimizing local tissue injuries, is critical to the postsurgical recovery, spinal stability, and overall functional success of the procedure.

Introduced by Cloward in 1953 [15, 16], the posterior lumbar interbody fusion (PLIF) offers great access for posterior instrumentation and the placement of interbody devices with good fusion rates [17–19]. However, PLIF is associated with

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extensive posterior musculature damages [20, 21] and iatrogenic neural injuries [22–24]. Anterior approaches (anterior lumbar interbody fusion – ALIF), described earlier (in 1948) by Lane and Moore [25], allow wider access to the anterior spinal column. They are also associated with more life-threatening complications, namely, injuries to major blood vessels [26, 27] and other internal organ damages [28, 29]. The lateral transpsoas approach (lateral lumbar interbody fusion – LLIF) reduces the neurovascular complications seen in the anterior and posterior ones. However, neuromonitoring practices are required for LLIF since this minimally invasive technique may add considerable compression to the surrounding lumbar plexus [30, 31].

Despite the numerous achievements of minimally invasive surgical approaches, optimal spinal stability relies on the ability of the implants to promote fusion between two or more adjacent vertebrae. Therefore, as done in both anterior and posterior approaches, laterally inserted cages are often reinforced with supplemental fixation. These additional devices include pedicle screws, integrated screws, anterior plates, and interspinous process implants. Several authors reported that supplemental fixation techniques provide additional segmental rigidity to aid the fusion process and prevent cage migration [32]. This current review intends to explore the literature available on the most common devices and procedures used to enhance the biomechanical stability of the LLIF surgeries.

25.2 Pedicle Screw Supplemental Fixation

By preserving the surrounding soft tissues, standalone lumbar interbody implants placed via lateral approaches reduce the range of motion more than those from anterior and posterior techniques [33]. Still, Watkins et al. [34] found that the nonunion rate was higher with uninstrumented LLIF in comparison to other modern fusion techniques. Cappuccino et al. [11] found that LLIF with supplemental fixation decreased the range of motion more than stand-alone LLIF did. Supplemental fixation provides increased stability that is needed to ensure sufficient rigidity for the fusion process to occur [35].

Currently, the "gold standard" for supplemental fixation with LLIF is a bilateral pedicle screw construct [36]. After the LLIF, the patient is either repositioned for the posterior fixation or the procedure is performed a few days after. Using bilateral pedicle screws requires a more invasive operation than a stand-alone LLIF or an LLIF with other forms of supplemental fixation. However, numerous biomechanical studies have shown that bilateral pedicle instrumentation provides the greatest reduction in range of motion in all directions [11, 35, 36]. Dougleris et al. [36] compared bilateral pedicle screw stabilization to an interspinous fusion device and found that the two are similar except that the bilateral screws provide greater coronal rigidity. In their biomechanical testing of cadaveric spines, Cappuccino et al. [11] saw greater range of motion reduction after LLIF with bilateral pedicle screws than with either stand-alone implants or lateral plates.

Clinical studies have confirmed the efficacy of bilateral screws but have shown that unilateral screw fixation can also be an effective alternative to bilateral screws. Sharma et al. [37] examined the outcomes of LLIF after 1 year. Unilateral screw fixation and bilateral screw fixation were both included in their study. They found significant improvements in the patients' VAS (visual analog score), ODI (Oswestry Disability Index), and SF-12 (short form-12) physical component scores. Moreover, the LLIF procedure with pedicle screw fixation was successful in restoring lumbar lordosis and correcting scoliosis in affected patients. Similarly, Kotwal et al. [38] reviewed the clinical and radiographic outcomes of LLIF after at least 2 years. One-, two-, three-, and four-level procedures were performed between T12 and L5. Of the 118 patients, 102 received posterior instrumentation. Except for the lordotic angle at T12–L1, there was significant restoration and correction of disk height, coronal angulation, and the lordotic angle at all surgical levels. In patients with degenerative

scoliosis, Cobb angles were also improved. VAS, ODI, and SF-12 physical component scores all showed significant improvement. Pawar et al. [39] compared patients receiving LLIF with either unilateral or bilateral fixation to patients receiving PLIF and found that LLIF with posterior screw fixation resulted in lower estimated blood loss (EBL), fewer surgical complications, and better radiographic outcomes than PLIF [39].

Several studies have also specifically compared unilateral to bilateral screw instrumentation. Using the transforaminal lumbar interbody fusion (TLIF) procedure, Chen et al. [40] compared bilateral and unilateral pedicle screw fixation in one-level fusions and found that there was no significant difference between the clinical outcomes of the two groups after 2 years. Furthermore, the unilateral fixation was associated with shorter surgical time, less EBL, and a faster recovery. Molinari et al. [41] performed a review of numerous studies that compared unilateral and bilateral pedicle screw fixation and found that the fusion rates when using unilateral and bilateral pedicle screw fixation are high and not significantly different. Since the clinical results between the unilateral and bilateral procedures are similar, the less invasive unilateral procedure as a supplement to LLIF may be a more effective option in certain cases.

25.2.1 Case Example

The patient was a 60-year-old male with severe low-back and right leg pain and weakness in the right leg and foot. He previously had a laminectomy at the L4–L5 level that provided about two and a half years of relief. Physical therapy exacerbated his symptoms, and epidural steroid injections failed to provide relief. Figures 25.1 and 25.2 display his preoperative images, which show lumbar (L4–L5) spinal and right foraminal stenoses, degenerative spondylolisthesis, lumbar radiculopathy, and a bilateral synovial cyst at L4–L5. A one-level LLIF procedure was performed. Immediately following the LLIF, the patient underwent a spinal decompression, excision of the synovial cyst, and posterior bilateral fusion with bilateral pedicle screws. One year after surgery, the patient reported a significant

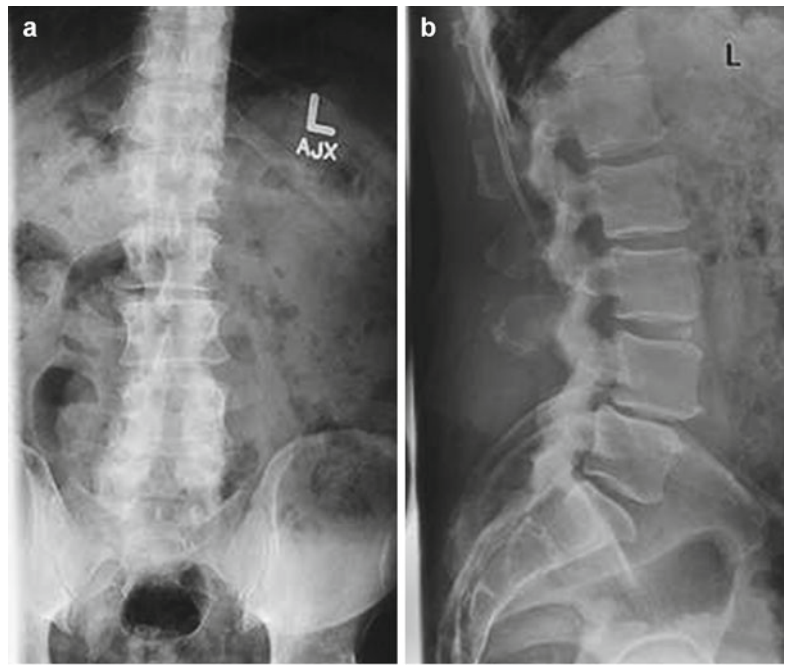


Fig. 25.1 Preoperative radiographs. (**a**) AP, (**b**) lateral, (**c**) extension, and (**d**) flexion

Fig. 25.1 (continued)

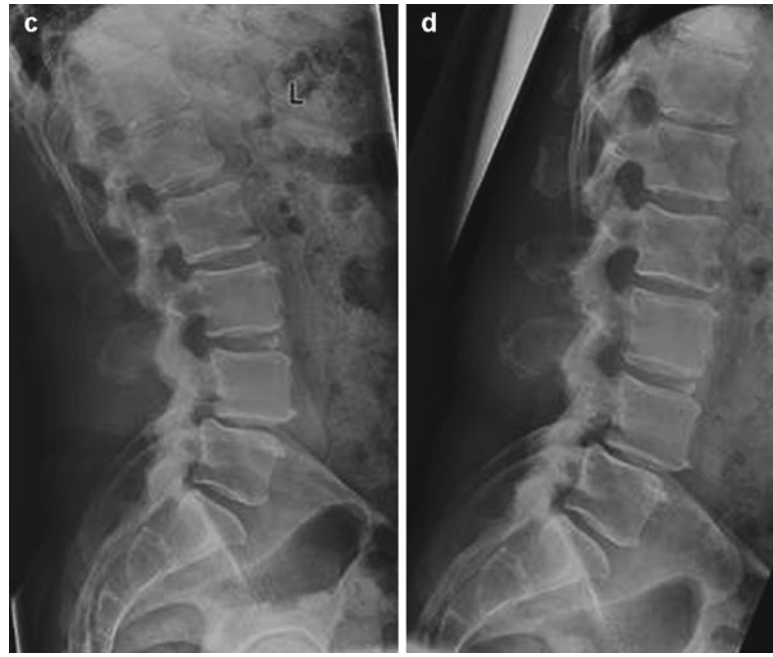




Fig. 25.2 Preoperative sagittal MRI

improvement in all of his preoperative symptoms. Postoperative radiographs (Fig. 25.3) showed solid fusion at L4–L5 with reduced motion in both flexion and extension.

25.3 Interspinous Fusion

Interspinous fusion devices are being evaluated as an alternative to bilateral and unilateral pedicle screw constructs in augmenting lumbar interbody fusion rates. The devices are designed to take advantage of the biomechanical loading processes of the posterior aspect of the vertebral column in order to immobilize the affected segment, thus stabilizing the spine. The interspinous devices are intended to create construct stability comparable to pedicle screws, while being less invasive, therefore reducing blood loss, risk of infection, and postoperative muscle pain [42–45]. In contrast to interspinous process devices (IPDs), which primarily work as stand-alone decompressive materials (i.e., X-STOP), interspinous fusion devices (IFDs) are designed for fixation and fusion. Early attempts at interspinous fusion failed, as the pilot implants had a small surface area with the spinous processes, meaning all of the force due to the axial load of the superior spine was applied on a small area. Contemporary devices include paired plates with teeth or U-shaped device with wings that attach to the spinous process [46].

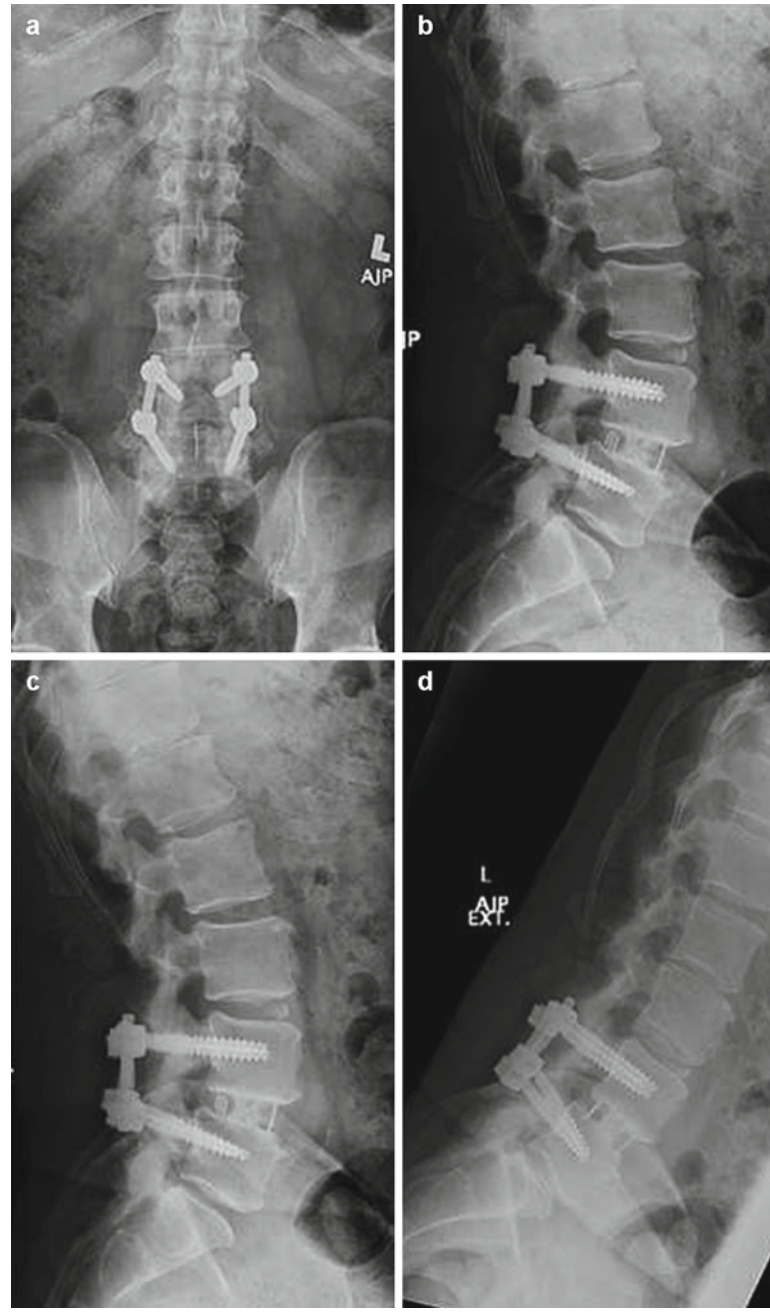
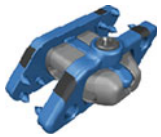


Fig. 25.3 Postoperative radiographs. (**a**) AP, (**b**) lateral, (**c**) extension, and (**d**) flexion

The US Food and Drug Administration (FDA) have approved a significant number of IFDs (Table 25.1). Despite the fact that they are composed of different designs and materials, they share similar indications and implantation techniques with the aim of maintaining a constant degree of distraction between the spinous processes and stabilize the spine in a minimally invasive manner [46]. As per 510 (k) premarket notifications, the indications for the use of these devices are to achieve supplemental fusion in the following conditions: degenerative disk disease (defined as back pain of discogenic origin with degeneration of the disk confirmed by history and

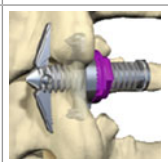
Table 25.1 Partial list of interspinous fixation devices that have received clearance to market by the FDA

#	Name	Company	510 (K) approval	Image	Material	Testing performed	Clinical study?	Additional
1	Spire™	Medtronic	November 2004		Titanium	Cadaver testing: ±6.0 Nm nondestructive quasi-static loading in axial rotation, flexion/extension, and lateral bending with a constant displacement/ rotation rate	X	Intended for use with autograft and/ or allograft. For single use only
2	PrimaLOK™	OsteoMed	August 2010		Titanium alloy	Static: compression, tension, and torsion Dynamic: compression and torsion	X	Intended for use at one level, with bone graft material
3	Inspan™	Spine frontier	September 2010		Titanium alloy	Static: compression and torsion Dynamic: compression and torsion	X	Intended for use with bone graft material
4	Axle™	X-spine	November 2010		Titanium alloy and PEEK	Cadaver testing Static: compression Bending, torsion Fatigue compression bending		Intended for use with bone graft material
5	SP-Fix™	Globus	January 2011		Titanium alloy and PEEK	Static: compression, torsion, plate dissociation, and tension Dynamic: compression and plate dissociation		Intended for single level with bone graft material

6	BacFuse®	Pioneer surgical	March 2011		Titanium alloy	Static: compression, tension, torsion, locking mechanism Dynamic: flexion, extension, locking mechanism		For use at a single level. Intended for use with bone graft material
7	BridgePoint™	Alphatec	June 2011		Titanium	Cadaver testing Static and fatigue performance characteristics		Window allows for bone graft placement. Telegraphing plates allow for extension or compression
8	Octave™	Life spine	November 2011	Unavailable	Titanium alloy	Static: axial compression, torsion, axial pullout, axial grip strength Dynamic: axial compression		Intended for use with bone graft material. Single-level use only
9	Coflex-F®	Paradigm spine	February 2012		Titanium Alloy	Cadaver testing. Static: compression, rotation/torsion Dynamic: compression, tension	X	Intended for use at a single level
10	Aileron™	Life spine	March 2012		Titanium	Static: axial grip Engineering analysis, compression Dynamic: compression		Intended for use with bone graft material. Single-level use only

(continued)

Table 25.1 (continued)

#	Name	Company	510 (K) approval	Image	Material	Testing performed	Clinical study?	Additional
11	Aspen™	Lanx, acquired by BioMet	September 2012		Titanium	Cadaver testing Static: compression bending, torsion Fatigue compression bending	X	Intended for use with or without bone graft material
12	Interbridge	LDR spine	March 2013	Unavailable	Titanium	Static: axial, torsion, compression, pullout resistance, plate dissociation Dynamic: axial compression bending		Intended for single-level use only
13	Affix™	NcixuVasive	July 2013		Titanium	Static: axial compression, torsion, post distraction Dynamic: axial compression	In progress	The FDA issued a warning letter for selling the device for uses not approved by its 510 (k) clearance [7]
14	Zip Mis	Aurora spine	November 2013		Titanium alloy	Static: compression bending, torsion Dynamic: compression bending	X	Intended for use with bone graft material
15	Minuteman™	Spinal simplicity	August 2015		Titanium alloy with hydroxyapatite coating	Static: shear strength Tensile strength Solubility, dissolution products and rates, XRD pattern, and FTIR spectra	Recruiting	Can be placed under fluoroscopy through lateral or posterior MIS approach. Intended for use with bone graft material. Single-level use only

Information retrieved from device 510 (k) summary when possible. References for images included below

radiographic studies), spondylolisthesis, trauma (i.e., fracture or dislocation), and/or tumor (510 K doc). These devices can be used in elderly patients or those with bone quality too poor for pedicle screw instrumentation. The vast majority of devices are implanted via a midline incision followed by muscle dissection lateral to the supraspinous ligament. The paraspinal muscles are then stripped off the laminae, and the interspinous ligament is sacrificed. Before implantation, a microsurgical decompression is performed (per manufacturer instruction manual).

Currently, 15 IFDs have received clearance to market by the FDA. There are numerous designs to these implants as shown in Table 25.1, but each device claims the same advantages over the pedicle screw fixation including reduced risk of cerebrospinal fluid leakage and nerve damage, less muscle dissection and intraoperative estimated blood loss, shorter hospital stay and rehabilitation period, and reversibility of the surgical procedure that does not limit future surgical treatment options [47].

In contrast, while biomechanical studies indicate that IFDs may be similar to pedicle screw-rod constructs in limiting the range of flexion-extension, they may be less effective in reducing axial rotation and lateral bending [48]. Also, there is a potential for a negative impact on the interbody cage and bone graft due to focal kyphosis resulting from the interspinous device [48]. Due to the lack of long-term clinical studies and these uncertainties, further prospective clinical studies are needed to compare the functional outcomes between interspinous fusion devices and pedicle screw constructs.

25.3.1 Case Example

A 51-year-old male presented with worsening low-back and leg pain and paresthesia in his feet. He attempted multiple forms of conservative treatment including physical therapy, epidural steroid injections, acupuncture, and massage without significant relief of his symptoms. Figure 25.4 displays his preoperative plain radiographs, which confirm the presence of degenerative disk disease with narrowing at L4–L5, anterior and posterior osteophytes, and mild degenerative retrospondylolisthesis. A one-level X-LIF procedure and posterior bilateral fusion at L4–L5 with Coflex-F® stabilization were performed. Eleven months postoperatively, the patient reported complete improvement of his preoperative symptoms. Postoperative radiographs (Fig. 25.5), performed 11 months after surgery, demonstrated fusion at L4–L5, increased disk and foraminal height, and no motion with flexion.

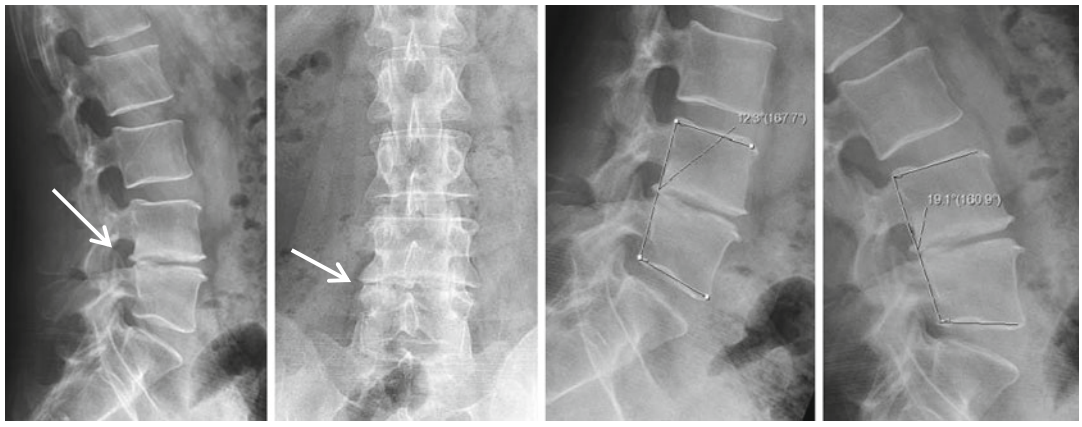


Fig. 25.4 Preoperative radiographic images of a 51-year-old male. From *left* to *right*: lateral view, AP, flexion, and extension. The flexion image shows a Cobb angle of 12.3°, whereas the extension shows a Cobb angle of 19.1°

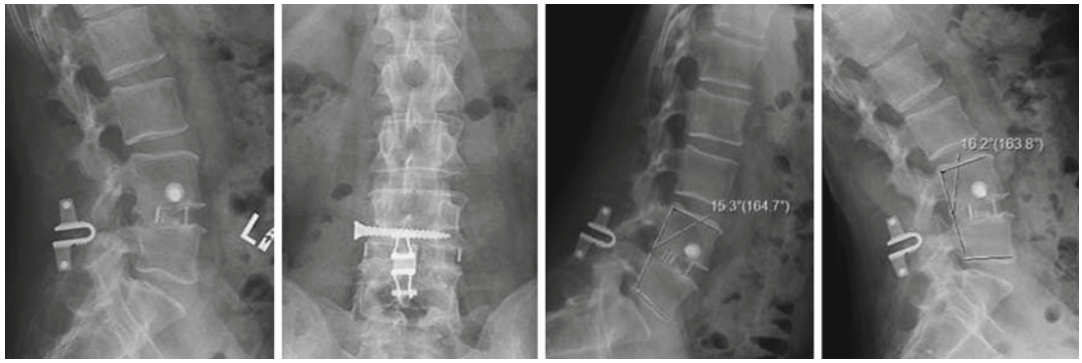


Fig. 25.5 Radiographic images at 11 month post-surgery. From *left* to *right*: lateral view, AP, flexion, and extension. A one-level X-LIF procedure and posterior bilateral fusion at L4–L5 with Coflex-F® stabilization was performed. Cobb angle in the flexion image (15.3°) is less than 1°, and then the Cobb angle in the extension image (16.2°) confirming the procedure decreased motion

25.4 Integrated Fixation Fusion

The combination of fixation integrated into interbody fusion cages provides greater segmental rigidity and more physiologic loading through the segment, promoting optimal stability. Although integrated designs are used extensively in anteriorly placed cages both in lumbar and cervical, there are possible drawbacks associated with the introduction of these supplemental devices from a lateral approach. Screw angle, screw fixation, and plate designs are quite different than an anterior approach. However, additional surgical approaches may lead to prolonged operating time, larger skin incisions, soft tissue injuries, and higher infection rates. Certain authors reported screw or plate dislodgments, higher incidences of adjacent level degenerations, and heterotrophic ossifications [49] in multiple approach procedures. If sufficient stabilization can be achieved in a single approach without supplemental fixation from a secondary approach, then it may avoid such adverse effects resulting from additional posterior surgery and minimize the hospitalization time. Integrated fixation cages are a recently developed technology to reduce adverse effects from procedures involving interbody fusion cages.

Integrated fixation cages (IFCs) are designed with screws incorporated into the cages. These screws are often inserted at an angle through the front face of the cage, drilling through the vertebral end plate into the vertebral body. The stand-alone design of IFCs allows the device to be lower profile than traditional cages with supplemental screws or plates by minimizing the number of implanted devices. The reduced exposure can potentially lower the rate of complications and morbidity. The pioneering design of what is now known as IFCs was that of the Hartshill horseshoe by John Dove in 1987 [32]. Numerous IFC designs have been developed since then.

IFCs have different characteristics of stability and fixation strength as compared with traditional cages with supplemental fixation. For example, screws used in IFC implants have different insertion location and trajectory than screws of traditional supplemental fixation devices such as anterior plating [50]. Additionally, the performance of IFCs is highly dependent on how well the device interfaces with the surrounding environment. Specifically, screw fixation strength in IFCs relies on the quantity and quality of trabecular bone and end plate [51]. In fact, cadaveric biomechanical studies have demonstrated that stand-alone IFCs and supplemental fixation through plates show similar fixation behavior [50, 52, 53]. Clinical data to confidently support IFCs' efficacy is lacking due to the recent nature of the device, but the available evidence shows promise. These results indicate that no significant difference was observed between stand-alone IFC cases

and traditional supplemental fixation cases in the range of motion and intervertebral foraminal height post-surgery [49, 54, 55]. Further data are needed to conclude IFCs' efficacy, but eliminating additional surgery and supplemental fixation is a considerable achievement.

25.5 Simultaneous Combined Anterior and Posterior Fusion

O'Brien performed the simultaneous combined anterior and posterior fusion for the first time in 1960 [56]. More than 20 years later, he reported results from 150 individuals treated with the joint procedure. An average of 86 % of the patients showed general improvement, while 60 % were significantly improved [56]. Other surgeons published satisfactory data making it a well-established technique in current lumbar surgery with excellent clinical and radiological outcomes [57–60]. Kozak et al. [61] operated on 69 patients who received the simultaneous combined anterior and posterior fusion for disabling LBP. After an average follow-up of 2.5 years, the fusion rates were over 90 % for one- and two-level fusions, whereas the three-level cases produced 77.8 % success [61]. In a prospective study, Finn et al. [62] used and compared the standard PLIF with the combined ALIF plus PLIF. Although both techniques showed good results, there was a trend for a better overall functional outcome for patients treated with the combined version. Furthermore, they observed significantly higher fusion rates in the combined group [62]. In summary, according to the previous authors, one can conclude that the combined procedure could be performed safely in an acceptable time if surgeons are properly trained [61, 62].

Conclusion

Low-back pain is reasonably prevalent among the working population of the USA. This chapter reviewed various methods for lateral lumbar interbody fusion. Pedicle screw or plating devices have been shown to be useful supplemental devices in LLIF surgeries. When considering interspinous devices for spinal fusion (IFDs), physicians must remember that, while requiring less muscle dissection, these implants might also provide less restriction of axial rotation and lateral flexion than either unilateral or bilateral screw fixation. Integrated fixation cages (IFCs) have an overall lower profile than other fixation alternatives. This characteristic reduces the risk of both complications secondary to the therapeutic device, as well as the risk of mortality. However, the performance of these devices can vary significantly as screw fixation strength in IFCs is dependent on both the quantity and quality of trabecular bone and end plate. Although some studies support the use of IFCs, they are still relatively new with a small body of clinical evidence to support their efficacy. Due to the lack of research, further prospective clinical studies are necessary to compare the long-term functional outcomes of these novel techniques and devices.

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Anterolateral Fixation in LLIF

26

Gregory M. Malham, Rhiannon M. Parker, and Kevin A. Seex

26.1 Introduction

Lateral lumbar interbody fusion (LLIF) is a procedure for anterior interbody fusion through a 90° lateral retroperitoneal, transpsoas corridor with the introduction of a wide footprint interbody cage for immediate significant segmental stability. The large LLIF cage optimizes cage-endplate interface, restores disc height, and provides indirect neural decompression and correction of sagittal/coronal deformity [1]. In conventional anterior [anterior lumbar interbody fusion (ALIF)] or posterior [posterior or transforaminal lumbar interbody fusion (PLIF/TLIF)] approaches for interbody fusion, supplemental fixation is required as the approach resects important stabilizing structures of the spine [2]. These include the anterior +/− posterior longitudinal ligaments (ALL/PLL) in ALIF, and the facet joints, pars interarticularis, or posterior ligaments in both PLIF and TLIF. These structures are preserved and placed under tension in LLIF, leading to improved stability of the spinal segment [3, 4].

Supplemental fixation is indicated in LLIF for three main reasons: to avoid subsidence, add stability, or correct deformity.

Three questions:

1. *Why* is supplemental fixation needed?
2. *When* should supplemental fixation be used?
3. *Which* supplemental fixation option is best for the clinical situation?

26.2 Why? The Benefits of Supplemental Fixation

Insertion of a lateral interbody cage immediately improves the mechanical stability of the spinal segment even without supplemental fixation. This can be supported by external orthotics alone, but supplemental internal fixation provides higher fusion rates, facilitates deformity correction, and maintains correction until fusion [5]. Importantly, fixation reduces the risk of cage subsidence that can have serious consequences including loss of indirect decompression requiring revision surgery.

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26.3 When? The Indications for Supplemental Fixation

Factors influencing the need for supplemental lateral or posterior fixation in LLIF include bone density, degree of facet arthropathy, coronal or sagittal imbalance, radiographic or clinical instability, pars defects, spondylolisthesis, cage width, number of proposed levels, presence of an adjacent fusion [5], intraoperative vertebral endplate injury during cage insertion or endplate preparation, and planned or unplanned ALL rupture. An algorithm indicating the need for supplemental fixation with bilateral pedicle screws is shown in Fig. 26.1.

26.3.1 Reduced Bone Density

Reduced bone density is the main risk factor for subsidence that may result in the loss of indirect decompression and deformity correction. Both osteopenia and osteoporosis are strong indications for bilateral pedicle screws [6]. Cement augmentation of the vertebral body is a useful technique by direct vertebral injection or via the pedicle. This provides resistance to subsidence and screw pull out and can be used to prevent adjacent segment collapse.

26.3.2 Facet Arthropathy

Facet disease is graded by CT as 0 (normal), 1 (mild), 2 (moderate), and 3 (severe) [7].

If facet arthropathy is present (≥ grade 2), additional fixation is indicated regardless of any other factor [5], unless the joints are clearly ankylosed. Degeneration in the lumbar facet joints is important because moderate or severe degeneration indicates excessive loading or motion on these joints. Patients with symptomatic facet disease require supplemental posterior fixation for immediate pain relief.

26.3.3 Deformity

LLIF is a powerful tool in the correction of sagittal or coronal imbalance, scoliosis, and spondylolisthesis. Coronal imbalance due to asymmetrical disc heights may be restored easily with lateral cages, but still requires supplemental fixation to maintain correction. Supplemental fixation in LLIF augments deformity correction and maintains alignment until fusion, with bilateral pedicle screws remaining the fixation of choice.

26.3.4 Instability

Radiographic instability can be defined on standing lateral flexion and extension x-rays as having >3 mm difference and >11° of angular difference [8]. Clinical instability may manifest as mechanical pain and should question the integrity of the facet joints, especially in patients who have undergone prior surgery.

26.3.5 Pars Defects

Pars interarticularis defects at the level of LLIF warrant pedicle screws independent of the presence of spondylolisthesis.

26.3.6 Cage Width and Levels

Wider cages (22 mm or 26 mm) provide substantially more stability than the earlier narrow cages (18 mm), with reduced subsidence rates since the introduction of wider cages [9]. Supplemental posterior fixation is recommended with 18 mm cages.

One- and two-level LLIF can be performed with wider stand-alone cages [5]; however, supplemental fixation is recommended for three or more levels of lateral cages, although evidence for these preferences is limited.

26.3.7 Adjacent Segment Disease

Assessment of sagittal balance in adjacent segment disease (ASD) is important in planning supplemental fixation. Symptomatic ASD below a prior fusion, treated with a LLIF, must be stabilized with pedicle screws given the high biomechanical stressors involved and the risk of resultant nonunion.

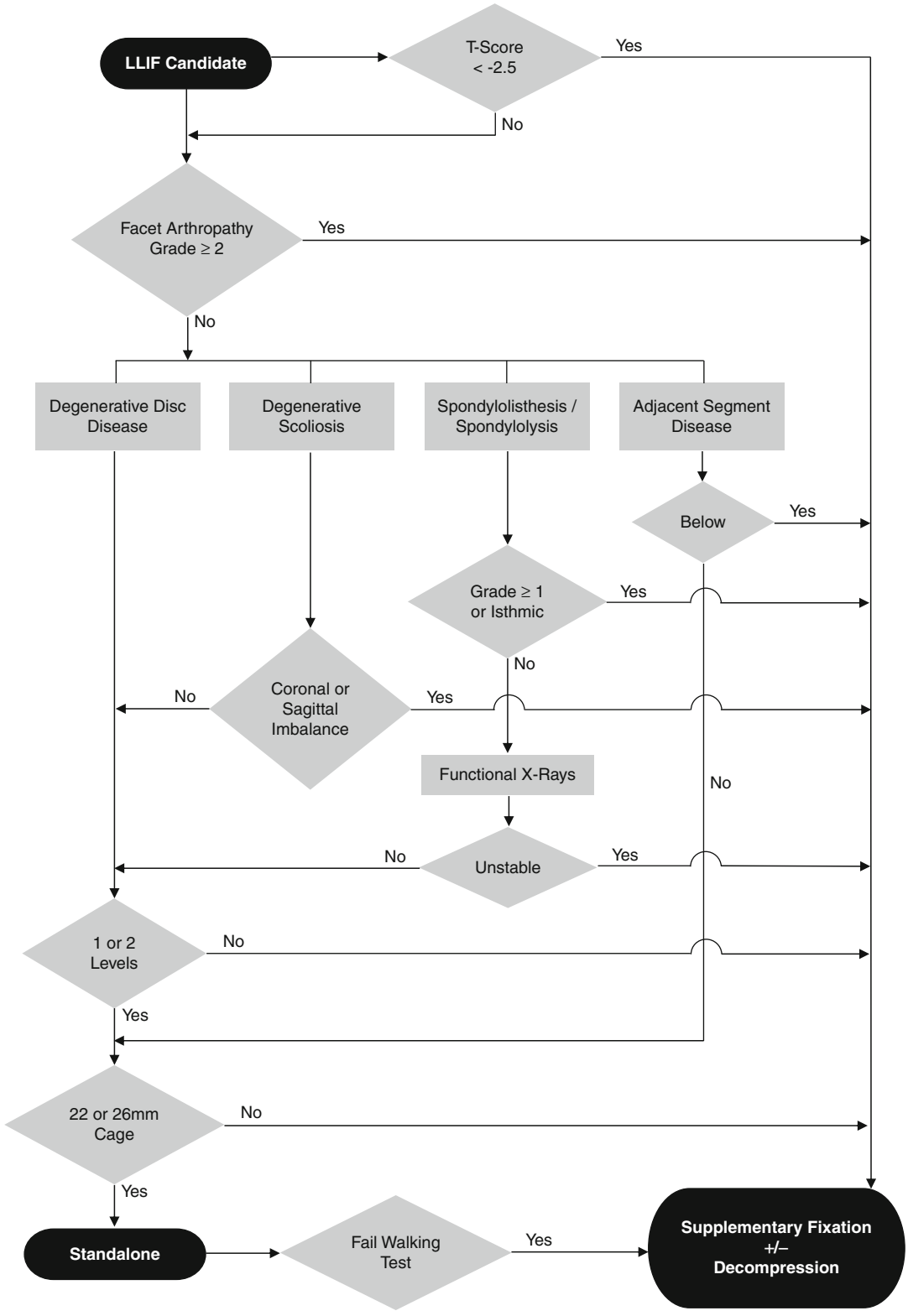


Fig. 26.1 Algorithm for supplemental fixation (Adapted from Malham et al. [5])

Above a prior fusion, a wide stand-alone lateral cage can be considered, but only if the spine is in sagittal balance. A lateral plate with an interspinous clamp is also a reasonable option in a balanced spine and avoids dealing with preexisting hardware.

26.3.8 Previous Surgery

Prior microdiscectomy or laminectomy at the target LLIF warrants assessment of facet joint compromise and spinous process removal but does not necessarily mandate supplemental fixation.

26.3.9 Intraoperative Vertebral Endplate Injury

Endplate injuries recognized during surgery or identified on the early postoperative imaging warrants pedicle screw fixation to reduce subsidence.

26.3.10 Planned Section or Unplanned ALL Rupture

With planned section of the ALL, cages with integrated screws are used to secure the cage prior to posterior bilateral pedicle screw fixation [10, 11]. Unplanned ALL rupture, often detected by an audible snap during trial or cage placement, should be treated the same, but if integrated cages are not available, the salvage is a PLIF/TLIF to avoid anterior cage migration.

26.4 Which? Fixation Options in LLIF

Biomechanical data indicates improved stability of the spinal segment with lateral fixation, posterior fixation, or both [3, 4].

26.4.1 Lateral Fixation

Separate lateral plates or integrated cage-screw devices restrict axial rotation and lateral bending, with less rigidity in flexion and extension than posterior fixation. A 4-screw plate is more rigid than a 2-screw plate in all motion planes but is technically challenging to insert without psoas trauma. The integrated cage with 1- or 2-screw fixation limits cage migration after ALL disruption. The advantages of lateral fixation on its own are that it reduces operating time and avoids patient repositioning for posterior fixation (Fig. 26.2).

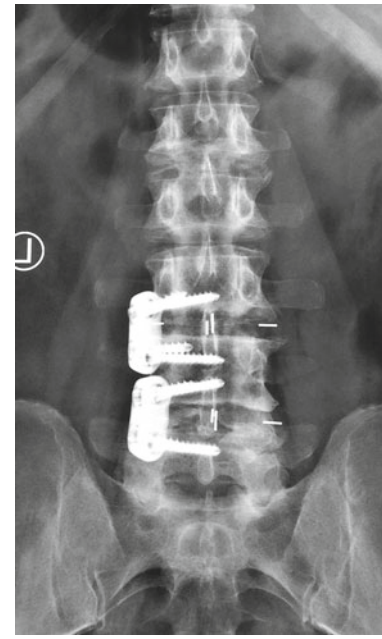


Fig. 26.2 Lateral fixation

26.4.2 Posterior Fixation

Posterior fixation constructs provide substantial rigidity to the segment in all planes – axial, coronal, and especially sagittal. Posterior fixation also maintains segmental lordosis. Percutaneous screws add 1° of lordosis, while open screws allow the option for osteotomies for increased sagittal correction [5, 8]. Repositioning in the prone position may also increase lordosis after lateral cage insertion. Importantly, pedicle screws protect against cage subsidence and improve interbody fusion rates. Bilateral pedicle screws remain the fixation of choice where stability is a concern and are the standard against which other fixations are judged.



Fig. 26.3 Bilateral pedicle screw-rod construct

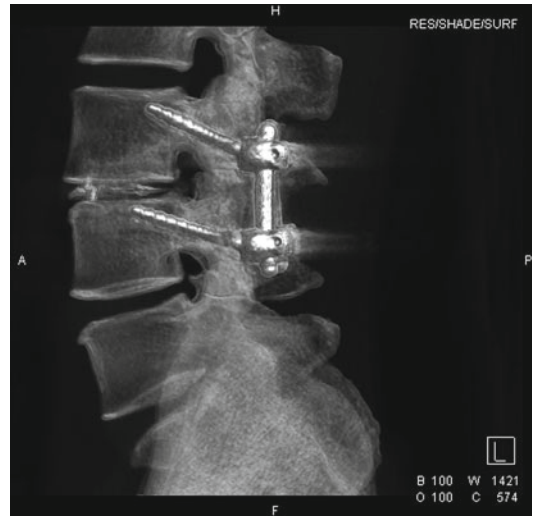


Fig. 26.4 Transcortical screws

Technique options:

(i) *Pedicle screws*
Bilateral pedicle screw-rod constructs provide the most rigid biomechanical fixation via a traditional midline or bilateral paramedian muscle-splitting (Wiltse) incision [4]. However, placement of the contralateral lower screws in the lateral position raises sterility concerns and is technically challenging. Insertion of bilateral pedicle screws is easier in the prone position, but this necessitates repositioning the patient. Hence, unilateral pedicle screws inserted in the lateral position are an option, but rigidity is reduced in all planes, especially axial rotation, and anecdotally promotes ipsilateral unilateral fusion (Fig. 26.3).

(ii) *Facet screws*
Transfacet screws inserted via a small midline incision, under fluoroscopy, provide rigidity comparable to bilateral pedicle screws [12].

(iii) *Cortical screws*
Transcortical screws provide similar biomechanical rigidity to bilateral pedicle screws despite a smaller diameter screw. They are inserted from a midline approach with less muscle retraction than for open pedicle screws and medial to superolateral screw orientation. Entering the cortical bone of the pars, these screws have high pull out strength in patients with reduced bone density [13] (Fig. 26.4).

(iv) *Interspinous clamps*
Of the fixation options available, interspinous clamps offer the most technically straightforward insertion via a small midline incision in patients with intact spinous processes. They can be performed in a lateral or prone position to effectively resist flexion-extension, but have limited stability in axial rotation and lateral bending [14]. Thus, in partnership with a lateral plate, addressing each other's relative weakness, together they provide rigidity comparable to bilateral pedicle screws.

26.4.3 Combination Lateral and Posterior Fixation

Combined constructs such as a lateral plate plus contralateral unilateral pedicle screws or a lateral plate with an interspinous clamp can be placed in the lateral position to provide similar stability to bilateral pedicle screws without repositioning the patient. Other combinations are possible and reasonable.

Conclusion

Supplementary fixation is indicated for three main reasons in LLIF: to avoid subsidence, to provide more stability, or to correct deformity. Instrumentation is recommended in all patients with osteoporosis, radiographic or clinical instability, and intraoperative unplanned events such as endplate injury or ALL rupture. However, there is no comparative clinical data on the multiple fixation options. Biomechanical cadaveric studies comparing stability of constructs may not predict the longevity required to complete fusion nor have they been shown to correlate with clinical outcome. Thus, until there is more evidence, the default supplemental fixation remains bilateral pedicle screws.

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Anterior Column Realignment

27

Juan S. Uribe, Chun-Po Yen, and Joshua M. Beckman

27.1 Introduction

The lateral retroperitoneal approach offers unique access to the lumbar spine, specifically the anterior spinal column. This approach provides a direct corridor with minimal tissue disruption for a more substantial correction of sagittal, rotary, and coronal deformities when compared to traditional posterior techniques [20, 23]. Previously, the amount of segmental lordosis achieved with single or multilevel lateral interbody fusions was limited by the anterior longitudinal ligament (ALL). This drawback was circumvented with the introduction of the anterior column realignment (ACR), which allows the vertebrae to "fish-mouth" open. This technique permits a significant amount of lordosis correction while maintaining indirect decompression of the foramen and is only limited by the shingling effects of the posterior elements.

Anterior column realignment (ACR) is a relatively new, minimally invasive technique for treating sagittal imbalance [9, 10]. The ACR procedure involves a lateral transpsoas approach to perform a complete discectomy and deliberate release of the anterior longitudinal ligament and annulus. Hyperlordotic interbody cages are then placed and fixed with either 20 or 30° of lordosis. The procedure is completed by placing posterior instrumentation for stabilization or further correction of sagittal plane deformity, using either MIS or open techniques, depending on the desired posterior release, surgeon preference, and experience.

In this chapter, relevant regional anatomy, degree of sagittal correction, surgical technique, applications, and potential complications will be discussed. Sectioning of the ALL (also known as the ACR) is a highly advanced lateral technique and should only be performed by surgeons who are experts in both minimally invasive (MIS) and lateral surgery. The surgeon is working in very close proximity to both the inferior vena cava/iliac veins and the abdominal aorta/iliac arteries. A complication can be potentially fatal.

27.2 Applications

The lateral MIS-ACR has been proposed as an alternative to traditional open techniques (such as the Smith-Peterson osteotomy) (SPO) and pedicle subtraction osteotomy (PSO) for adult spinal deformity correction. Though open techniques are time tested, they have been associated with increased morbidity and blood loss with perioperative and postoperative complications ranging from 15.5 to 80 % [1, 3, 5, 7, 12–16, 19, 21]. In an attempt to circumvent some of these complications, MIS techniques have been applied in the treatment of spinal deformities and restoration of spinopelvic harmony.

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In both cadaveric and clinical studies, the ACR has been shown to increase segmental lordosis by 12–13° per level without disruption of the posterior elements [1, 9, 10, 17, 23]. For comparison, the traditional open technique of a SPO has a segmental lordosis correction of only 10° per level [4, 6, 8, 17]. The amount of lordosis achieved from an ACR is typically inhibited by posterior element obstruction. If the ACR is complimented with a Ponte osteotomy or SPO, it has the potential of gaining lordotic correction on par with that of a PSO but without the associated blood loss and spinal shortening nature of the procedure (Figs. 27.1 and 27.2).

27.3 Regional Anatomy

The MIS-ACR exposes spine surgeons to unfamiliar regional anatomy associated with the anterior spinal column such as visceral organs, the autonomic plexus, and the great vessels. The ALL itself is a very strong band of fibers that extend along the anterior aspect of the vertebrae consisting of three layers: superficial, intermediate, and deep. It is typically thicker and more narrow at the level of the vertebral body (VB) and thinner and wider at the level of the disc space and more adherent to the disc than the VB [10].

Directly anterior to the ALL at its lateral border lies the sympathetic plexus. It typically resides where the psoas major meets the ALL and is in direct communication with the lumbar plexus through white and gray rami communicantes (via the paravertebral ganglia). These communicating fibers reside along the lateral vertebral body and are rarely encountered at the level of the disc space where an ALL release is performed (Fig. 27.3).

The great vessels (aorta, inferior vena cava, common iliac arteries/veins) reside along anterior lumbar vertebral bodies, immediately anterior to the ALL and the sympathetic plexus. The aorta typically bifurcates 18 mm rostral to the

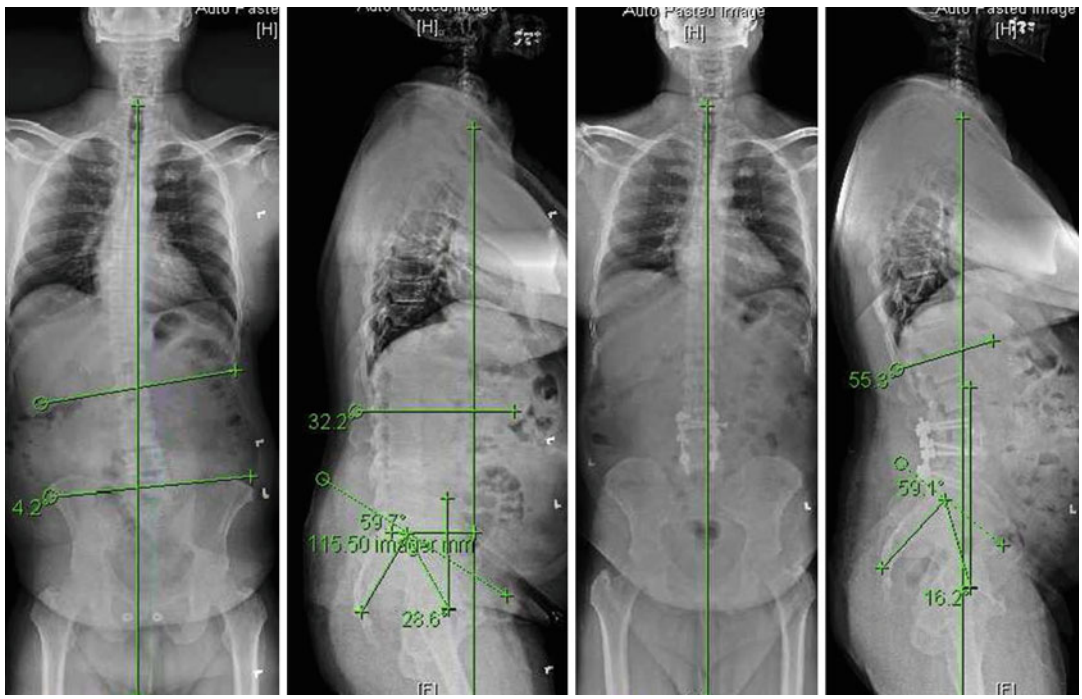


Fig. 27.1 Pre- and postoperative 3 ft standing scoliosis X-rays demonstrating an adult deformity case with global sagittal imbalance and the application of ACR technique at L3/L4 level

L4–5 disc space, and the inferior vena cava bifurcates within 2 mm of the L4–5 disc space [11]. Between the ALL and the great vessels resides an adipose-lined anatomic plane that allows blunt dissection immediately dorsal to the vessels to safely isolate the ALL for sectioning.

27.4 Surgical Technique

The MIS-ACR entails a more extensive dissection of critical anatomic structures (listed above) from the lateral transpsoas retroperitoneal approach. This procedure is highly dependent on anterior-posterior (AP) and lateral fluoroscopy and detailed patient positioning. The patient is positioned in the lateral decubitus position in the same manner used for the traditional lateral transpsoas approach. Laterality is typically dictated by the concavity of the coronal deformity. We choose to approach from the concave side so that more levels can be accessed from a single incision. If there is not a significant coronal deformity, then we choose to approach from the right to place the more durable aorta or iliac artery to the blind side and keep the veins on the side of our operative field. The most common levels for ACR at our institution are L2/L3 and L3/L4. The L4/L5 level is typically avoided due to the anterior migration of the lumbar plexus.

The anterior lumbar column is accessed through the typical lateral retroperitoneal transpsoas approach with the use of directional triggered electromyogram (tEMG) to help prevent a lumbar plexus injury. Once the retractor is docked in a safe location (typically posterior third of the disc space or working zone 3) [22], a discectomy is performed, and the endplates are prepared in the same manner

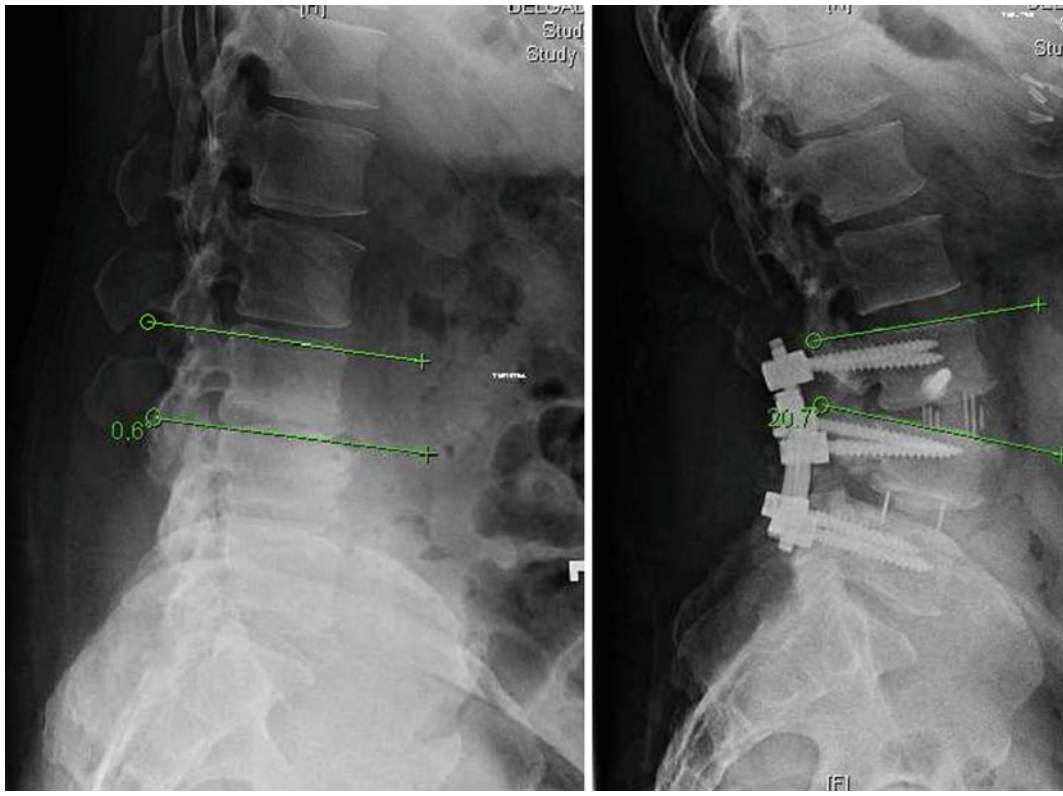


Fig. 27.2 Pre- and post-op lateral X-rays showing with detail the amount of segmentary lordosis at L3/L4 after ACR procedure

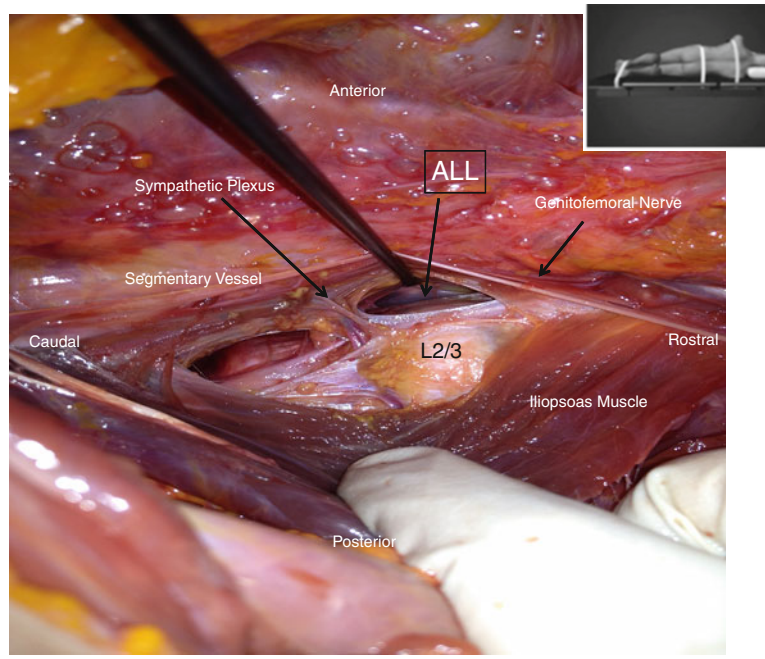


Fig. 27.3 Cadaveric anatomical dissection showing the anatomical relationship of the anterior longitudinal ligament and nearby structures

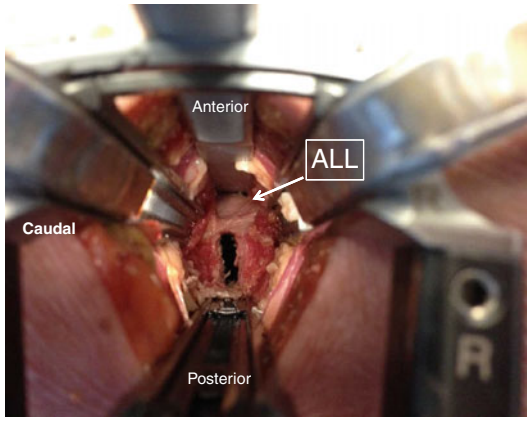


Fig. 27.4 Intraoperative view of the L3/L4 lumbar interspace with the retractor in place after discectomy and anterior longitudinal ligament dissection

as a basic lateral interbody fusion. The retractor is then opened more anteriorly, and the ALL is identified (Fig. 27.4). It is a thick (white) fibrous structure bridging the two vertebral bodies anteriorly.

A natural anatomic plane is then developed (with a blunt instrument) directly ventral to the ALL and dorsal to the autonomic plexus and great vessels. Under AP fluoroscopic guidance, the blunt dissector is advanced while applying slight posterior pressure against the ALL. Very little resistance should be encountered during this maneuver. Resistance means that the wrong plane has been accessed and risk for vessel injury is substantial. We only advance to the medial border of the contralateral pedicle (under AP fluoroscopy) for safety reasons.

While the blunt dissector is protecting the ventral vascular structures, bipolar cautery is used to coagulate the ALL, and an annulotomy blade is slid down the dissector making cuts in and anterior to posterior direction. The surgeon should never cut in a downward manner. Only the first two-thirds of the ligament need to be sectioned (once again, for safety reasons), and the remaining component is broken with a specifically designed disc space distractor. The dissector is slowly removed and the disc space distractor is placed under AP fluoroscopic guidance. The distractor is opened in a gradual manner (multiple minutes) until the final third of the ligament of broken. A hyperlordotic cage is then placed with unicortical lateral screws to prevent anterior migration (Figs. 27.5, 27.6, and 27.7).

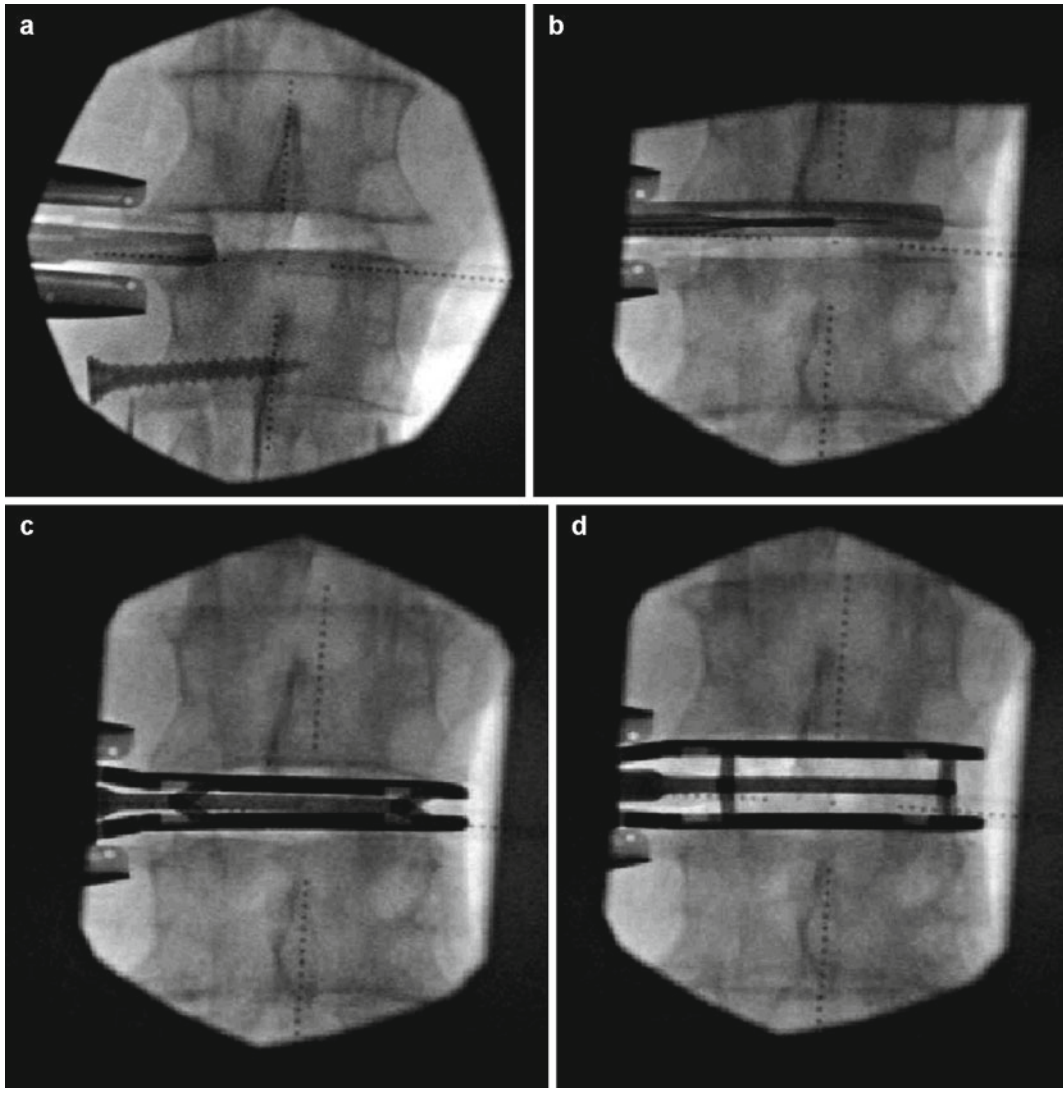


Fig. 27.5 Intraoperative fluoroscopic anteroposterior images showing (from **a** to **d**). The progression of dissection and sectioning of the anterior longitudinal ligament and final widening of the disc space

27.5 Potential Pitfalls

- A strict contraindication for ACR is the presence of a large anterior osteophyte such as those seen in diffuse idiopathic skeletal hyperostosis (DISH). The natural anatomic plane is typically obliterated and cannot be safely dissected without significant risk of major vascular injury.
- Vascular anatomic position should be reviewed prior to the case to assure the great vessels are not too laterally oriented, and there is not an aberrant vessel that crosses the field.
- Specific detail must be applied to positioning and fluoroscopy. Any small variance from a direct AP or lateral shot may allow anterior migration of surgical instruments resulting in a major vascular injury.

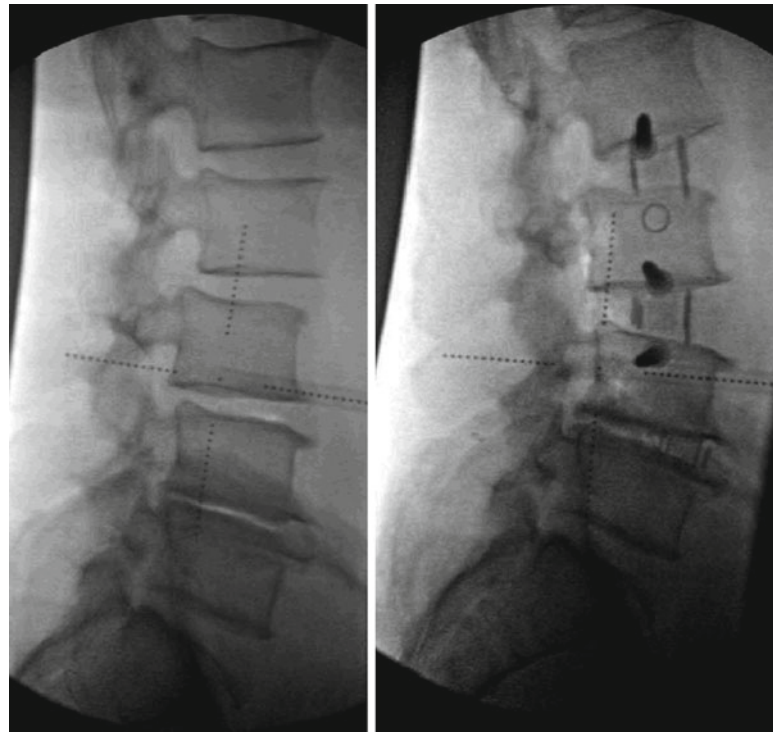


Fig. 27.6 Intraoperative lateral fluoroscopic images showing before and after sectioning of the anterior longitudinal ligament and lordosis gain

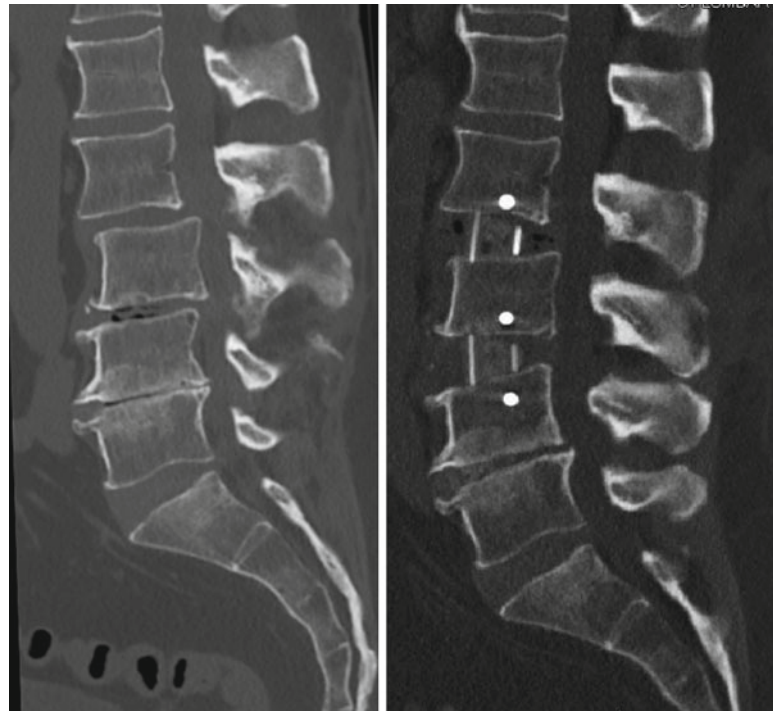


Fig. 27.7 Pre- and postoperative CT sagittal images showing the amount of lordosis achieved after the ACR procedure

27.6 Complications

The ACR technique can provide substantial sagittal correction from a minimally invasive approach but comes with a unique and potentially catastrophic set of complications. It is a demanding procedure that requires meticulous surgical technique to avoid fatal vascular injury. In a review of complications specific to ALL sectioning from the lateral approach, Murray et al. assessed 31 patients with a total of 47 ACRs. Nine out 47 ACRs (19 %) were associated with a major complication. The most common complication ($n = 8$) was ipsilateral iliopsoas weakness (not femoral nerve injury) hypothesized to be associated with multiple entry points within the psoas during multilevel lateral fusions. All but one patient had recovery of their weakness. Retrograde ejaculation was the other major complication. There were no vascular, visceral, or infections complications in their study [18].

Other studies have reported complication rates specific to the lateral approach (femoral nerve injury, visceral injury, and vascular injury), with one reported death from a major vascular injury [2]. Though there have been no reported vascular complications from the ACR, the risk remains evident. Only surgeons considered experts in lateral access should attempt this procedure.

Conclusion

Sectioning of the ALL using the minimally invasive lateral retroperitoneal transpsoas approach (the ACR technique) may provide an alternative to traditional open techniques for sagittal balance correction. With the use of meticulous surgical technique and detailed preoperative planning, this procedure can become a feasible tool in the treatment of adult spinal deformity.

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Subsidence in LLIF

28

Gregory M. Malham, Rhiannon M. Parker, and Kevin A. Seex

28.1 Introduction

Intervertebral cage settling during bone remodelling is a common occurrence in the normal healing process following lumbar interbody fusion (LIF). Subsidence is the progression of this cage settling with endplate collapse; it may lead to a loss of indirect decompression and alignment correction, with a reduced chance of successful fusion and possible reoperation. However, the presence of radiographic subsidence does not always correlate to clinical findings. Subsidence can be related to many factors including bone quality, surgical technique, cage morphology and the use of osteobiologics.

Regardless of the surgical approach used, subsidence can be a potential complication. However, subsidence is of particular concern for patients undergoing anterior or lateral lumbar interbody fusion (ALIF/LLIF/OLIF) because these techniques often rely entirely on indirect decompression of the neural elements for relief of radicular symptoms. This is in contrast to posterior or transforaminal lumbar interbody fusion (PLIF/TLIF) that includes direct foraminal decompression, which may tolerate subsidence better.

28.2 Classification

A number of classification systems for subsidence after LLIF have been described. Le et al. [1] defined radiographic subsidence as any compromise of either endplate on postoperative x-rays. The authors further described clinical subsidence as radiographic subsidence with recurrent pain, recurrent neurological symptoms or a significant decline of clinical outcome measures related to loss of indirect decompression. A similar method was used by Tohmeh et al. [2] where subsidence was measured as any amount of cage settling into the endplates $\geq$1 mm on lateral x-rays.

Sharma et al. [3] combined location and severity to describe four classes of subsidence. Grade 0 represents a normal endplate without fracture, grade I represents a breach of the endplate at one side (anterior or posterior) of the cage, and grade II represents a fracture of the endplate at both the anterior and posterior sides of the cage, whereas grade III signifies an endplate fracture with cage subsidence of more than one-third of the cage height into the vertebral body.

The classification system most commonly used in the published literature [4–6] is by Marchi

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et al. [7, 8] who measured and classified subsidence based on the amount of cage subsidence into the vertebral endplates: grade 0 as 0–24 %; grade I, 25–49 %; grade II, 50–74 %; and grade III, 75–100 % collapse of the level. Grades 0 and I were considered low grade, while grades II and III were considered high-grade subsidence. Our concerns about including up to 25 % subsidence as grade 0 prompted us to propose an alternative. This system used the quantitative measurement of subsidence as per Tohmeh et al. [2], distinguished between early and delayed subsidence and described three types [9]. Radiographic subsidence was measured from the vertebral endplate to the caudal or cranial margin of the cage (in millimetres). Subsidence was deemed early cage subsidence (ECS) if it was evident on postoperative day two CT images and was therefore the result of an intraoperative vertebral endplate violation (Fig. 28.1). If subsidence was only detected on subsequent CT scans (≥6 months postoperative), it was deemed delayed cage subsidence (DCS). Endplate breaches were categorised as caudal (superior endplate) and/or cranial (inferior endplate) and as ipsilateral, contralateral or bilateral with respect to the side of cage insertion. Despite the nine potential patterns possible, only three types of subsidence were seen in the clinical series: type 1, cage subsidence into the contralateral caudal endplate; type 2, bilateral cage subsidence into the anterior aspect of the caudal endplate, producing an anterior tilt of the cage; and type 3, cage subsidence into both the caudal and cranial endplates bilaterally (Fig. 28.2).

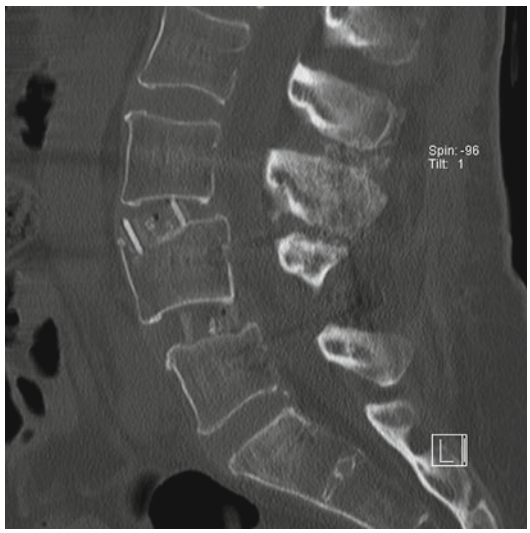


Fig. 28.1 Early cage subsidence (ECS) described by Malham et al. [9]

28.3 Rates

The rate of subsidence after LLIF has been reported as 10–62 % [2, 4–8, 10]; however, the inconsistencies in evaluating, defining and reporting subsidence after this procedure make the significance of such findings unclear. In our early experience with LLIF, we reported a radiographic subsidence rate of 13 % (4 of 30 patients) using CT [11]. In the next 40 cases, the subsidence rate was 7.5 % (3 of 40), with all cases occurring in patients with standalone cages [12]. In a later series of 128 patients (178 levels), we reported a subsidence (DCS) rate of 10 % (13 of 128) of patients in 8 % (14 of 178) of levels [9]. Tohmeh et al. [2] reported higher rates of ECS and DCS with 20.2 % (45 of 223) of cages immediately postoperatively and 62.3 % (139 of 223) at 12 months.

Clinical (symptomatic) subsidence occurred in 3 % (4 of 128) of our patients. The depth of subsidence in this series ranged from 1.6 to 6.0 mm. Type 2 subsidence was the most common in 64 % (9 of 14 levels), followed by type 3 in 21 % (3 of 14 levels) and type 1 in 14 % (2 of 14 levels). Four cases of ECS were identified, all of which corresponded to type 2 subsidence. Le et al. [1] reported a similar rate of subsidence with 14.3 % (20 of 140) of patients in 8.8 % (21 of 238) of levels and clinical subsidence in 2.1 %. The depth of subsidence ranged from 2 to 9 mm.

28.4 Risk Factors

28.4.1 Caudal Endplate

The caudal endplate is 40 % weaker than the cranial endplate [13] and thus is at higher risk of subsidence. This has been confirmed in most case series reported [1, 2, 8, 9]. In addition, the central regions are thinner and weaker than the peripheral regions of lumbar endplates [14].

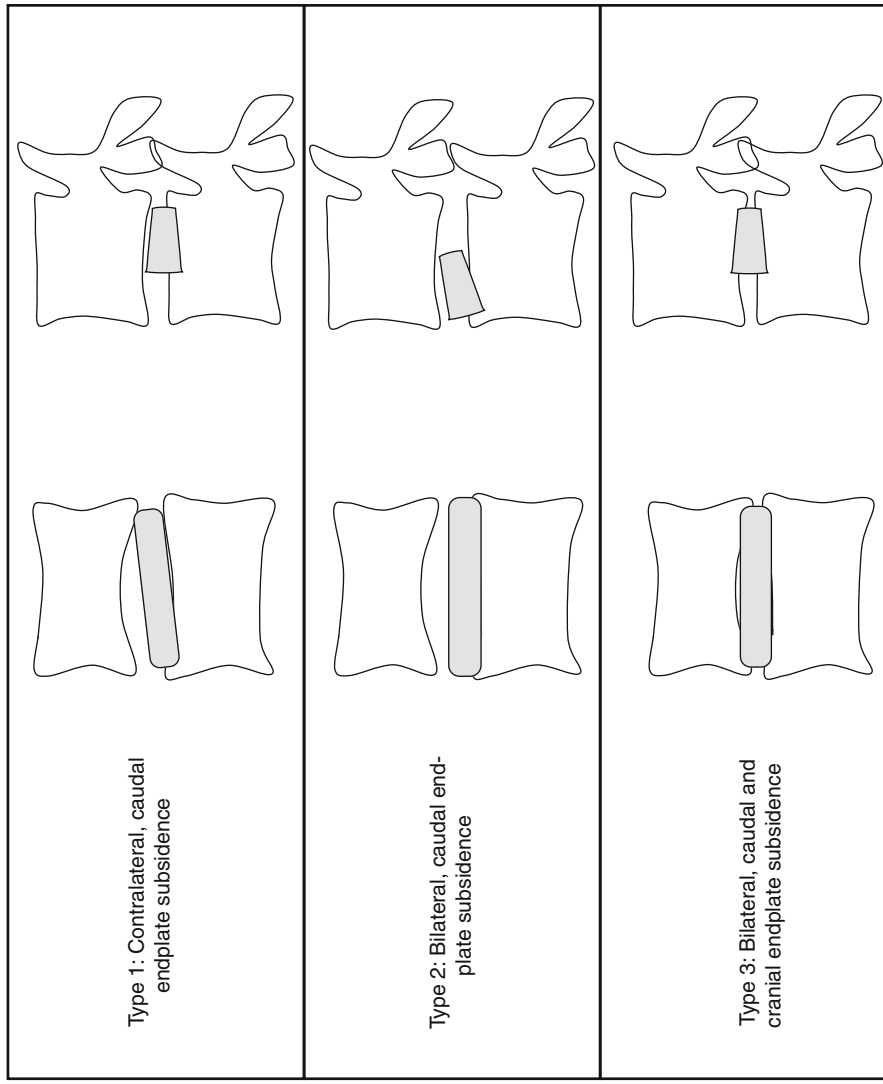


Fig. 28.2 Three types of subsidence (Adapted from Malham et al. [9])

28.4.2 Level

Although lumbar endplate strength increases from L1–2 to L4–5 [15], L4–5 is technically the most challenging level in LLIF because the lumbar plexus can force an anterior cage position. Also the height of the iliac crest may prevent parallel trial and cage insertion, and even with angled instruments, the force vector is not parallel, but into the weaker caudal endplate. Marchi et al. [7] reported the L4–5 level to have the highest rate of subsidence. We had a similar experience with 71 % of subsidence occurring at the L4–5 level [9].

Regarding specific levels, Le et al. [1] found subsidence rates of 20 %, 10.4 % and 4.1 % at L1–L2, L2–L3 and L3–L4, respectively. Although this was not statistically significant, it is consistent with endplate strength increasing in the lower levels of the lumbar spine and the subsidence rate at L4–5 of 10.3 % may relate to the technical factors described above.

28.4.3 Bone Quality

A lower bone mineral density (BMD) leads to a lower failure load of the vertebrae; this increases the subsidence risk, especially with severe osteoporosis [14, 16]. Patients with decreased BMD still have the same failure load distribution as patients with normal BMD [14]. Thus, in these instances it is important to place the cage where there is the greatest resistance to subsidence. The relationship between BMD scores and graft subsidence was examined by Tempel et al. [5]. The mean DEXA T-score in patients with subsidence was −1.65 (SD 1.04) compared to −0.45 (SD 0.97) in patients without subsidence ($P < 0.01$).

28.4.4 Cage Size

Cage width is an important factor in resisting subsidence. LLIF enables insertion of a wide footprint cage spanning the endplate apophyseal rim. The larger surface area of the 22- and 26-mm cages cover more of the stronger peripheral endplate [17] and lead to more efficient transfer of force to the endplate than that of the narrower 18 mm cage. Significantly higher subsidence rates using 18 mm cages compared to 22 mm cages were reported by Le et al. [1], with 14.1 % and 1.9 %, respectively ($P < 0.0001$). Subsequent studies have confirmed similar results [2, 8, 9].

The greater the cage height, the higher the rate of subsidence [2, 18]. Both Le et al. [1] and Malham et al. [9] restricted cage height to 8–12 mm in a conscious effort to avoid overdistraction and subsequent endplate violation. Importantly, limiting disc height to this amount still provided adequate indirect decompression [19].

The cage length may only be relevant if is not sufficient to cover the periphery of the endplates [13]; this was confirmed by Le et al. [1] who found that implant length had no effect on subsidence.

28.4.5 Bone Morphogenetic Protein

Recombinant bone morphogenetic protein-2 (rhBMP-2) can be used as a bone graft substitute in LLIF that avoids iliac crest harvest and provides high fusion rates without cancer risk [20]. Theoretically, rhBMP-2-related osteolysis is of concern in the first four to six postoperative weeks because of bone softening in the initial rhBMP-2-induced osteoclastic inflammatory response and resorption phase prior to osteoblastic bone formation and consolidation [21, 22].

28.5 Effect on Clinical Outcomes and Fusion Rates

Subsidence has been shown to have no influence on bone fusion rates [9]; however, it may contribute to early postoperative pain [7, 8, 23]. Some surgical goals may not be achieved in cases of subsidence, namely, mechanical stabilisation, correction of sagittal/coronal alignment, distraction of the disc space and decompression of neural elements [1, 23]. However, studies comparing subsidence to final clinical outcomes have not identified a clear relationship [7, 8]. We found

that neither interbody fusion rates nor clinical outcomes were affected by radiographic subsidence [9]. Despite a significant difference in fusion rates between the subsidence and non-subsidence groups at 6 months (0 % and 30 %, respectively; $P = 0.0195$), by 18 months, the fusion rates for both groups were similar (73 % and 88 %, $P = 0.1792$). Sharma et al. concurred that subsidence did not affect fusion rates [3].

28.6 Prevention/ Recommendations

To minimise the rates of subsidence, surgeons must protect the integrity of the weaker and thinner caudal endplate. Particular attention must be taken when advancing the Cobb elevator, using care with the mallet, remaining orthogonal and constantly referencing the real-time intraoperative fluoroscopy. In addition, aggressive endplate preparation with curettes and rasps should be avoided. Protective slides on the caudal endplate are recommended during disc space distraction and insertion of trials and cages [9]. If an endplate breach is recognised intraoperatively, then rhBMP-2 should not be used, and an alternative graft material should be chosen. Supplemental posterior fixation with bilateral pedicle screws is also recommended to provide the most biomechanically supportive long-term construct [24].

28.6.1 Standalone Cages/ Supplemental Posterior Instrumentation

Biomechanical data in LLIF indicate that there is greater stability of the spinal segment with supplemental fixation than with standalone cages [24].

Conclusion

Mild subsidence is common and not a clinical concern, but surgeons should be diligent in their care of the weaker caudal endplates. Surgeons should have a low threshold for supplemental fixation with low bone density and any possibility of intraoperative endplate injury. With experience most surgeons trend towards the use of less tall and wider cages.

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Osteobiologics

29

Zorica Buser, Lance Smith, and Jeffrey C. Wang

29.1 Introduction

The evolvement of the lateral transpsoas approach to the anterior lumbar spinal column has given surgeons another technique to achieve interbody fusion. Fusion rates have been reported to be 97 % based on computed tomography [1]. In addition, sagittal and coronal balance can be corrected with augmented posterior fixation [2]. The role of bone grafts in the lateral approach is to promote rapid healing and bone formation. The biology of fusion is divided into three stages: (1) the inflammatory phase (first 3 weeks), decortication leads to secretion of various cytokines resulting in vascular invasion and initial bone formation (collagenous matrix); (2) the reparative phase (week 4–5) further healing, stem cell differentiation, and early bone formation which take place; and (3) the remodeling phase (week 6–up to few years) – mature bone formation [3]. A solid spine fusion is thus greatly affected by the cellular and biomechanical properties of the graft. The ideal bone graft should be osteoconductive, osteoinductive, and osteogenic. Osteoconduction is an acellular, mechanical characteristic of the scaffold, providing a porous environment (150–600 μ) to the blood vessels and cells for migration and bone synthesis. Osteoinduction provides growth factors for stem cell differentiation, and osteogenicity provides mature osteoblast and stem cells that drive the crucial bone metabolism and the healing cascades. Grafts used for spine osteobiologics have some or all "ideal" graft characteristics and are classified as autografts and allografts. Non-autologous grafts can be further divided in bone graft extenders (combined with autologous bone, reducing the amount of autologous bone needed while achieving similar fusion rates), enhancers (combined with autologous bone to enhance the fusion), and substitutes. The most commonly used grafts are summarized in Table 29.1.

29.2 Autografts

The first spinal surgery using autograft bone was done by Hibbs in 1911. Three types of autograft bone have been used since then: cancellous, cortical, and vascularized cortical [4]. Autograft bone has all properties for an ideal spine graft material: osteoinduction (bone morphogenic pro-

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Table 29.1 Bone grafts used for spine fusions

	Ideal graft characteristics		
Grafts	Osteoconductive	Osteoinductive	Osteogenic
Autologous bone	+	+	+
Allograft bone	+	+	
DMB	+	+	
Ceramics	+		
BMP			+
BMA		+	+
Platelet gels			+

DBM demineralized bone matrix, *BMP* bone morphogenetic proteins, *BMA* bone marrow aspirate

teins (BMPs), particularly BMP2 and BMP7), osteoconduction (bone matrix/collagen), and most importantly osteogenic potential (stem cells and osteoblasts). Accordingly, autografts can provide immediate and long-term mechanical stability. Autografts used for spine fusion can be classified in two categories: local bone, which is harvested from the lamina, facets, or processes during decompression, and extraspinal material, most commonly an iliac crest bone graft (ICBG). With both grafts there are no issues with donor compatibility and the costs are low. Local bone is a cortical graft and provides immediate mechanical stability, but due to the pore size, cell migration and differentiation is impaired. This leads to lower rates of bone remodeling and long-term instability. The advantage of local bone over ICBG is that no extra procedure or harvest site is needed, causing fewer complications. In contrast, ICBG is the most commonly used graft and often referred to as a "gold standard" for spinal fusion. A purely cancellous structure is easily revascularized, and the large surface provides an ideal environment for bone formation. Although ICBG lacks compressive strength, the rapid bone formation leads to an increase in fusion mass that provides mechanical stability. If the fusion approach is posterior, ICBG can be harvested without an additional surgical incision. An important parameter when choosing the autologous bone graft is the patient's age, as elderly patients will have less ICBG and a lower bone quality. A challenge with both types of autografts is the large amount of material needed for multilevel fusions. Sengupta and co-workers found that the ICBG was superior in overall fusion rates and that both grafts performed similarly for single-level fusions. In multilevel fusions ICBG outperformed the local bone graft (fusion rates of 66 % vs. 20 %) [5]. However, ICBG grafts carry more complications than local bone grafts. The most serious complications are related to the harvest and can lead to subsequent fractures, hernia, ureteral injury, instability, infection, and prolonged length of stay [6]. Even though postoperative pain at the donor site is one of the most common issues, Howard et al. found that the pain incidence was similar in patients with or without ICBG harvest [7]. A study done by Gruskay found that an increase in blood transfusion rates, surgical time, and length of stay were the only short-term complications associated with the use of ICBG as a graft material [8].

29.3 Allograft Bone

This bone graft is harvested from cadaver tissues and is usually used for anterior cervical and lumbar fusions. Allografts are depleted of cells and growth factors and therefore have osteoconductive and minor osteoinductive properties. Allograft bones can be fresh, fresh frozen, or freeze-dried. The mechanical properties of fresh-frozen allografts are superior to freeze-dried ones, but have higher immunogenicity. In the posterolateral approach, freeze-dried allografts failed to produce fusion, whereas ICBG led to an 80 % fusion rate [9]. Cortical allografts can provide immediate stabilization, but the remodeling

process is slow and the resorption of the graft is increased. On the other hand, corticocancellous grafts do not have an immediate mechanical benefit, but due to the large contact area, they are easily integrated and can promote bone remodeling. One of the main health concerns with allografts is the transmission of diseases. Mroz reported that between 1994 and 2007, 96.5 % of musculoskeletal allografts were recalled due to contamination and recipient infection [10]. Furthermore, a study done by Jurgensmeier found frequent inconsistencies in tissue banks, with 39 % accepting samples from elderly donors (≤80 years of age) and only 50 % of banks excluding grafts from osteoporotic patients [11]. Those discrepancies in graft collection have a significant impact on the mechanical properties of the graft and can contribute to fusion failure. However, the use of allografts in surgeries avoids complications associated with ICBG harvest. Allografts are manufactured in various forms as strips, chips, or demineralized bone matrix.

29.3.1 Demineralized Bone Matrix

Demineralized bone matrix (DBM) is a human, demineralized, cell-free allograft bone graft. During the extraction process, antigenic markers are removed, making DBM less immunogenic. The bone type used for DBM production is crucial, as tubular and cortical bones are more osteoinductive than flat bones [12]. The demineralized matrix consists of collagen (93 %), glycoproteins (3 %), debris, and calcium phosphate. The collagen matrix provides osteoconductivity to DBM; it is mainly composed of collagen I and a small fraction of collagen IV and X. Growth factors contribute to the osteoinductivity of DBM and include bone sialoprotein, osteopontin, and TGF-β superfamily [13]. BMP2 and BMP7 play a central role in cell differentiation toward osteoblasts. However, aging leads to decreased amounts of BMPs in DBM matrix. Conversely, tumor growth factor beta (TGF-β) and insulin growth factor 1 (IGF-1) are not affected by aging and thus have an important role in bone osteoinduction and interaction with major BMPs [14]. After bone demineralization, DBM is produced in powder form. Studies have shown that the particle size of DBM determines its osteoinductive properties by affecting host interaction and the release of growth factors. A size range between 420 and 840 μm was found to be the most osteoinductive [15]. DBM is mixed with various carriers at a ratio of 15 % DBM and 85 % carrier for easier delivery, precise surgical localization, and containment. The type of the carrier defines the final form of the DBM graft such as chips, putty, gel-filled syringes, and powder. Common carriers are calcium sulfate, glycerol, gelatin, and hyaluronic acid. DBM graft potentials have been evaluated in a large number of animal studies and clinical trials. Morone and co-workers have found that in a rabbit fusion model, a DBM gel (Grafton) alone or in combination with ICBG produced similar fusion rates compared to ICBG alone [16]. Studies have shown that the Grafton DBM in form of putty or flex led to higher fusion rates, even achieving 100 % when mixed with a small percentage of autologous bone. Both putty and flex are fibrous in structure, promote better osteoconductivity, and are similar to the native tissue. In our study we found that both the Grafton putty and the Osteofil paste led to fusion, whereas Dynograft did not promote fusion [17]. Furthermore, Osteofil induced fusion at earlier time points (4 weeks) and had the highest overall fusion rate (Fig. 29.1).

In spine orthopedics DBM is commonly used as bone filler or graft extender. Because the DBM is biodegradable, the scaffold can be used as a slow-release delivery vehicle for growth factors, antibiotics, cells (with/without gene modifications), and other active components. DBM has been used as an exogenous delivery system in numerous studies. In our study DBM was combined with an adenoviral Nel-like molecule 1 (NELL-1), BMP2, or BMP7. NELL-1, one of the key proteins in osteoblastic differentiation, caused the formation of a well-defined tissue mass similar to cortical bone and a continuous connection of newly formed bone and transverse processes [18]. We observed significantly higher fusion rates in the NELL-1 group compared to other studies that used BMP (Fig. 29.2).

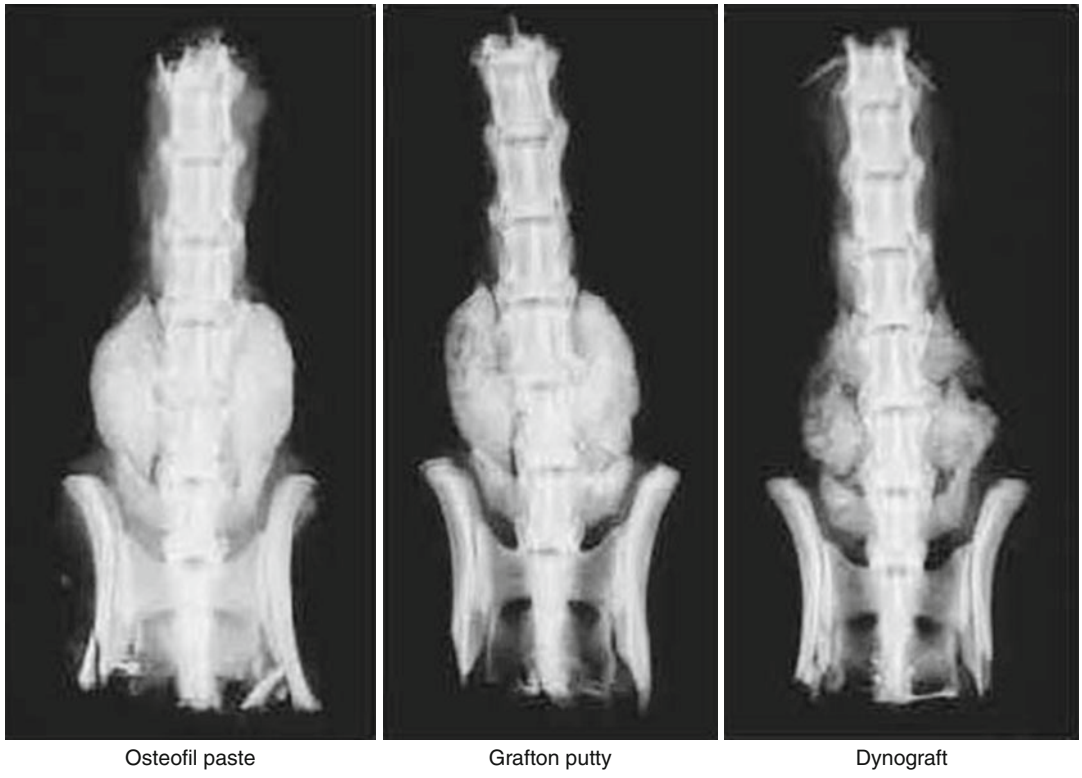


Fig. 29.1 L4–5 posterolateral fusion at 6 weeks in athymic rat using various DBMs: Osteofil paste, Grafton putty, and Dynograft (Reproduced from Wang et al. [17])

Clinical trials for cervical and lumbar fusion have shown that DBM can act as a bone graft leading to fusion and that there are no differences in the complication rates or duration of surgery when compared to ICBG. For example, Sassard and co-workers reported similar fusion rates in patients with autologous bone graft and Grafton putty vs. autologous graft only, with no significant differences in bone mineralization [19]. However, DBM's disadvantage is a large variability due to donor demographics, type of bone, carrier, amount of growth factors, and the extraction procedure.

29.4 Ceramics

Ceramics are osteoconductive grafts deficient in growth factors and cells. They are easily obtainable in large amounts, are disease-free, and are with a pore size that is suitable for cell and blood vessel ingrowth. Hydroxyapatite and β-tricalcium phosphate (β-TCP) are mainly used for spine surgeries due to their prolonged rate of resorption, up to a year for hydroxyapatite and several months for β-TCP. Furthermore, the structure and pore size of hydroxyapatite and β-TCP are very similar to cancellous bone. Once implanted, β-TCP is populated with a fibrovascular stroma that is soon replaced with osteogenic cells, leading to bone formation. Several clinical studies have found that both ceramic grafts induced similar fusion rates compared to patients who received ICBG [20, 21]. One of the most commonly used hydroxyapatites is Pro Osteon Coralline Hydroxyapatite (Interpore Cross International, Irvine, CA). It is derived from a sea coral and mainly consists of calcium carbonate. Another graft mixture is Collagraft (NeuColl, Inc., Palo Alto, CA), consisting of collagen and a mixture of hydroxyapatite and β-TCP closely resembling the natural bone structure. Silicate-substituted calcium phosphate and calcium sulfate have been used in the recent years as synthetic graft extend-

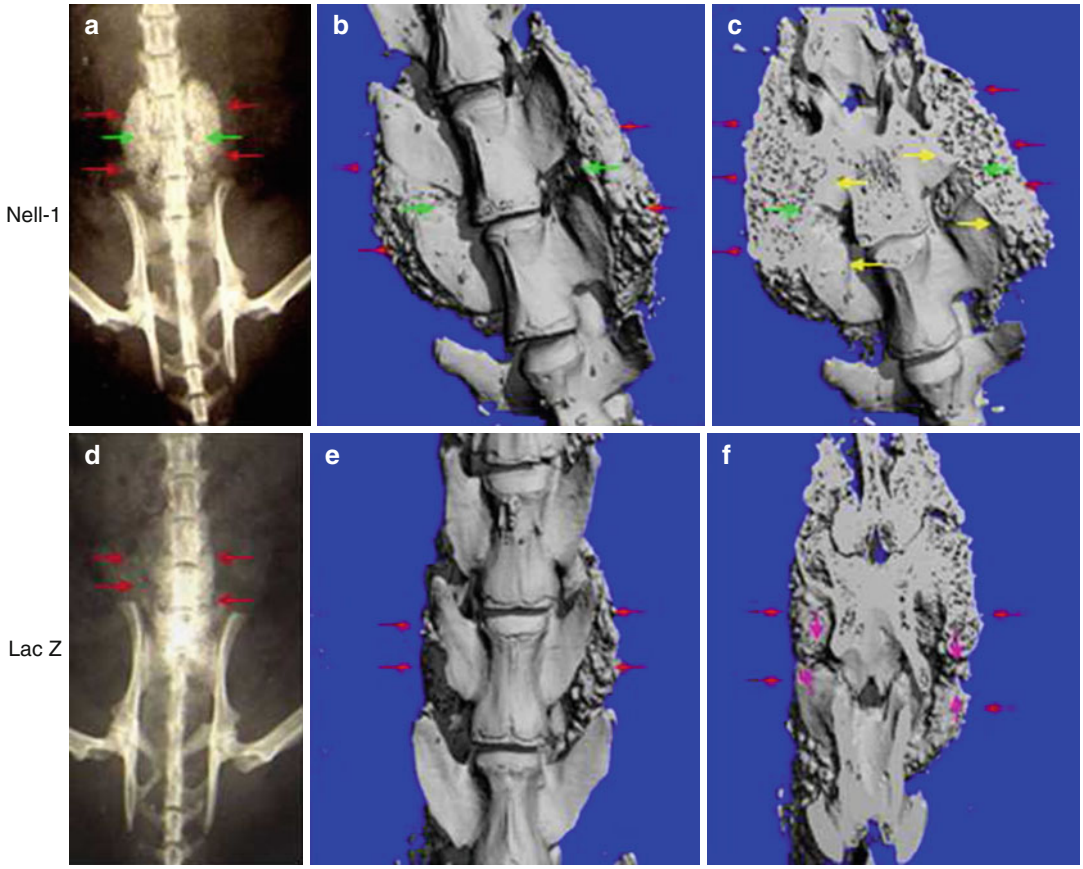


Fig. 29.2 Lumbar X-rays (**a**, **d**) and micro-CT scans (**b**, **c**, **e,** and **f**) of Nell-1 and LacZ (control) 6-week fusion samples. The *red arrows* identify the radiopaque tissue masses on both sides of spine at L4 and L5 segments. The medial edge (*green arrows*) of each mass displayed the highest density similar to cortical bone (Reproduced from Lu et al. [18])

ers, showing variable fusion rates. The general disadvantage of ceramic grafts is its brittleness and inability to sustain heavy loads. Due to the low mechanical stability, ceramics are usually combined with fixation instruments. Because ceramics lack osteogenic and osteoinductive properties, they are often combined with materials containing growth factors and cells.

29.5 Bone Morphogenetic Proteins

Bone morphogenetic proteins (BMPs) are part of the TGF-β superfamily of growth factors involved in bone and cartilage formation by stimulating stem cell differentiation. Through their control of cell proliferation, differentiation, and tissue architecture, BMPs play an important role in pathological conditions such as bone ossification and cancer. Depending on the signaling pathway and tissue, both down- and upregulation of BMP can lead to cancer progression. BMPs can be isolated from donor bone or produced from recombinant DNA. Because of their powder form, BMPs require the use of a carrier. The successful use of BMPs depends on the structural and mechanical properties of the carrier, which enable proper delivery and maintenance of the concentration. Commonly used carriers in spine fusions are ceramics, absorbable collagen I sponges (ACS), allografts, and polylactic acid. Even though ACS is the most commonly used carrier, it lacks mechanical strength. A study done by Minamide showed that ACS with BMP2 performed poorly and that the combination of ceramics and collagen I with BMP2 provided

high fusion rates and tensile strength [22]. There is a large body of clinical studies on BMP2 and BMP7 and their effectiveness in spine fusions. In 2002 BMP2 was approved by the Food and Drug Administration (FDA) for anterior lumbar interbody fusion (ALIF). Because of high fusion rates (98 %), BMP2 use was extended to posterior lumbar interbody fusion (PLIF), transforaminal lumbar interbody fusion (TLIF), and cervical fusion. Since then there has been a debate about the positive effects and complications related to the "off-label" use of BMP2 [23–26]. In our study we found that the initial fusion mass was larger, and the time to solid fusion was shorter in patients with low pseudarthrosis risk in both rhBMP2 and ICBG groups [27]. Furthermore, we found higher fusion rates in the rhBMP2 group compared to ICBG.

BMP7 (OP-1) has been used under a humanitarian device exception for the posterolateral lumbar approach in patients where an autologous bone harvest is not possible or when the bone quality would not lead to fusion. Vaccaro and colleagues found that among 12 patients who received OP-1, 20 % showed clinical improvement, 50 % had a solid fusion, and no complications were observed [28]. The use of recombinant DNA technology for the delivery of BMPs and stem cell differentiation shows promise. In our study we used human adipose stem cells expressing BMP2 and BMP7 from a lentiviral vector. The cells were loaded onto the collagen carrier and placed at the decorticated L4–5 transverse processes. Animals that received cells with BMP2, BMP7, or BMP2+BMP7 had a solid fusion by 8 weeks [29]. We found that the group expressing both BMP2 and BMP7 had a significantly greater area of bone formation compared to stem cells expressing BMP2 or BMP7 alone (Fig. 29.3).

29.6 Bone Marrow Aspirate (BMA)

Bone marrow aspirate has osteoinductive and osteogenic properties. Since it lacks mechanical stability, BMA is always combined with a carrier, usually collagen I sponges or DBM (Fig. 29.4).

The main disadvantages are harvest site morbidity, naturally low numbers of stem cells, and donor quality. The bone marrow of young, healthy patients contains one mesenchymal stem cell (MSC) on every 50,000 nucleated cells, and those numbers decrease with age. In addition, aspiration of more than 2 cc of bone marrow per site will lead to a reduction of stem cell numbers. Once aspirated, BMA can be processed for stem cell isolation, and the cells can be expanded in vitro for several passages without losing their differentiation potential. Several animal studies have confirmed the benefits of expanded MSCs during spine fusion, which in some cases was superior to whole bone marrow [30]. In a retrospective cohort study, we found differences in single- and multilevel fusion rates when BMP2, BMA, or autograft was used [31]. BMA led to the same fusion rates for single level (100 %), but was inferior for multilevel fusions when compared to BMP2 and autograft (63 % vs. 100 %, respectively). This leads to the conclusion that BMA is suitable for single-level procedures and is cost advantageous compared to BMPs. Even though MSCs can provide a great alternative to autologous bone, there are several logistical issues with their use in a clinical setting, such as in vitro expansion, potential contamination, and revision surgery for implantation.

29.7 Platelet Gels

Platelet gels contain platelets, platelet-derived growth factor (PDGF), and transforming growth factor (TGF-β) and can be combined with an auto- or allograft. Even though animal studies presented encouraging data, several clinical studies have found that platelet gels led to lower fusion and higher nonunion rates.

29.8 Summary

The risk and benefit profile of any technique used to deliver an interbody placement is unique. The lateral transpsoas approach has evolved to allow surgeons to avoid potential complications

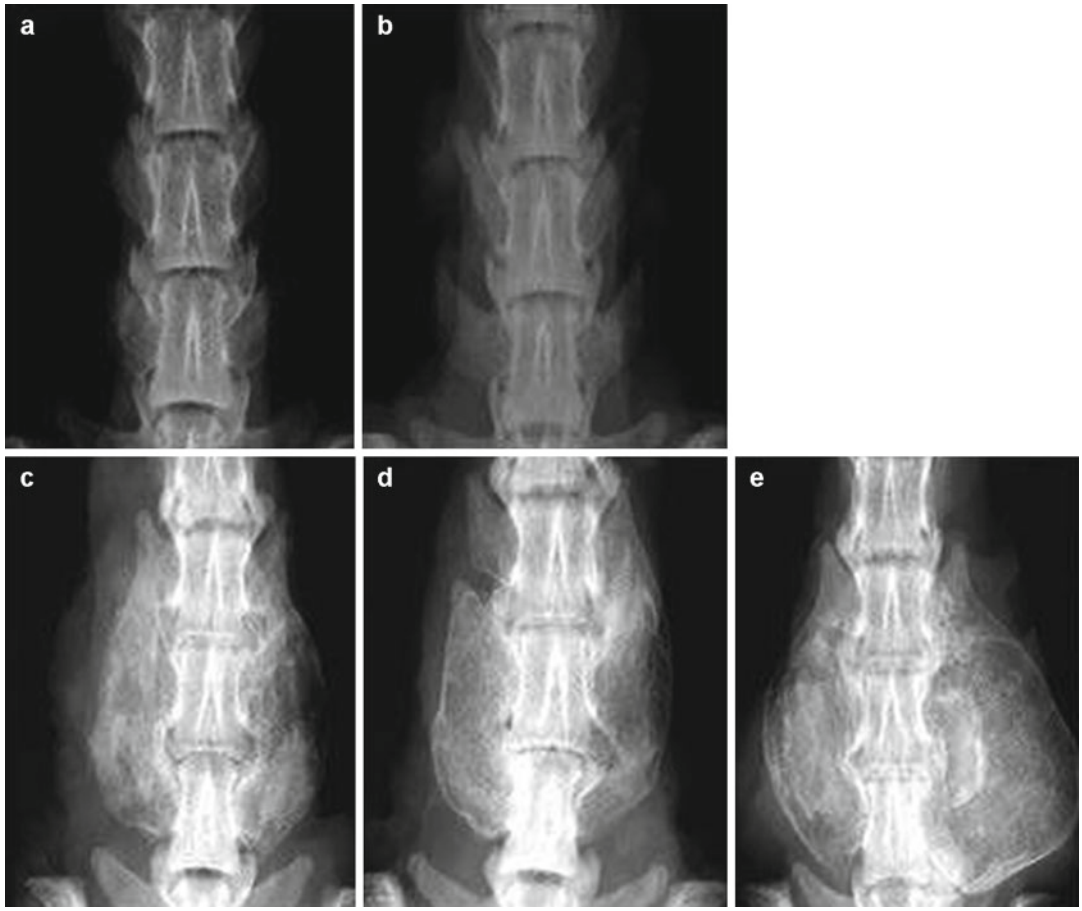


Fig. 29.3 Radiographs of L4–5 fusion. (**a**) Cells only, (**b**) cells with GFP, (**c**) cells expressing BMP2, (**d**) cells expressing BMP7, and (**e**) cells expressing BMP2/BMP7 (Reproduced from Kaito et al. [29])

associated with the traditional fusion. Several grafting materials have been widely used and represent viable ICBG substitutes. However, one must be cautious when choosing the graft material and keep in mind that most of the grafts do not require FDA approval and therefore lack preclinical studies. Further research in bone biology will improve the engineering of scaffolds to provide a mechanically stable, porous matrix, which enhances cell proliferation.

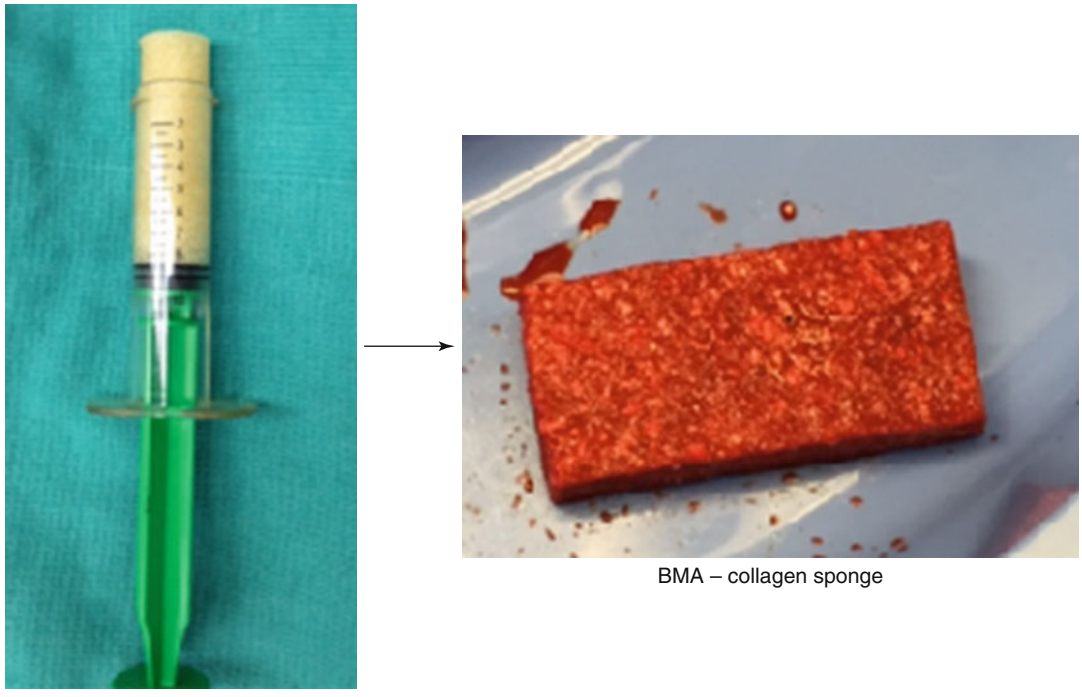


Fig. 29.4 Bone marrow aspirate graft

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Indirect Decompression

30

Yu-Po Lee and Vinko Zlomislic

30.1 Lumbar Stenosis

Lumbar spinal stenosis (LSS) is the most common indication for lumbar spinal surgery in the elderly population [1–4]. A combination of disc protrusion, facet joint hypertrophy, and buckling of the ligamentum flavum contributes to narrowing of the spinal canal and the neuroforamen [1–4]. Symptoms include loss of sensation, weakness, and pain, which may radiate down the leg to the feet [1–4]. Additional symptoms in the legs may be fatigue, heaviness, paresthesias, as well as bowel or bladder symptoms [1–4]. Symptoms are most commonly bilateral and symmetric, but they may be unilateral. Patients may also complain of back pain [5]. Back pain may be secondary to disc degeneration or facet arthropathy. However, compression of the sinuvertebral nerve may result in back pain [6].

Symptoms typically worsen with standing or walking and improve with sitting. These symptoms have been referred to as pseudoclaudication in the past due to the similarities in these symptoms to vascular claudication. Now, this constellation of symptoms is often referred to as neurogenic claudication [1–4]. Symptoms are typically exacerbated with standing or walking because the spine is extended during these activities. Extension of the spine causes further narrowing of the spinal canal and greater compression on the nerve roots [1–4]. This is due to buckling of the ligamentum flavum and narrowing of the neuroforamen. Patients often report improvement of their symptoms with flexion of their spine or sitting. Flexion increases the canal diameter via ligamentotaxis of the ligamentum flavum, and this relieves pressure on the nerve roots [1–4]. Patients may report that they can walk further while leaning forward on a shopping cart. They may also report that they can walk more easily uphill or that riding a bicycle is their preferred form of exercise because they are able to lean forward. This helps to distinguish neurogenic claudication from vascular claudication because walking uphill or riding a bicycle results in pain from ischemia when the patient has vascular claudication.

When nonoperative pain management fails to alleviate symptomatic low back pain, surgical intervention may be considered. Procedures such as laminotomy or laminectomy and facetectomy may be considered in those patients who have failed attempts at nonoperative care. Surgery in these cases has been shown to be very successful. In a study by Atlas et al., 148 patients with lumbar spinal stenosis were followed prospective for 10 years [7]. They found that low back pain

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relief, predominant symptom improvement, and satisfaction were similar in patients initially treated surgically or nonsurgically. However, leg pain relief and greater back-related functional status continued to favor those initially receiving surgical treatment. In another study by Weinstein et al., the authors followed 654 patients in a randomized clinical trial comparing operative versus nonoperative care for patients with lumbar stenosis [8]. Patients with symptomatic spinal stenosis treated surgically compared to those treated nonoperatively maintain substantially greater improvement in pain and function through 4 years. Hence, surgical intervention is appropriate and beneficial in patients with lumbar spinal stenosis who have failed attempts at conservative care.

However, complications may occur during lumbar laminectomy. Nerve root injury, postoperative radiculitis, and incidental durotomies are just a few of the complications associate with direct lumbar decompression [9–11]. Similar complications have also been noted with minimally invasive decompressions [12, 13].

30.2 Lateral Interbody Fusion

Minimally invasive spine surgery has gained increasing popularity over the past few years. Advantages of minimally invasive spine surgery include less tissue trauma during the surgical approach, less postoperative pain, improved cosmesis, shortened recovery time, and quicker return to normal daily living for the patient compared to traditional open approaches of lumbar interbody fusion [14–17]. Lateral interbody fusion (LIF) accesses the spine via a more lateral position through the retroperitoneal fat and psoas muscle. This allows for a less invasive access to the spine while still affording direct visualization of the disc. This procedure allows the surgeon to correct coronal plane deformity and to restore the disc height. Also, this technique has the ability to correct spondylolithesis as well. The process of correcting these deformities often will indirectly decompress the central canal, the lateral recess, and neuroforamen [18–23].

The interbody cage provides an indirect decompression by restoring disc height, which reduces spinal deformities through ligamentotaxis since the anterior and posterior ligamentous structures are left intact. Reduction of the spinal deformities has been shown to increase the foraminal and central canal area (Figs. 30.1, 30.2, and 30.3) [18–23]. Both the indirect decompression and percutaneous pedicle screws are accepted minimally invasive surgical (MIS) techniques that require little soft tissue dissection and minimal blood loss.

30.3 Evidence for Indirect Decompression

The earliest evidence for indirect decompression came from the development of interspinous spacers. Interspinous spacers were developed to treat lumbar spinal stenosis. Distraction of the intervertebral segment stretches the ligamentum flavum and increases the central canal. Also, distraction of the disc space increases the diameter of the neuroforamen. This effectively relieves pressure on the traversing and exiting nerve roots to relieve patients of their neurogenic claudication and radiculopathy symptoms. In 2004, Zuckerman et al. published the results of their prospective study on the X-STOP [24]. They randomized 191 patients in a prospective study comparing the X-STOP versus nonoperative care. At 6 months, the success rates were 52 and 9 %, respectively, and at 1 year, 59 and 12 %. The authors determined that the X-STOP was a significant improvement over nonoperative therapies at 1 year with a success rate comparable to published reports for decompressive laminectomy, but with considerably lower morbidity. In another study by Siddiqui et al., MRI studies were performed on patients before and after surgery [25]. Significant increase in the dimensions of the neural foramen and canal area were demonstrated after surgery. The problem with the interspinous spacers is they would erode through the spinous processes over time, and patients would have recurrent symptoms as the distraction was lost [26, 27]. Hence, interspinous spac-

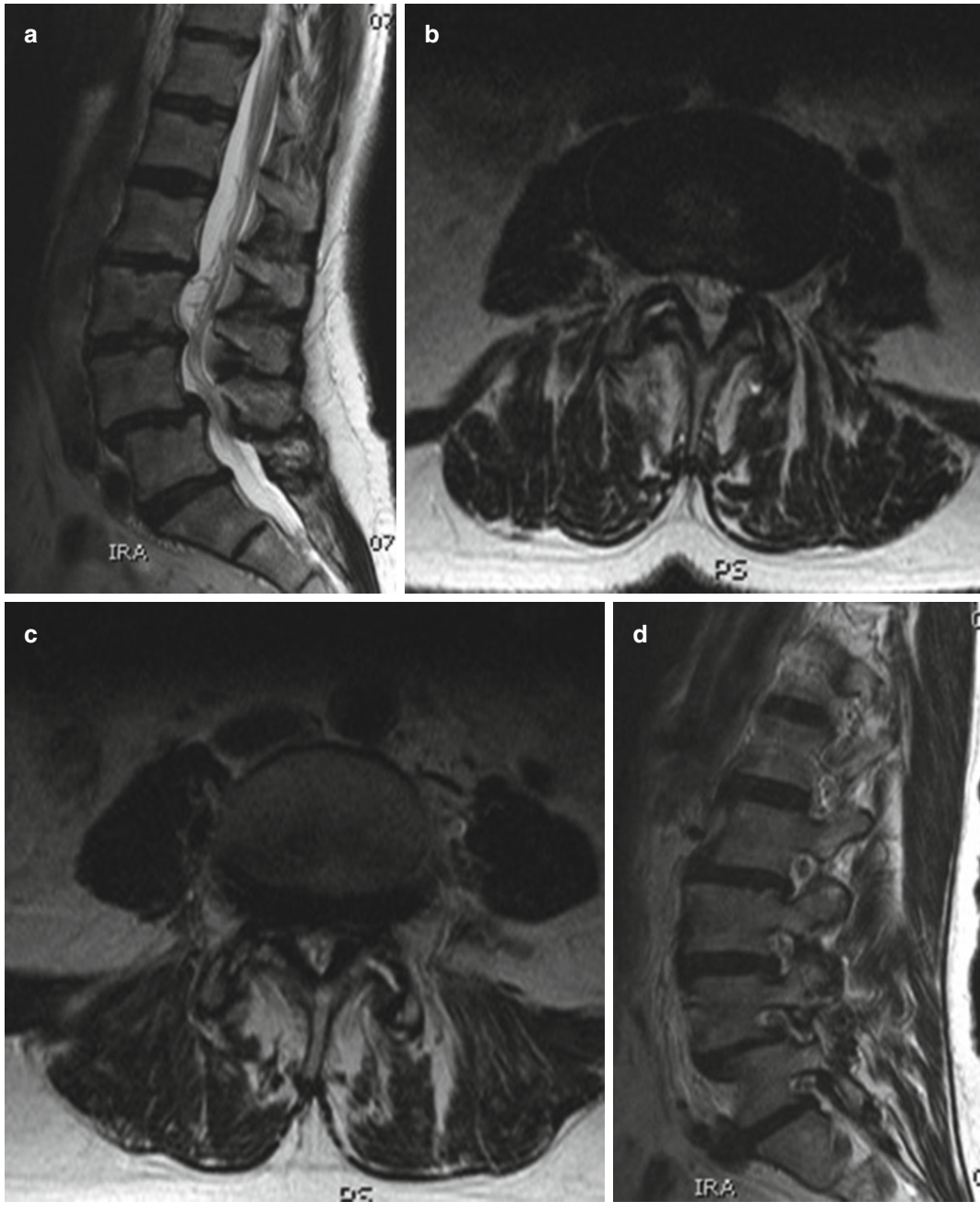


Fig. 30.1 (**a**) Preoperative sagittal MRI showing L4–5 spondylolisthesis with stenosis at L3–4, L4–5. (**b**) Preoperative axial MRI of L3–4 level. Note the lateral recess and foraminal stenosis on the left side. (**c**) Preoperative axial MRI of L4–5 level. Note the central and lateral recess and foraminal stenosis bilaterally. (**d**) Preoperative parasagittal view of the neuroforamen

ers demonstrated the ability to decompress the spinal canal via indirect decompression, but the concern was that the effect may not be long lasting.

With lateral interbody fusion, indirect decompression would be achieved by placement of the interbody spacer, and the benefit would be maintained via the pedicle screws and ultimately

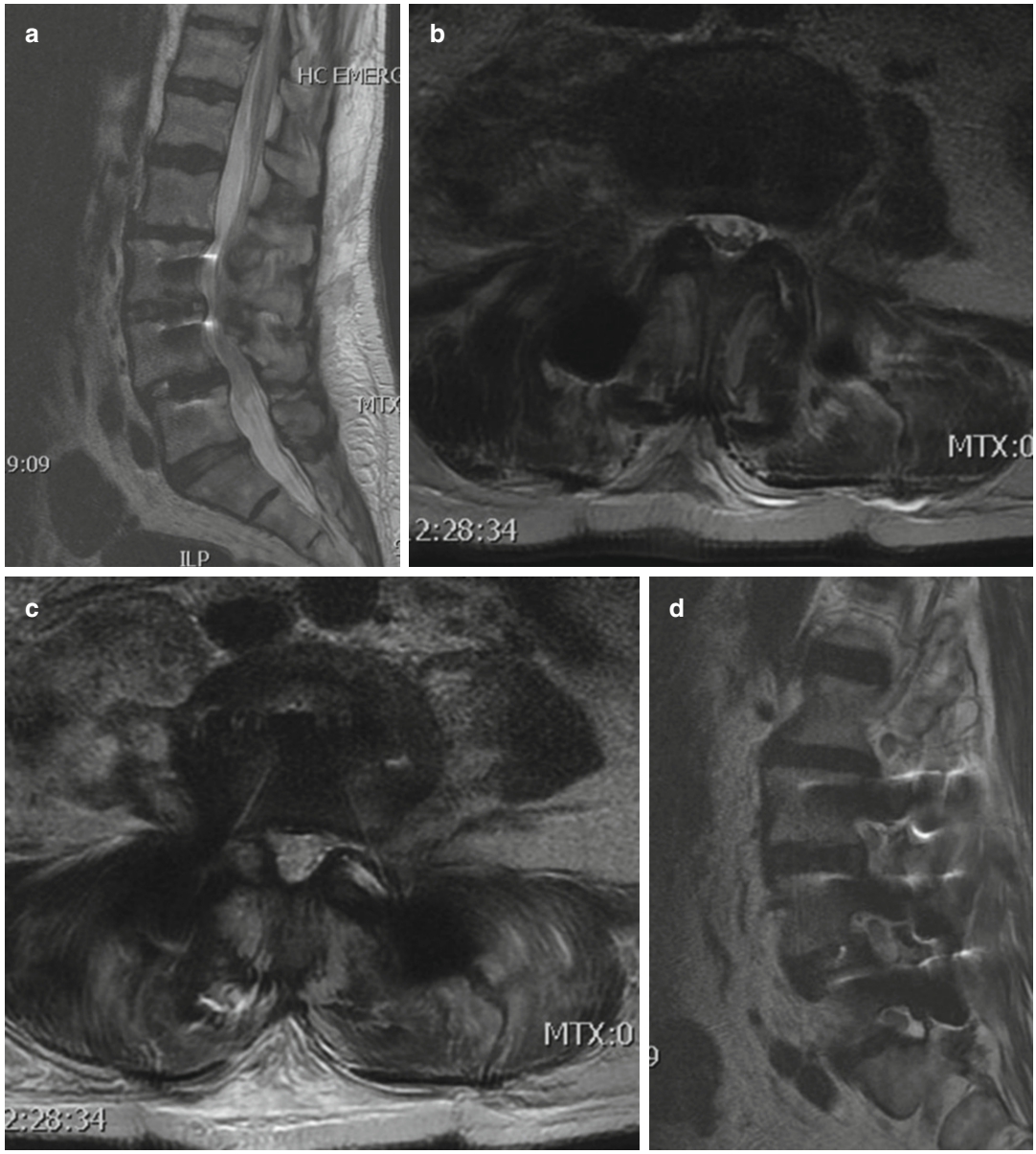


Fig. 30.2 (**a**) Postoperative sagittal MRI showing improvement of L4–5 spondylolisthesis with improvement in central stenosis. (**b**) Postoperative axial MRI of L3–4 level. Note the improved lateral recess and foraminal stenosis. (**c**) Postoperative axial MRI of L4–5 level. Note overall improvement. (**d**) Postoperative parasagittal view of the neuroforamen

the fusion. Currently, there is growing evidence that indirect decompression is a reasonable option in patients undergoing lateral interbody fusion. In a study by Oliveira et al., the authors performed MRI studies on patients before and after surgery [23]. Substantial dimensional improvement was evidenced in all radiographic parameters, with increases of 41.9 % in average disc height, 13.5 % in foraminal height, 24.7 % in foraminal area, and 33.1 % in central canal diameter. Two patients (9.5 %) required a second procedure for additional posterior decompression

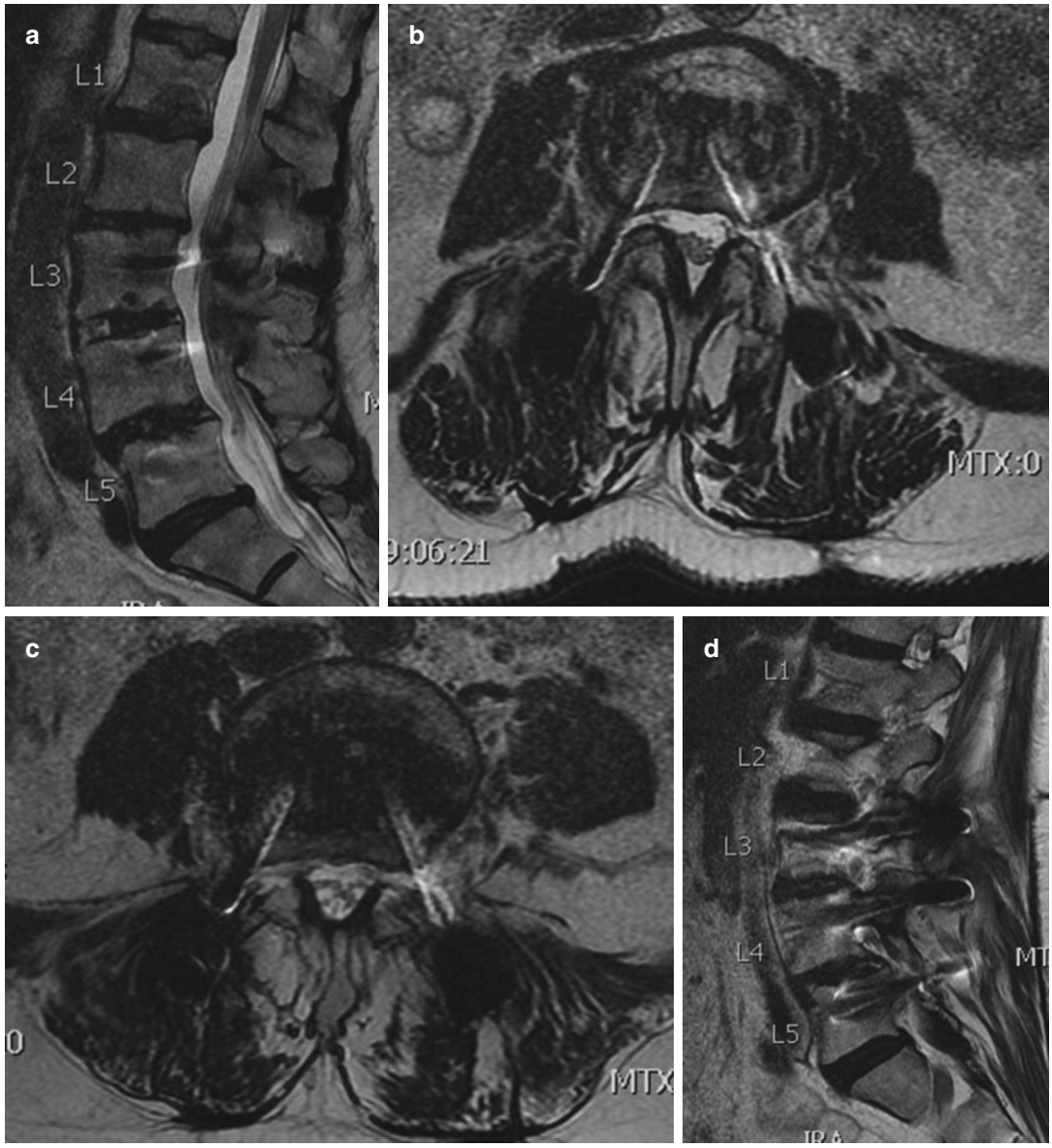


Fig. 30.3 (**a**) 1 year postoperative sagittal MRI showing maintained improvement of L4–5 spondylolisthesis with improvement in central stenosis. (**b**) 1 year postoperative axial MRI of L3–4 level. Note the maintained improvement of lateral recess and foraminal stenosis. (**c**) 1 year postoperative axial MRI of L4–5 level. Note continued overall improvement. (**d**) 1 year postoperative parasagittal view of the neuroforamen

and/or instrumentation. So, the authors concluded that the LIF procedure provided enough decompression of central and/or lateral stenosis in a minimally disruptive fashion. This then avoids the need for the direct resection of posterior elements and the associated morbidity. The authors did note that indirect decompression may be limited in cases of congenital stenosis and/or locked facets. Its effect may also be reduced by postoperative subsidence and/or loss of correction.

In another study by Elowitz et al., the authors performed a similar study on 25 consecutive patients [22]. Fifteen patients had grade I spondylolisthesis.

VAS for back pain intensity improved from 7.74 to 2.07. VAS for leg pain intensity improved from 7.24 to 1.87. Radiographic evaluation in 20 treated levels (15 patients) found an increase in dural sac dimension of 54 % in the anterior-posterior plane and 48 % in the medial-lateral plane. The calculated area of the dural sac increased an average of 143 %. In contrast to the interspinous spacers, these results also seem to be maintained because a fusion is concurrently performed. In a study by Castellvi et al., the authors performed MRIs on 158 consecutive patients preoperatively and 1 year postoperatively [19]. Increases in disc height (67 %, $p<0.001$), foraminal area (24–31 %, $p<0.001$), and canal area (7 %, $p=0.011$) measured immediately postoperatively were sustained at 1-year follow-up. VAS pain score and ODI both improved ($p<0.001$) at 3 months and were maintained at 1 year.

In one more paper by Kepler et al., the authors evaluated patients preoperatively and postoperatively clinically and with CT scans [21]. The authors noted that average foraminal area increased approximately 35 % after cage placement without variation based on cage position. This was correlated with statistically significant improvements in ODI scores. Overall, ODI scores improved from an average of 32.8 ± 9.8 (range 16–44) preoperatively to 19.8 ± 9.8 (range 2–37) postoperatively. This meets the criteria for minimum clinically significant differences. The amount of indirect decompression was enough to result in a meaningful clinical improvement in terms of ODI scores. Hence, the amount of indirect decompression was not only statistically significant; it also led to increased functional capabilities in these patients.

However, the benefits of indirect decompression may be lost if the implant subsides through the endplates. In a study by Nemani et al., the authors performed a retrospective study on 117 patients who had stand-alone LIF [28]. A total of 10.3 % of patients who underwent stand-alone lateral lumbar interbody fusion ultimately required revision surgery. The most common reason for surgery was for persistent radiculopathy and symptomatic implant subsidence. Average time to revision was 10.8 months. A similar study was also performed by Marchi et al. [29]. At 12 months, 70 % in the standard group and 89 % in the wide group had grade 0 or I subsidence, and 30 % in the standard group and 11 % in wide group had grade II or III subsidence. Subsidence was detected early (6 weeks), at which point it was correlated with transient clinical worsening, although progression of subsidence was not observed after the 6-week time point. Moreover, subsidence occurred predominantly (68 %) in the inferior endplate. Fusion rate was not affected by cage dimension or by incidence of subsidence. Hence, subsidence is a concern with stand-alone LIF, and the addition of pedicle screws to provide additional stability is a good consideration.

Conclusion

Lateral interbody fusion has grown in popularity as a minimally invasive procedure. The approach allows for a smaller incision, less tissue disruption, and a quicker recovery. Hence, LIF satisfies many of the tenets of minimally invasive surgery. There is growing evidence that LIF is able to indirectly decompress the central canal and neuroforamen enough to result in a clinically significant improvement in function. However, LIF is less likely to provide indirect decompression in cases of severe congenital stenosis or if the facet joint arthropathy is severe enough to cause ankylosis of the joints. Preoperative imaging is important to identify these patients so that a formal decompression may be performed. Also, subsidence of the implants is a risk until fusion is achieved. So, posterior stabilization with pedicle screws is advised to avoid subsidence and recurrence of the stenosis.

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Approaching a Deformity from the Concavity Versus Convexity

31

Matthew F. Gary and Michael Y. Wang

31.1 Introduction

The minimally invasive lateral lumbar approach is gaining popularity for treating adult degenerative scoliosis. These patients generally present with chronic back pain, neurological compromise, and spinal deformity in multiple planes. Unfortunately, the traditional open approach for treating these patients has a high morbidity [1, 2]. The lateral lumbar approach can correct adult deformities in both the coronal and sagittal planes with less tissue dissection. These surgeries have been found to have a low complication profile and can provide adequate radiographic correction and improved clinical outcomes for a select patient population [3–16]. Unlike a posterior-only approach, the transpsoas approach requires the surgeon to choose an approach side preoperatively. Most of the studies examining the lateral approach for degenerative scoliosis omit the side of approach relative to the curve apex or approached from either side. Thus, there remains controversy concerning which side, concave versus convex, leads to better corrective ability and reduced complications.

31.2 Concavity Approach

The proposed benefits of approaching from the concave side of the spine include easier access to multiple discs from a single incision, better coronal alignment with positioning (when breaking the table), and a more complete opening of the concave annulus. Given the collapsed nature of the spine on the concave side and the corresponding favorable trajectory of the disc spaces, multiple discs can be accessed from a single incision on the concave side. Up to three intervertebral disc spaces can be approached from a single incision, while those same discs may not have been approachable from the convex side even with multiple incisions. Approaching from the concave side is also beneficial since improved coronal alignment can be achieved with bed positioning alone as the table can be broken toward the convexity. This cannot be done when approaching the convexity since breaking the table would actually worsen the coronal alignment. In addition, the ipsilateral annulus can be opened readily under direct visualization, thus improving the ipsilateral height increase with serial dilation.

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The disadvantages of approaching on the concave side include a more difficult access to the disc space, a theoretical higher risk to the lumbar plexus, and a longer depth needed to reach the spine. On the concave side, the disc space is usually completely collapsed making it much more difficult to access. When the endplates are touching, the surgeon must be extremely careful not to fracture into them during dilation. Greater downward forces are also needed to access the disc, thus increasing the risk of disrupting the endplates. This greater downward force may also increase the risk to the lumbar plexus. In addition, this approach places the surgeon at a greater distance from the spine making visualization and manipulation of instruments challenging.

The lumbar plexus is grouped closer together on the concave side and stretched as the patient's deformity is being corrected. Placing a retractor on these nerves as they are stretched could theoretically lead to increased neurologic compromise versus the concave side where the stretched nerves are being relaxed during correction. Scheer et al. performed a retrospective analysis of 32 patients who had a lateral lumbar approach for scoliosis and grouped the patients as convex versus concave based on the side of approach [17]. They had 17 patients approached from the concave side and 15 patients approached from the convex side. There was a higher incidence of postoperative neurological deficit in the concave group; however, it did not reach statistical significance.

The sequence of disc removal can be important when approaching from the concave side. Particularly when spanning the whole lumbar spine, it can be difficult to reach the cranial and caudal ends of the construct. If one begins with discectomy and cage placement in the apex (mid-lumbar spine), then the cranial and caudal disc spaces are pushed away from the incision as the spine lengthens. Thus, one should potentially prepare to treat the cranial and caudal discs first. Managing the ends of the construct first allows for the best chance to reach the most difficult discs (Fig. 31.1).

31.3 Convexity Approach

The potential benefits of approaching from the convex side of the curve include more thorough and easier discectomy, uniform distraction of the disc space with downward forces, relaxation of the retracted lumbar plexus during correction, and shallower approach to the spine. The disc space on the convex side is usually readily accessible and lends itself to a more complete discectomy. In turn, less downward force is needed for the distraction of the contralateral side. As the curve is corrected, theoretically the ipsilateral lumbar plexus would be relaxed and be less affected by the retractor. Finally, the depth to the spine is shallower on the convex side making visualization and manipulation of the instruments less convoluted.

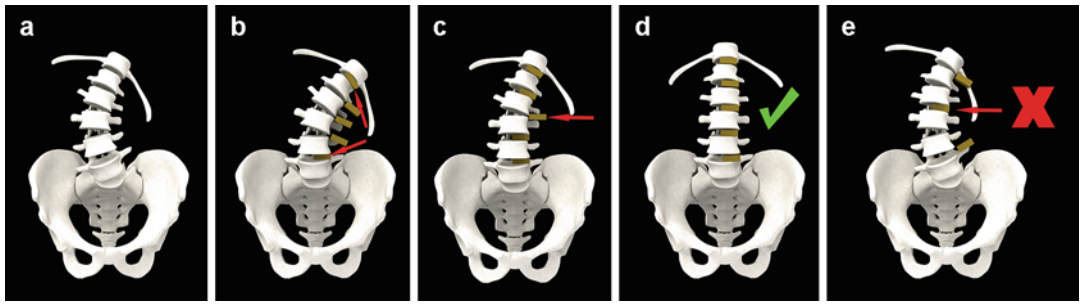


Fig. 31.1 Access through the concavity may have to be planned in regard to which discs are approached first. (**a**) The spine prior to interbody fusion; (**b**) accessing the most cranial and caudal disc spaces first (**c**) and fusing the apical discs last (**d**) allow for the most reliable correction; (**e**) fusing the apical disc first may lead to more difficulty reaching the ends of the construct as they are successively pushed farther from the access site with each interbody graft that is placed

A convex approach also means that entry into the disc space duplicates a natural wedge to open the concavity of the spine. The larger annulus and reduced osteophytic overgrowth on the convexity of the spine also make identification of the starting point easier. This minimizes the risk of inadvertent violation of the endplate, which is a particular concern with osteoporotic patients. As rectangular cages are inserted, the disc space will be distracted in a more natural manner.

On the other hand, the disadvantage to the convex approach is the inherent difficulty in approaching multiple disc spaces, worsening of the deformity with positioning and blind opening of the contralateral annulus. Given the trajectory of the disc spaces on the concave side, if one were to truly approach them perpendicularly, the required site of skin entry would be prohibitive. Thus, one must anticipate the degree of correction when planning the skin entry. Also, the surgeon cannot take advantage of the table break in correcting the deformity as the break actually worsens the coronal imbalance when approaching from the convex side.

Finally, the contralateral annulus (the concave annulus) must be completely opened to achieve adequate alignment. The concave annulus can only be opened blindly from the convex side with progressively wider dilators. Thus, the coronal correction could be hampered by an inadequate annulotomy on the concave side.

31.4 The Importance of L4/L5

Many surgeons will simply approach the spine from the side on which L4/L5 can be accessed. This is often the most challenging level in the sense that the risk of neural injury is the greatest, the psoas muscle is the thickest, the pelvis is often in the way, and it is the most distal segment to be treated. The L4/L5 disc space is often asymmetric in cases of lumbar degenerative scoliosis. Thus, one can choose to approach the side that is most open and approachable given the relationship of the spine to the pelvis (Figs. 31.2 and 31.3).

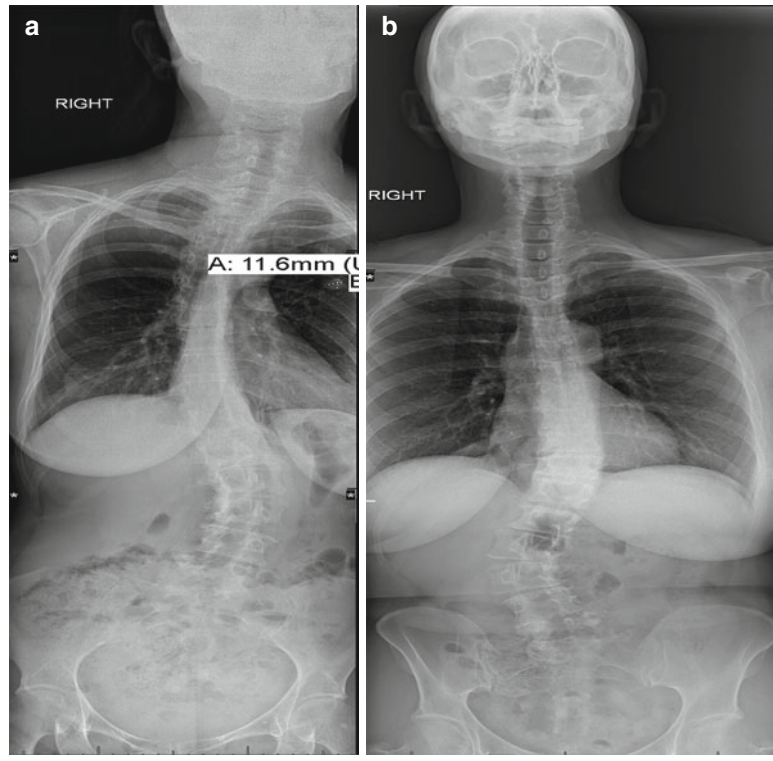


Fig. 31.2 Approaching from the side that allows access to the L4/L5 interspace is a common strategy, given the relationship of the spine to the pelvis. (**a**) A patient that should be approached from the right and (**b**) one that would be approached from the left if L4/L5 is to be fused

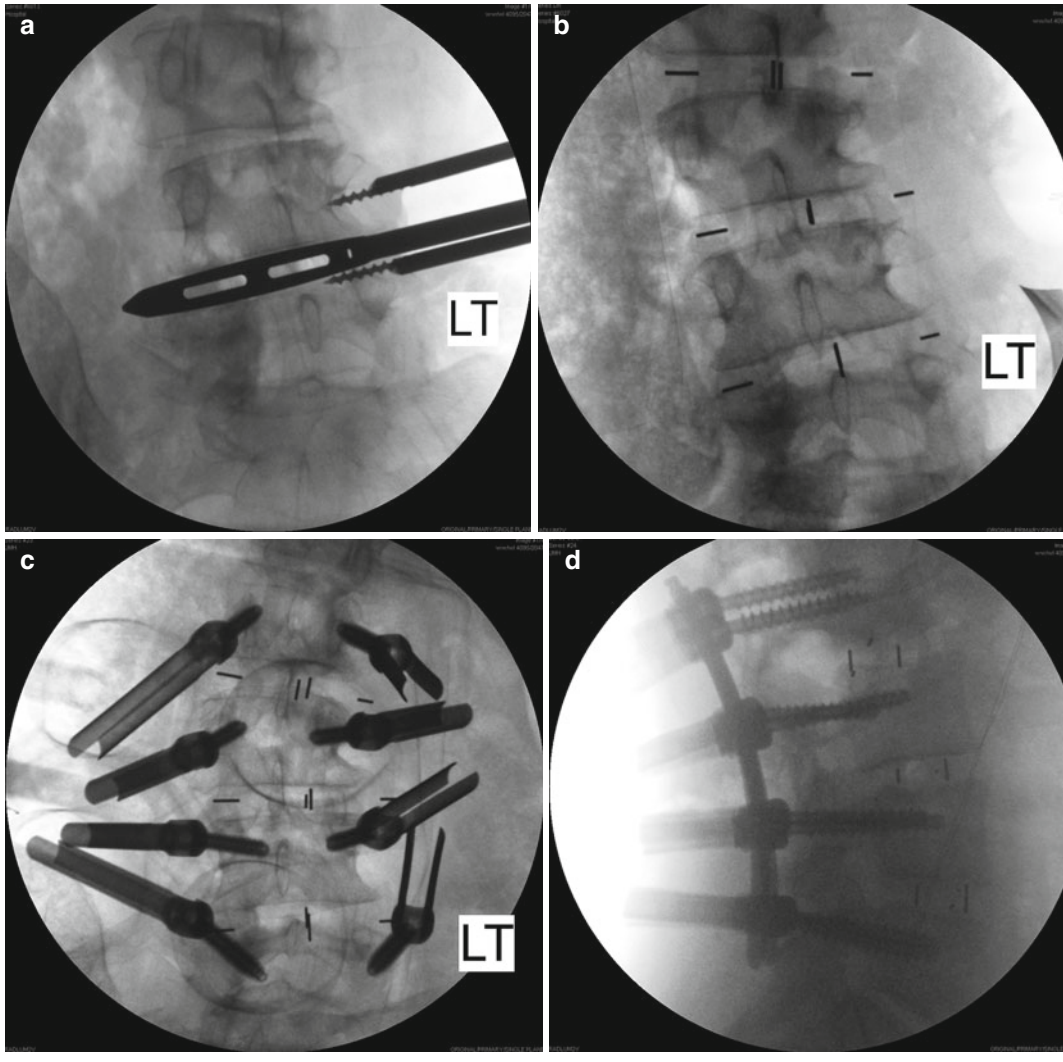


Fig. 31.3 Patient example of a fusion from L2–5 from a right lateral approach given the obscuration of the disc space on the right by the pelvis. (**a**) The interbody distraction at L4/L5, followed by (**b**) interbody cages being placed at all three levels. (**c**) Percutaneous screws are then placed, (**d**) followed by connecting rods and (**e**) the final construct

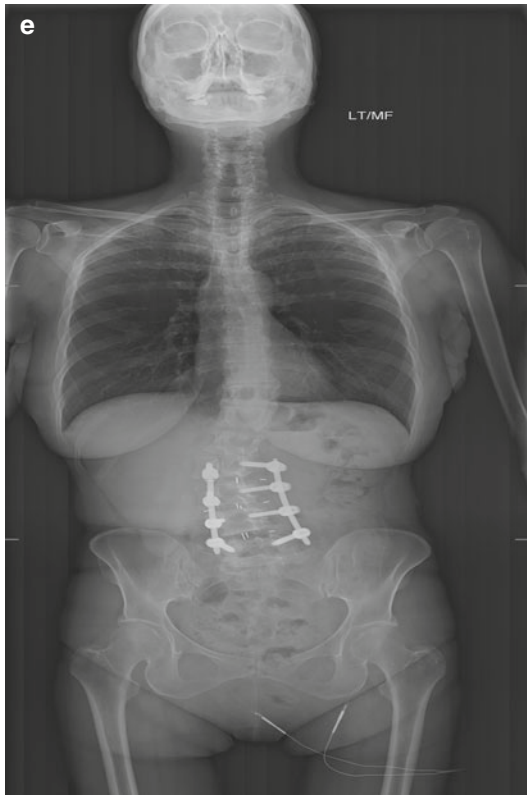


Fig. 31.3 (continued)

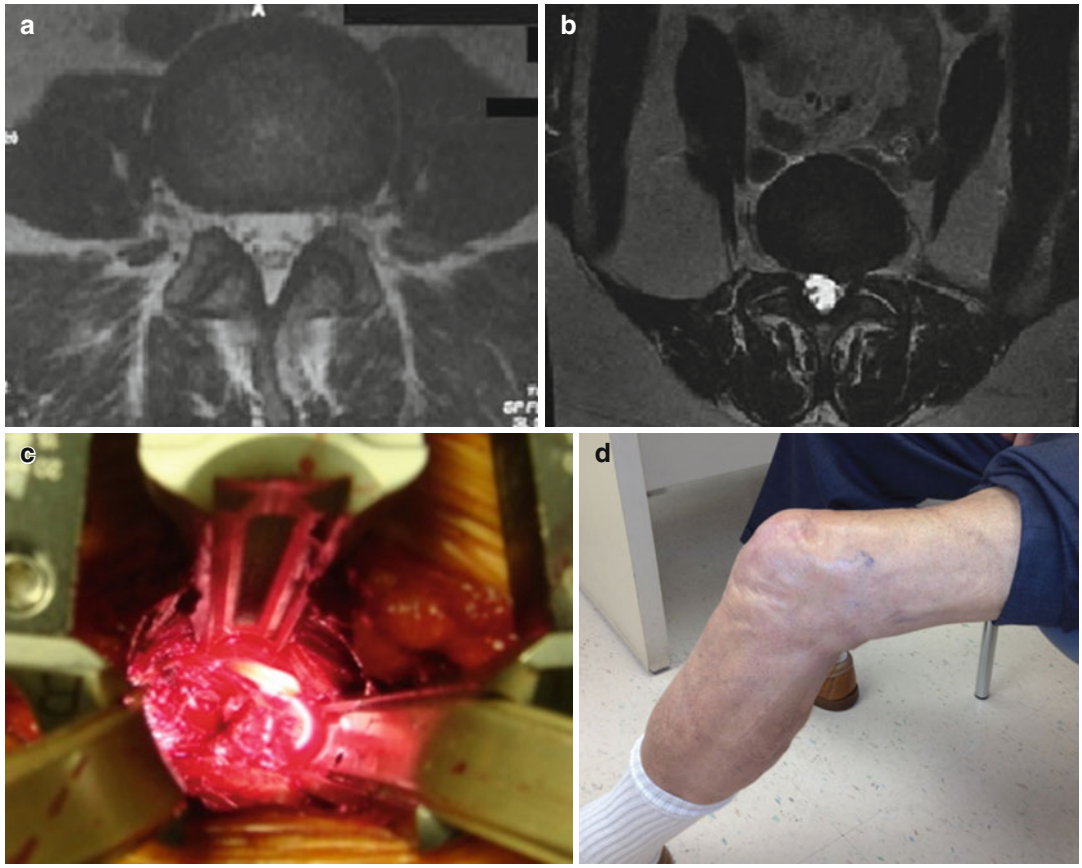


Fig. 31.4 The axial view of the psoas muscle on T2-weighted MRI demonstrating (**a**) a normal uniform muscle allowing for safe navigation of the lumbar plexus versus (**b**) a "rising psoas" which moves anterior to the spine, bringing the lumbosacral plexus with it and putting nerves at risk for a lateral approach. (**c**) A view through the tubular retractor showing a lumbar plexus nerve and (**d**) quadriceps atrophy in a patient with a femoral nerve retraction injury

31.5 Additional Considerations

The lateral surgeon must pay particular attention to anatomy not normally considered in spinal surgery. The size, shape, and location of the psoas muscle are important as the surgical corridor classically traverses this structure. In addition, the lumbosacral plexus is typically invested in this muscle, and avoidance of injury to this muscle also minimizes the risk of thigh numbness, dysesthesias, pain, and weakness. The finding of an anteriorly located muscle, called the "Mickey Mouse sign" or "rising psoas sign," should dissuade the surgeon from taking a direct lateral approach. In these instances and at these spinal levels, an anterior, oblique, or posterior approach is preferable (Figs. 31.4 and 31.5).

The surgeon must also respect the fractional curve, which is typically below the major curve at the L4–S1 levels. This curvature forms the base of the spine, and in many cases, straightening of the major curve but failure to address the fractional curve can result in turning a balanced scoliosis into one with a coronal malalignment.

Conclusion

The lateral lumbar approach for treatment of adult degenerative scoliosis is a powerful tool that can improve outcomes and reduce mor-

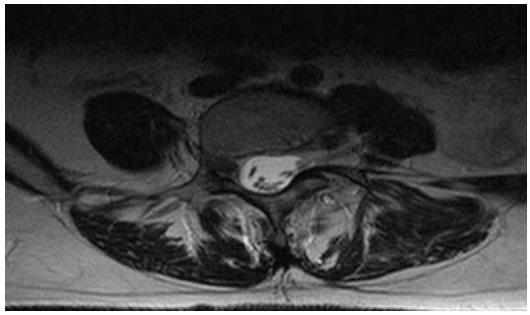


Fig. 31.5 Axial T2-weighted MRI showing asymmetry of the psoas muscle in a professional golfer. The anatomy on the side is more favorable for the approach from the left side given the likely location of the lumbosacral plexus as being more posteriorly located

bidity. However, surgeon experience and appropriate preoperative planning are important for a successful outcome. The choice in approaching from the concave versus convex side is, to date, based on surgeon preference. Larger studies are required to determine which side, if either, leads to less neurologic compromise, fewer incisions, better coronal and sagittal balance, and overall better outcomes.

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Awake Lateral Lumbar Fusion

32

Xifeng Zhang and Brandon Gaynor

Lateral lumbar fusion, performed on awake patients, under local anesthesia with conscious sedation, is not widely practiced. Proposed advantages of performing surgery under conscious sedation include reliable monitoring of femoral nerve function, decreased complications of anesthesia, decreased cost, and enhanced recovery time. Increased availability of long-acting local anesthetics, improvements in endoscopic visualization, and economic pressures to contain cost are likely to encourage the expanded use of awake lumbar fusion techniques. Particularly in China, intraoperative electrophysiologic monitoring is not commonly used in clinical practice, motivating us to perform this procedure without general anesthesia.

Careful titration of anesthesia has been refined as follows for sedation, analgesia, and anesthesia:

1. Dexmedetomidine hydrochloride injection with a dose of 1 μg/kg body weight, 4 μg/ml concentration, infused for at least 10 mins.
2. Droperidol 5 mg and 0.1 mg fentanyl infused for over 2–3 mins. If the desired anesthetic effect is not achieved in 5 min, repeat a half dose.
3. For single-level fusion, 40 ml 1 % lidocaine, and for multilevel, 120 ml 0.25 % lidocaine.

Once the patient is optimally sedated, the patient is positioned lateral decubitus as has been described elsewhere in this text. Access into the disc space is achieved after marking the entry site with CT-guided needle placement. A guide wire is placed through the spinal needle, and sequential tubular dilators are used to dock on the psoas muscle at the level of interest (Fig. 32.1). The discectomy and endplate preparation can then be performed in the usual fashion with the assistance of a microscope for magnification and illumination.

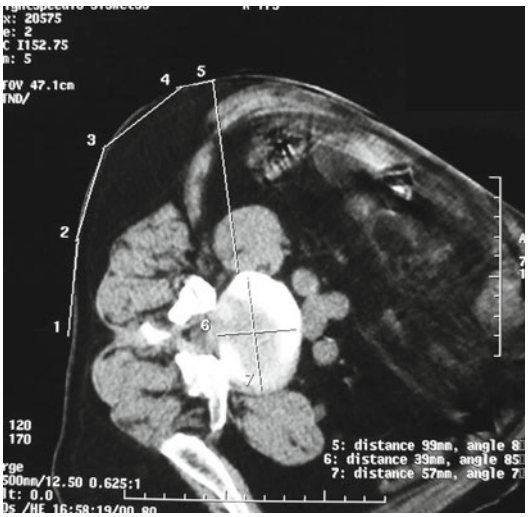


Fig 32.1 Marking the safe entrance point at the lateral position under the CT scanner

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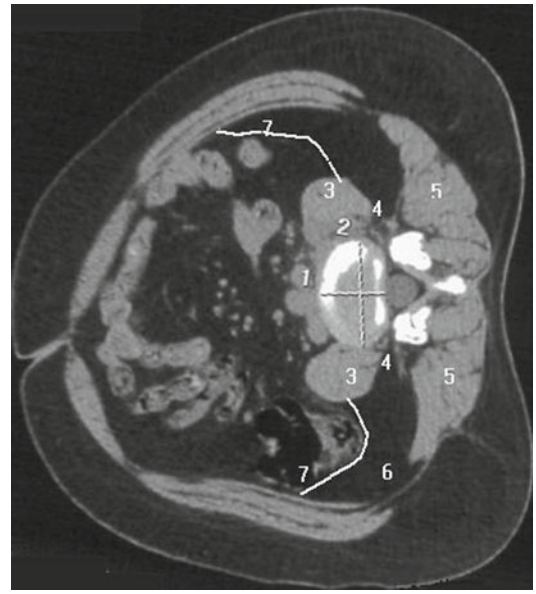
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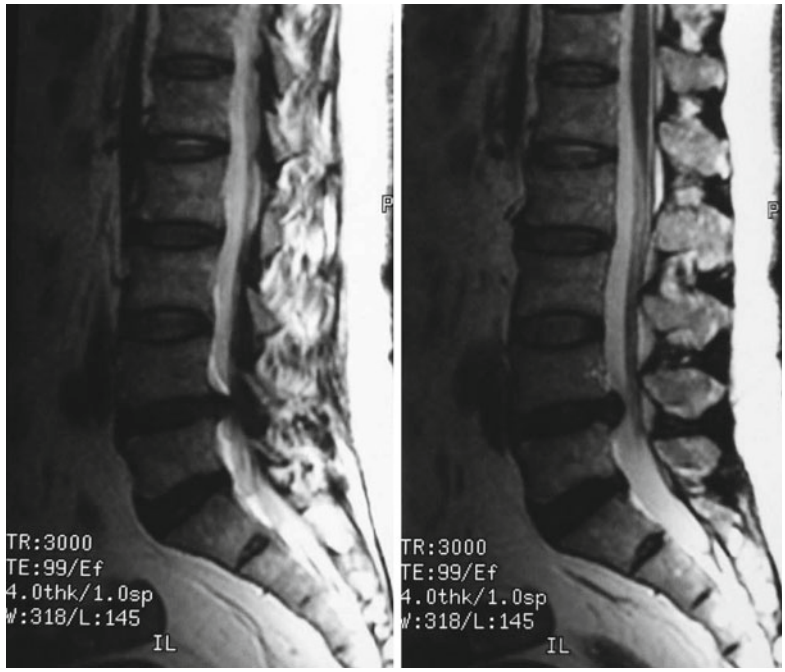
M.Y. Wang et al. (eds.), *Lateral Access Minimally Invasive Spine Surgery*,
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Illustrative Case 1 A 57 years old male presented with pain in the low back and leg with intermittent claudication combined. Past medical history was significant for diabetes. At first, his colon was scanned on his left side on the lateral position in the CT room, and the safe entrance point was marked. During the operation, the long needle punctured through L45 intervertebral disc space according to the premarked entrance point. After confirmation, the thread was placed. Under the guidance of the guide wire, the thread was expanded step by step, and the appropriate working tube was set up. Then the intervertebral disc was removed; the endplate was stricken off. The autogenetic iliac bone was taken from the spina iliaca posterior superior, and the cage was imbedded. The operation was finished. After 5 years of follow-up, the patient's symptoms were relieved, and no further treatment was needed.

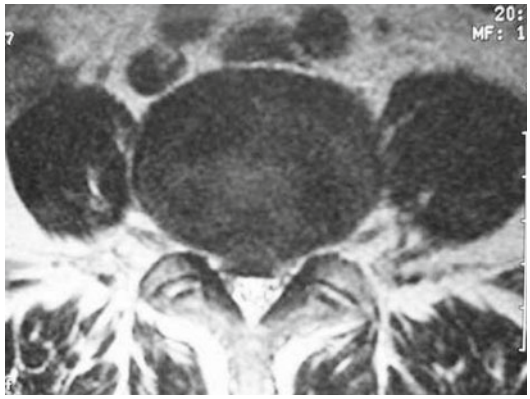


1 Aorta abdominalis, *2* intervertebral disc entrance point, *3* psoas major, *4* ischiadic nerve, *5* musculus sacrospinalis, *6* retroperitoneal fat, *7* colon descendents

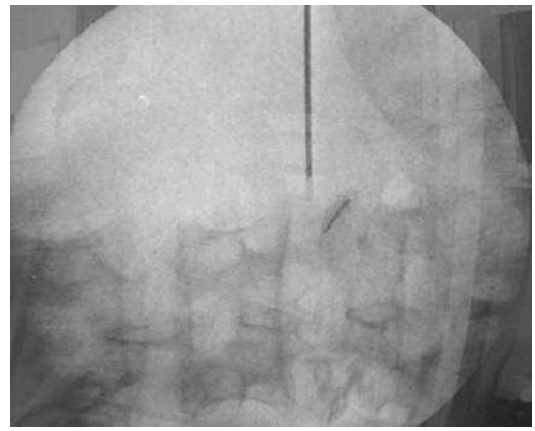




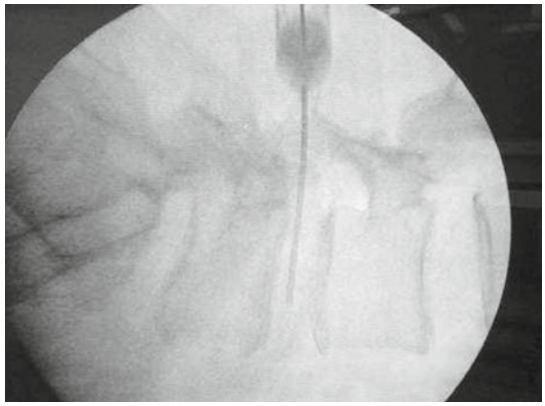
Preoperative MRI

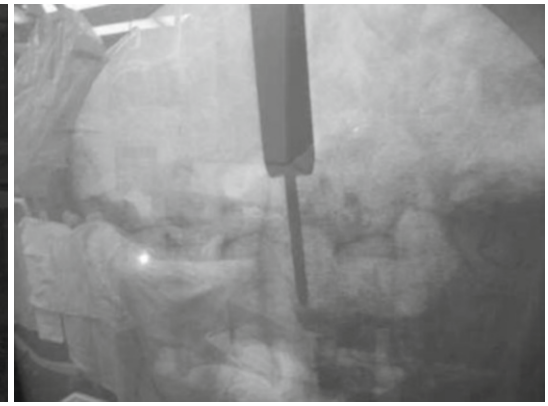


Percutaneous fluoroscopic-guided needle placement

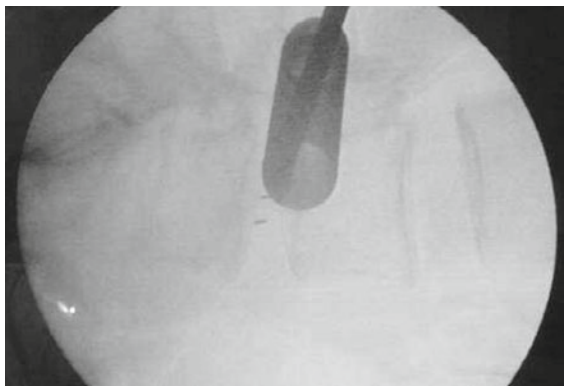


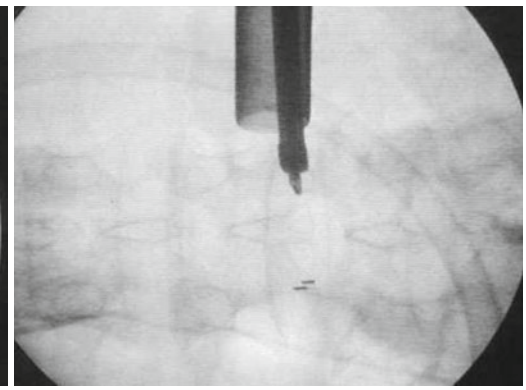
Port placement docked onto the surface of the disc over dilator

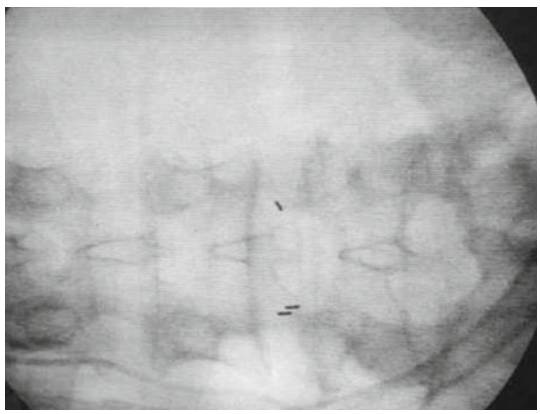


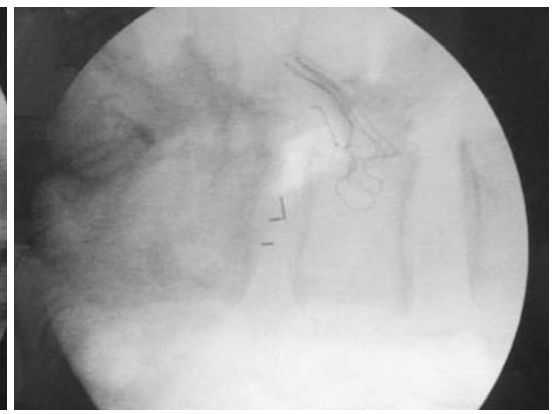


Placement of the structural allograft through the tubular dilator under fluoroscopic guidance







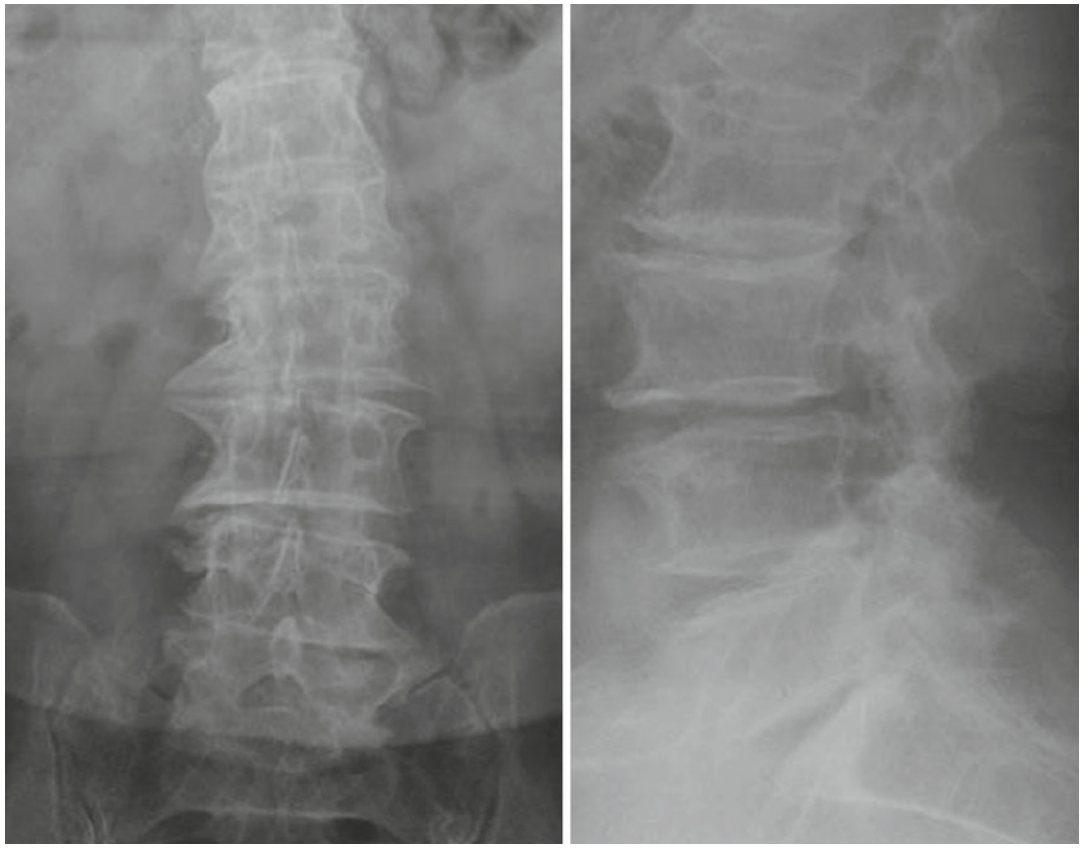


Simple closure of two small incisions

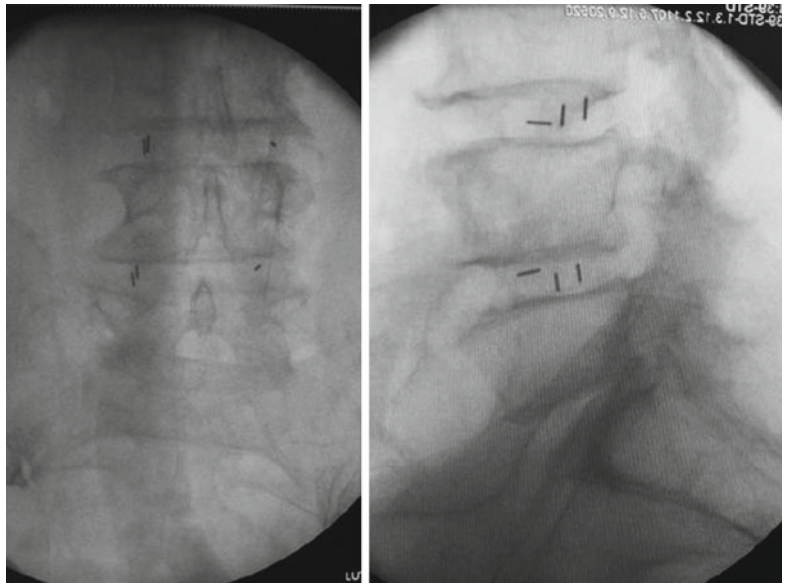


Illustrative Case 2 A 67 years old female with low back pain and neurogenic claudication diagnosed with lumbar stenosis and degenerative disc disease was treated with two-level lateral awake lumbar fusion. A two-year follow-up demonstrated failure of fusion; however, the patient's symptoms remained alleviated.

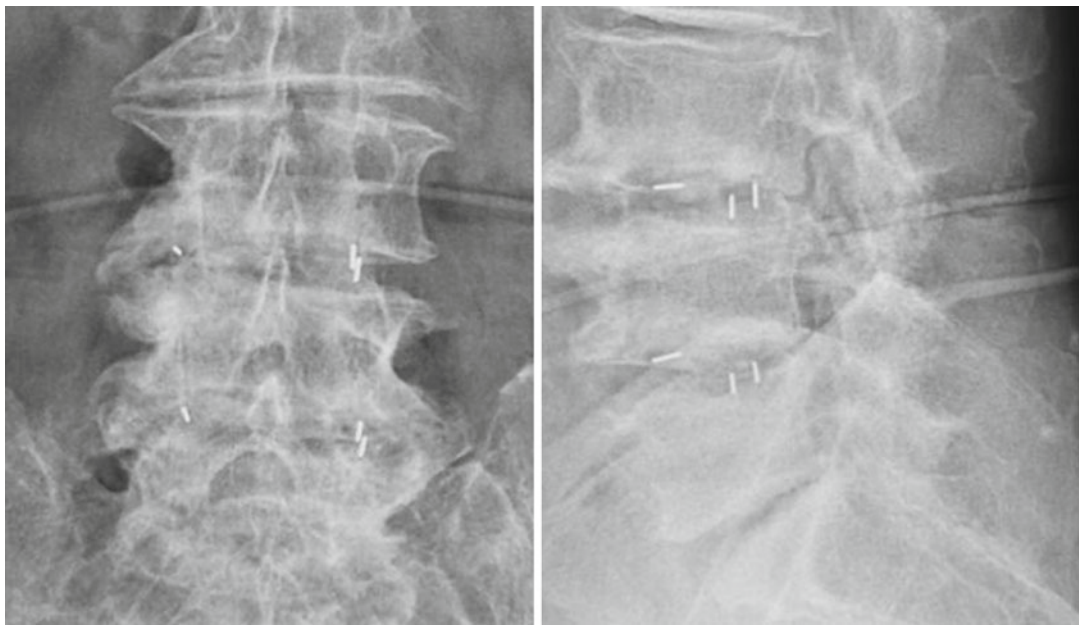
Preoperative radiographs demonstrating loss of disc height



Intraoperative radiographs confirming appropriate graft placement



30-month follow-up x-ray demonstrating failure of bony fusion

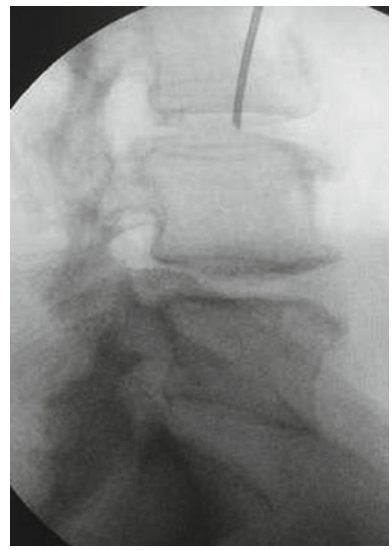


Our bias is now to supplement lateral lumbar fusion with posterior percutaneous pedicle screw fixation.

Needle accessing the intervertebral disc

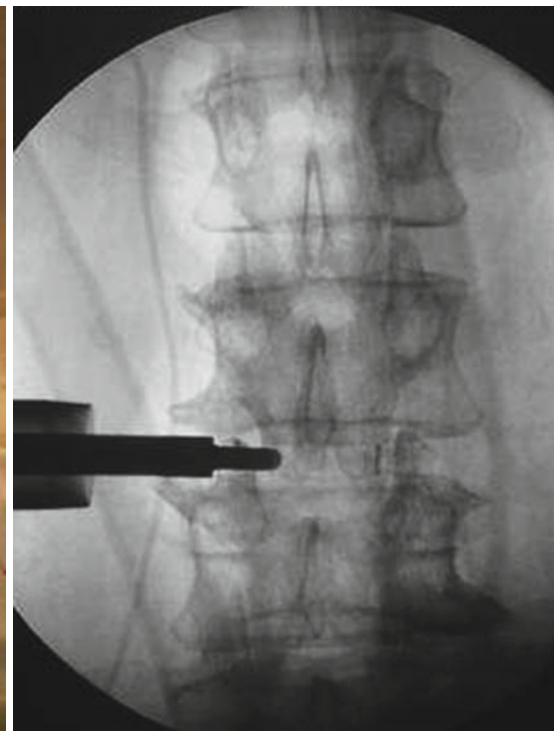


Confirmation of the needle placement into the center of the disc space. Care is taken to avoid being too close to the neural elements or viscera

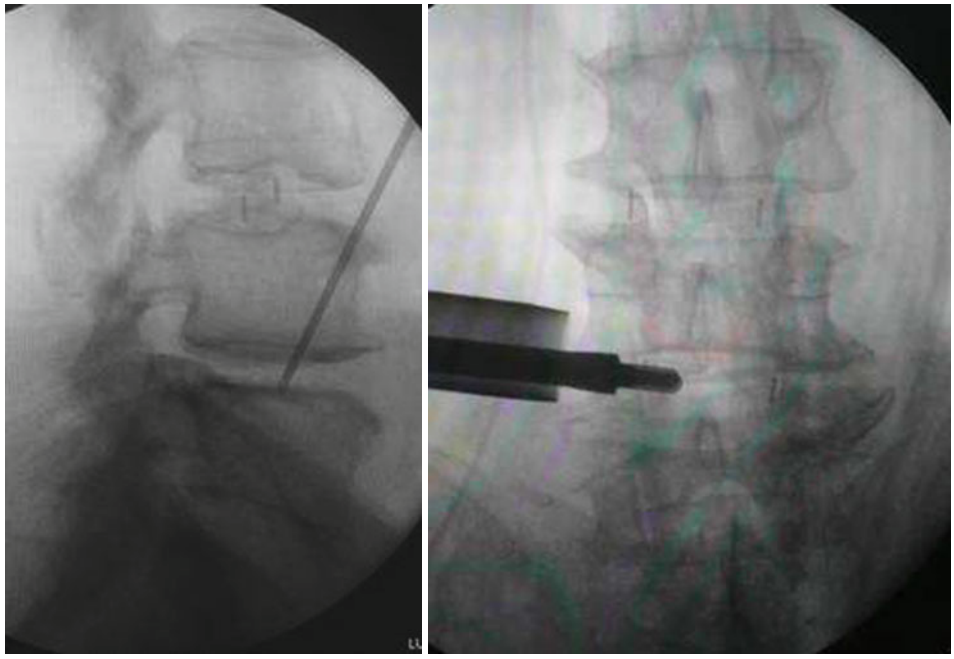


Placement of structural allograft through tubular port

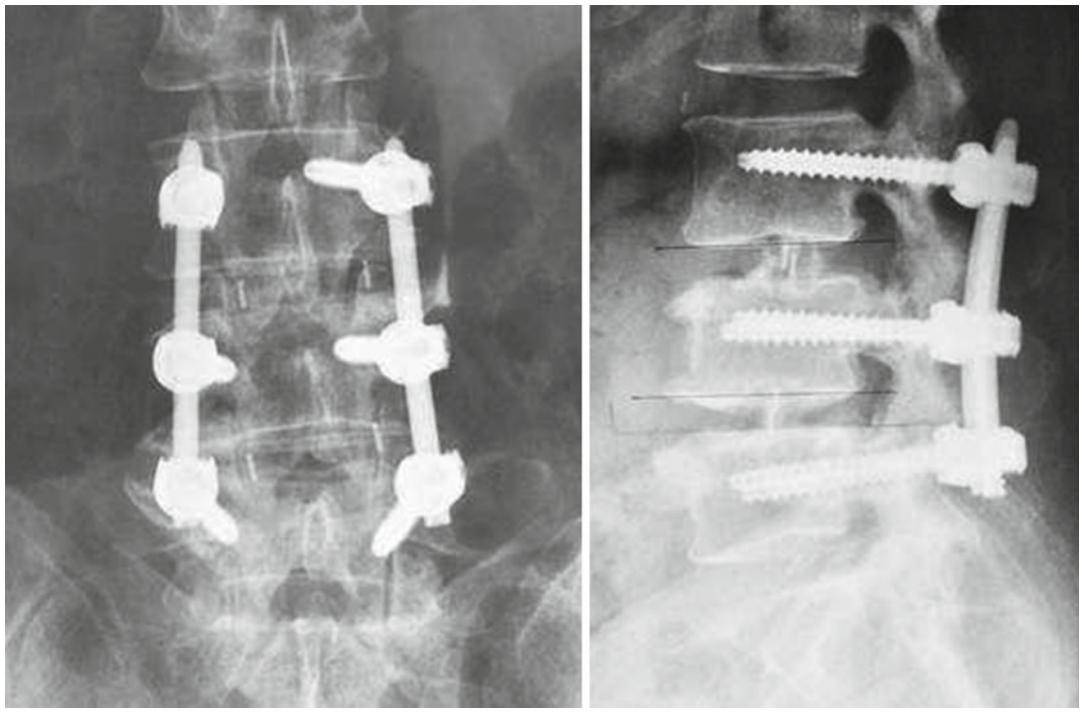




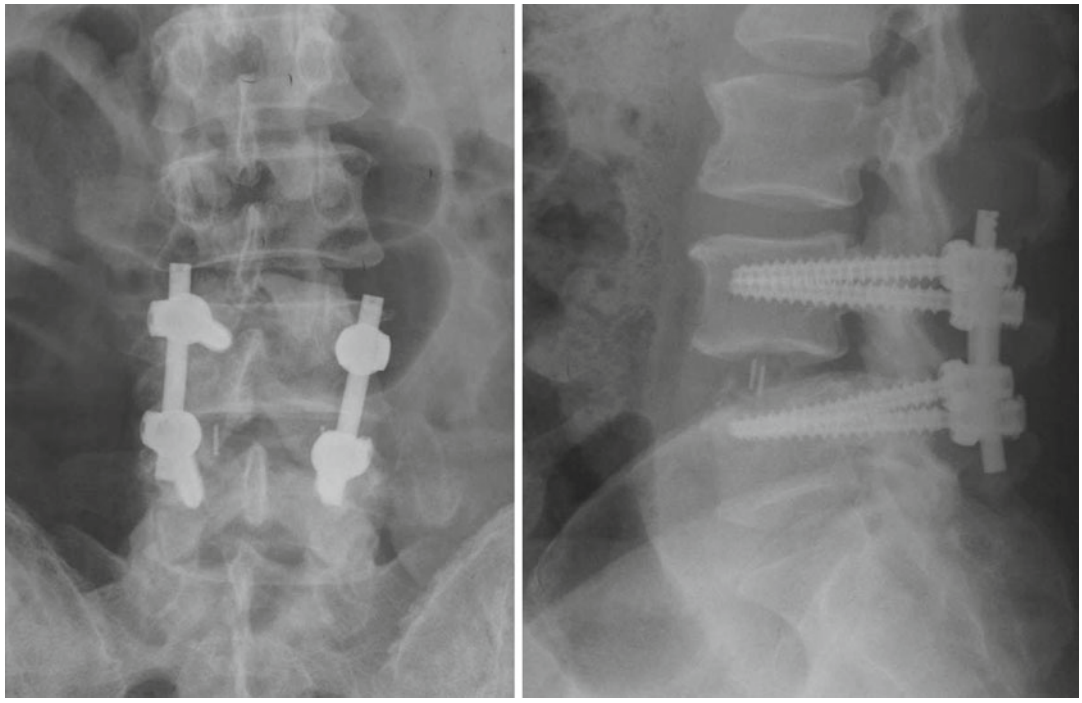
The technique is repeated for additional levels as indicated



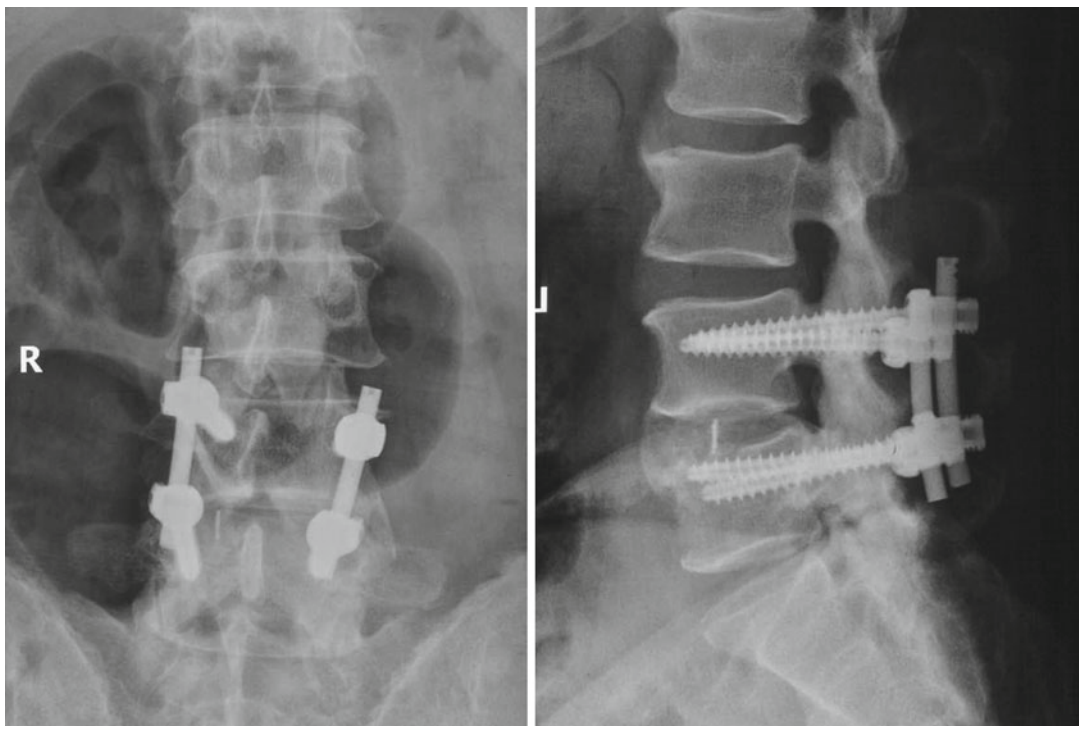
Postoperative AP and lateral radiographs after graft placement and segmental fixation. Most commonly, we use allograft cages packed with autogenous bone from the iliac crest sized 32 × 10 × 10 mm



Postoperative AP and lateral radiograph of single-level percutaneous awake lateral lumbar fusion

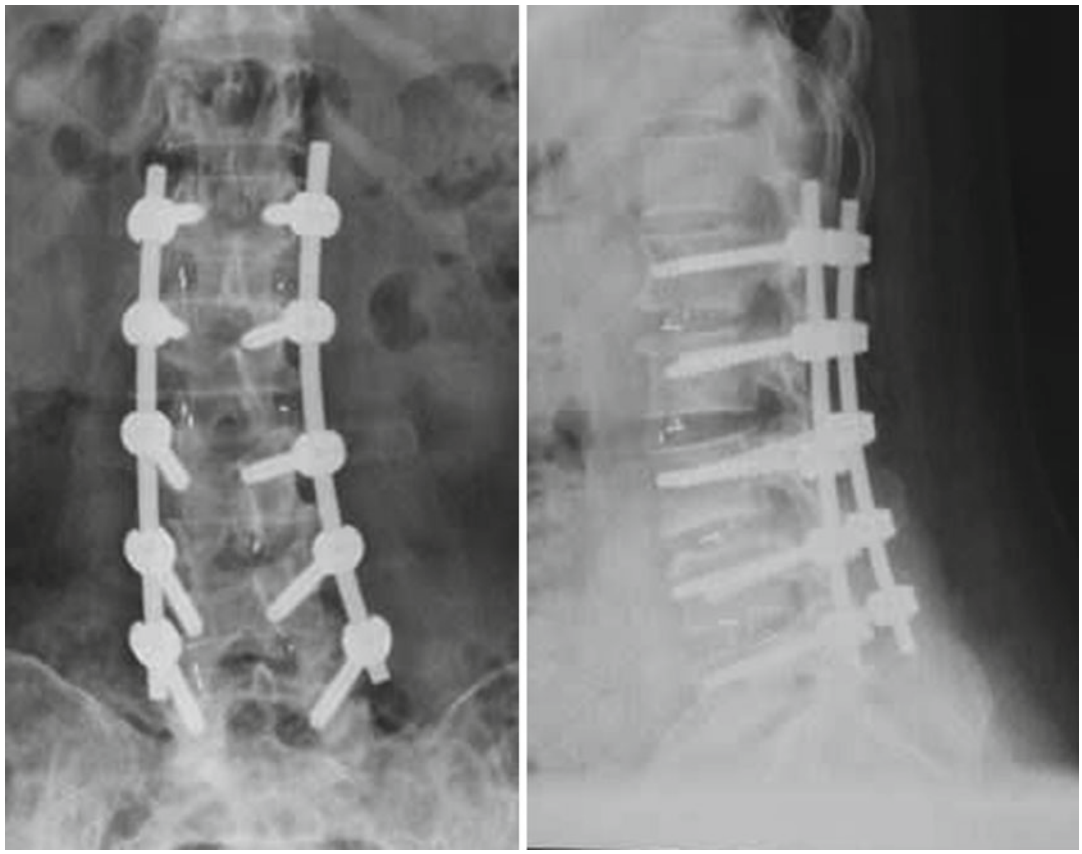


Two and a half years follow-up, solid fusion, and maintenance of intervertebral height. Percutaneous pedicle screws can be placed from the lateral position or prone position depending on surgeon preference



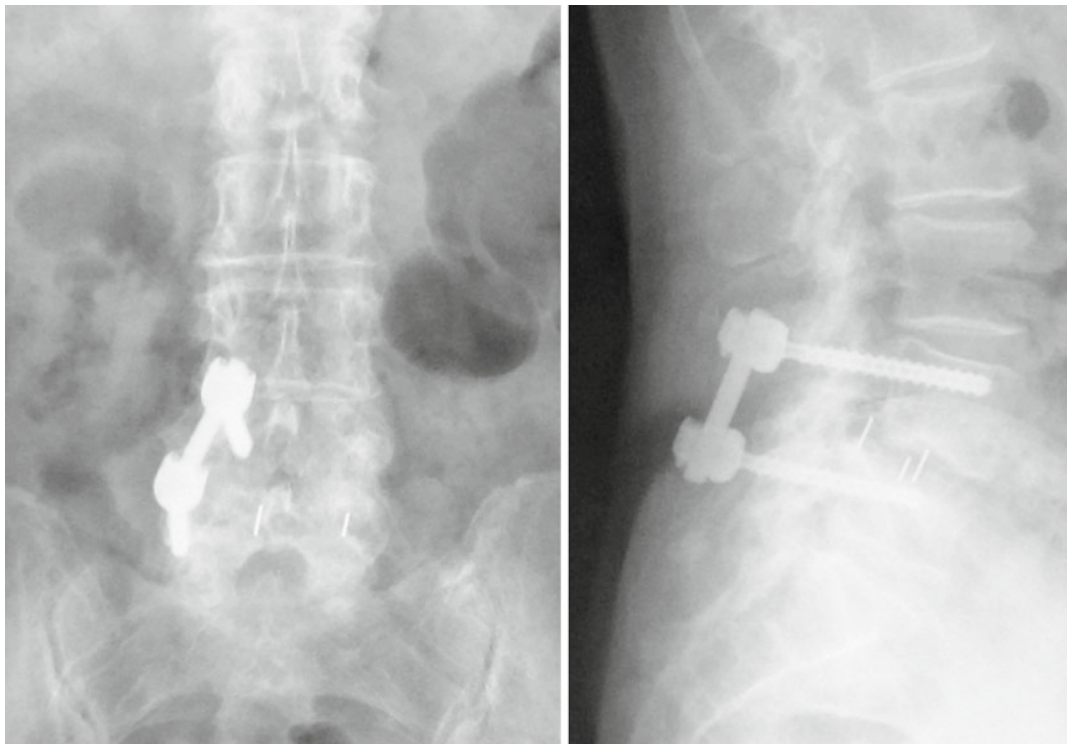
This technique has also been used successfully up to four levels; however, patient tolerance and procedure duration must be considered





4-year follow-up radiographs in a pain-free patient





The technique described in this chapter has been used in 32 conscious patients undergoing lateral lumbar fusion with local anesthesia. In 29 of these cases, pedicle screw fixation was also performed. One patient occurred (1 week) graft migration who requiring revision lumbar interbody fusion from a posterior approach. This technique has also been shown to be feasible for multilevel fusions. Three-level fusions were performed in six patients (five with scoliosis deformity); however, one case was converted to general anesthesia prior to posterior fixation. In the majority of cases (26/32), fusion was indicated for instability in lumbar stenosis. One case was converted to posterior transforaminal interbody fusion when neurological responses caused us to abort the procedure.

Part VI

Managing and Preventing Complications

Managing and Preventing Vascular Complications

33

Asdrubal Falavigna and Orlando Righesso Neto

33.1 Introduction

The anterior approach to the lumbar spine places the patient at risk for a number of significant intraoperative and perioperative complications. These complications include vascular injury (1.3–15.6 %), damage to the abdominal organs (<1 %), disruption of the sympathetic plexus (1.7–13.3 %), and postoperative ileus (0.6–5.6 %) [1–4]. Newer surgical techniques, innovation in instruments, and precise radiological localization and guidance have been constantly developed to minimize surgical risks, decrease the hospital stay, and potentially improve patient satisfaction [5].

The lateral approach to the lumbar spine is a relatively novel method for performing minimally invasive lateral interbody fusions. The lateral approach allows the surgeon to perform discectomy, anterior longitudinal ligament release, interbody cage placement at the apophyseal ring where the bone is strongest, disc height restoration, and deformity correction and fixation [5–7]. The technique can be further improved by the use of an endoscopic device to adequately view all the structures [6]. This approach can avoid some of the anterior complications of access [5, 6].

Despite the technological advances and surgeons' skill during the minimally invasive lateral interbody fusions, the patient can be at risk for a number of significant intraoperative and perioperative complications. Injury to the retroperitoneal vessels is one of these potentially catastrophic situations.

33.2 Vascular Anatomy of the Anterior and Lateral Region of the Lumbar Spine

The abdominal aorta artery runs the length from the diaphragm aortic hiatus at the level of the T12–L1 intervertebral disc to the level of L4 where it divides into the two common iliac arteries. The inferior vena cava is formed at the fifth lumbar vertebra by the union of the common iliac veins and ascends to the right of the median plane. The aorta artery is ventral to the inferior vena cava and lumbar vertebral bodies and sits slightly to the left, whereas the vena cava is located slightly to the right (Fig. 33.1).

The abdominal aorta arises and branches from the ventral wall (celiac, superior

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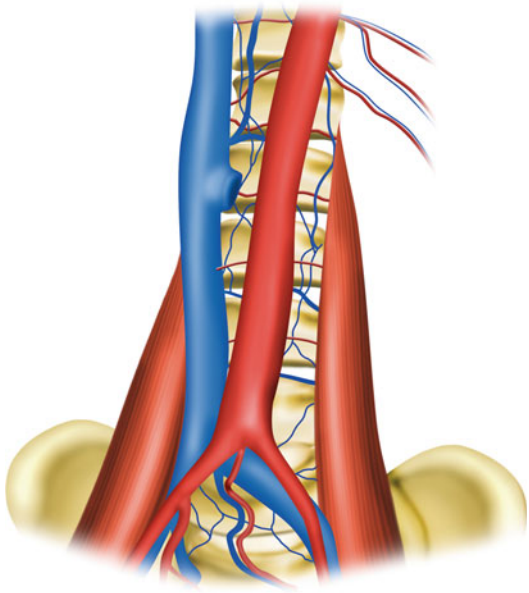


Fig. 33.1 Anterior view of the retroperitoneal vascular vessels. The aorta artery runs to the *left* and divides at the L4–L5 intervertebral disc into the two common iliac arteries. The inferior vena cava is formed at the fifth lumbar vertebra by the union of the common iliac veins and ascends to the *right* of the median plane

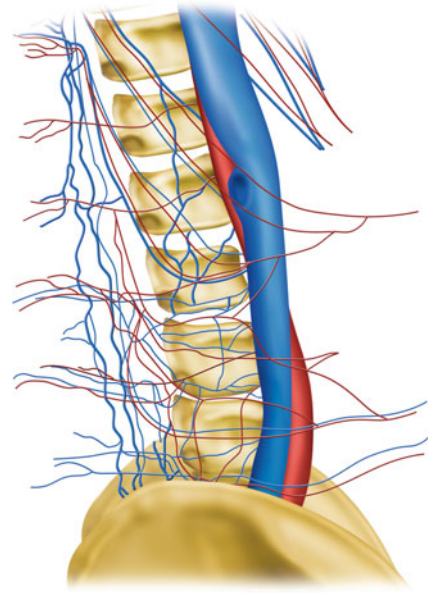


Fig. 33.2 *Right* lateral view of the lumbar spine where the lumbar arteries run dorsal to the inferior vena cava. The inferior vena cava migrates as it descends from zone A at L1 to zone I at L5

mesenteric, and inferior mesenteric arteries) and lateral wall (renal, the middle suprarenal, and the testicular or ovarian arteries). The four pairs of lumbar arteries arise dorsolaterally and their course is dorsomedial. On the right, they run dorsal to the inferior vena cava, dividing between the transverse processes into the ventral and dorsal branches (Fig. 33.2). The dorsal branch passes dorsally lateral to the articular processes and supplies mainly the spinal cord and cauda equina. The largest of these dorsal branches denominates the radicularis magna artery (Adamkiewicz).

Tributaries of the inferior vena cava are the common iliac veins (L5), the lumbar veins, the right testicular or ovarian vein (the left drains into the left renal vein), the renal veins, the azygos vein, the right suprarenal vein (the left also drains into the renal vein), the inferior phrenic veins, and the hepatic veins. The lumbar veins consist of four or five segmental pairs. They may drain separately into the inferior vena cava or the common iliac vein.

The distribution of abdominal large vessels and the psoas major of each lumbar intervertebral space is inconsistent. Lumbar intervertebral spaces were divided in six zones from the anterior to the posterior border of the vertebral body [8]. The anterior aspect of the anterior margin of the vertebral body was defined as zone A and the posterior aspect of the posterior margin as zone P; zones I, II, III, and IV were distributed equally between the anterior margin and the posterior margin from the anterior to the posterior, respectively.

The inferior vena cava on the right side migrates from zone A to zone I as it descends from L1 to L5 [9]. Based on the distribution of the inferior vena cava, the right-side extreme lateral interbody fusion (XLIF) approach does not injure the vena cava at zones II–P of intervertebral spaces L1/L2, L2/L3, L3/L4, and L4/L5 (Fig. 33.2) [10].

The abdominal aortas at intervertebral spaces L1/L2, L2/L3, and L3/L4 were located mostly to the left of zone A, 95.8 %, 85.4 %, and 79.1 %, respectively [9]. At the L4/L5 intervertebral space, about 62.6 % of the abdominal

aortas are divided into bilateral iliac arteries, and these branches were located at zone A (Fig. 33.3) [9]. Left-side XLIF approaches at zones II–P of L1/L2–L3/L4 intervertebral spaces and at the I–P zone of L4/L5 intervertebral space do not injure the aorta [9]. The approach must pass through the psoas major at zone II of L3/L4 to avoid injuring the aorta and nerve root or else pass through the psoas major at zones I–II of L4/L5 [9].

For convenient operation, the surgery should be performed through the psoas major via the location between zone II and zone III of both lumbar intervertebral spaces of L1/L2 and L2/L3 [9]. This would not injure the vena cava and nerve plexus. The approach must be through the psoas major at zone II of both L3/L4 and L4/L5 to avoid injury to the vena cava and plexus (Figs. 33.3 and 33.4) [9].

The position of either the inferior vein cava or right common iliac vein with respect to the anterior intervertebral plane measured −4.3 mm at L1–2, −1.3 mm at L2–3, even with the anterior intervertebral plane at L3–4, +2.1 mm at L4–5, and +4.9 mm at L5–S1 (Fig. 33.1) [11]. When a "typical" 20-mm operative corridor is used, the neurovascular structures would be vulnerable to injury at L4–5 in 21 and 44 % of patients when using left- and right-sided approaches, respectively (Figs. 33.2 and 33.3) [11].

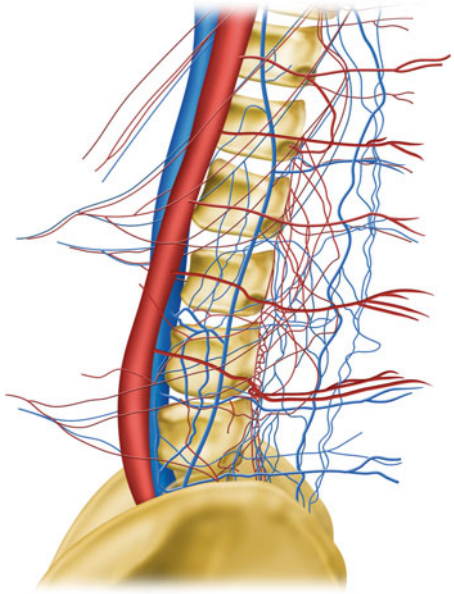


Fig. 33.3 *Left* lateral view of the lumbar spine where the aorta artery migrates is located at zone A in the intervertebral spaces L1/L2, L2/L3, and L3/L4. In the L4/L5 intervertebral space, about 62.6 % of the abdominal aortas are divided into bilateral iliac arteries, and these branches were located at zone A

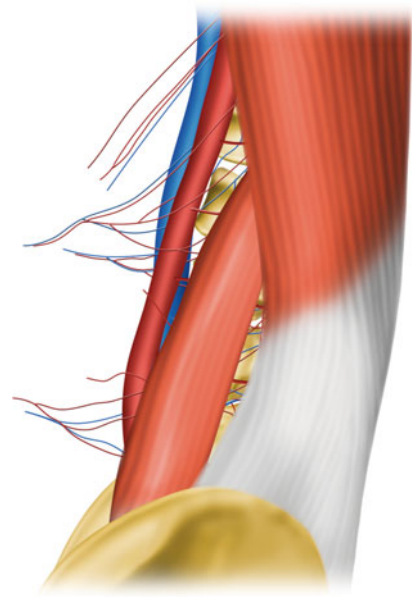


Fig. 33.4 *Left* lateral view of the lumbar spine where the psoas major is located over the lumbar spine

33.3 Incidence of Vascular Complications in Lumbar Spine Surgery

Injury to the retroperitoneal vessels can occur after posterior, anterior, or lateral approaches to the lumbar spine.

33.3.1 Posterior Approach

Vascular lesion in the posterior lumbar interbody fusion techniques is uncommon (0.05 %) and usually associated with discectomy [12] or guidewire advancement into the vascular vessels during the placement of percutaneous pedicle screws [13, 14].

33.3.2 Anterior Conventional Approach

There are a much greater number of vascular injuries by anterior approach. The number ranges from 1.3 to 15.6 % due to the presence of the great vessels and their branches and tributaries in the surgical field or nearby where they can be inadvertently injured either during dissection or during retraction [2].

33.3.3 Lateral or Extreme Lateral Retroperitoneal Transpsoas Approach

In the largest XLIF series published, there was no report of vascular complications following the surgery in 600 patients and at 741 levels [15]. Vascular injury by XLIF procedure is only published as a case report of iatrogenic lumbar artery pseudoaneurysm following XLIF when endovascular embolization was performed [16].

33.4 Surgical Features in Lateral Retroperitoneal Transpsoas Interbody Fusion

The use of XLIF in the lumbar spine cephalic to L5–S1 circumvents the dissection and retraction of the large retroperitoneal vessels that is one of the major complications of the anterior approach and consequently minimizes the risk of vascular injuries [15, 17, 18].

The XLIF technique uses a small 3-cm incision that limits the visualization of the surgical field and exposes the surgeon to problems and hazards that do not exist when doing similar procedures in an open technique. Surgeons depend on high-quality fluoroscopic imaging and must rely on intraoperative fluoroscopic images and electromyography monitoring during most of the procedure. Specific risks include injury to the exiting nerve root and laceration of the retroperitoneal vessels during the deployment of the surgical retractors and the discectomy procedure [18].

The neurovascular structures would be vulnerable to injury at L4–5 in lateral transpsoas approach with a higher incidence using right-sided (44 %) rather than left-sided (21 %) approaches [11].

The surgeons must bear in mind that it is usually during L4–L5 XLIF that a high percentage of patients require neurovascular retraction, especially on the right side. The neurovascular anatomy must be well studied during preoperative planning in order to detect the patients that may not be ideal candidates for this approach [11]. Besides neurovascular retraction, the risk of vascular lesion is significantly increased at the L4–L5 level because the more anterior position of the nerve root forces the discectomy window more anteriorly, which in turn increases the risk of injury to the ipsilateral and contralateral vessels and the relatively posterior location of the retroperitoneal vascular structures [18].

The risks are further increased with rotational deformity of the spine [18]. In the case of scoliosis, the vessels on the concave side of the curvature were positioned relatively posterior to their position in the normally aligned spines [18]. The overlap of the right vessels over the vertebral body reached 43.9 % in the levoscoliotic spines, compared with 12.2 % in the normal group. The left vessels' overlap in the dextroscoliotic spines reached 19.8 %, compared with 1.2 % in the normal group ($P<0.05$). As a result of the greater degree of overlap between the neurovascular structures and the vertebral body found in the scoliosis subgroup, the surgical safe zone decreased to 40 % in the levoscoliotic spines and 61 % in the dextroscoliotic spines, compared with 70 % in the nonscoliotic group. The altered location of the neurovascular structures depended mostly on the degree of rotatory deformity, measuring 12° in the levoscoliotic and 11° in the dextroscoliotic spines. Focal coronal deformity or lateral listhesis did not seem to affect the position of these structures [18].

Meticulous care and consideration of these anatomic characteristics are required for safe application of this minimally invasive technique [11, 15, 17, 18].

33.5 Preventive Measures of Vascular Complications in Anterior Lumbar Spine Surgery

The popularity and the increasing numbers of XLIF procedures highlight a better understanding of the expected complications, the predictive factors for the patient, and the surgical technique and preventive measures [5, 19]. The measures adopted to prevent vascular injury start with good preoperative planning, expert skills during surgery, and close monitoring in the postoperative period (Table 33.1).

33.5.1 Preoperative Period

Accurate preoperative planning means: (1) precise knowledge of the location of the lumbar nerve roots, abdominal wall nerves, and nerves on the surface of the psoas muscle; (2) identification of the vascular position and its relation to the pathology and the surgical corridor; (3) high point of the iliac crest and its correlation with the lumbar spine; (4) anatomy of the deformity with information about the coronal and sagittal angle, vertebra rotation, asymmetry of the intervertebral disc, lateral listhesis, and presence of the osteophytes; and (5) knowledge of the patient-related variables, such as age, BMI, bone densitometry, and comorbidities [20].

Preoperative planning in XLIF surgery after the study of the neurovascular anatomy will detect a significant percentage of patients who may not be ideal XLIF candidates. The radiological preoperative evaluation of the spine and vascular anatomy dictate the decision to adopt a right or left lateral decubitus approach.

Table 33.1 Preventive measures for vascular complications in anterior or lateral lumbar spine surgery during the preoperative, operative, and postoperative period

Patient care	Preventive measures
Preoperative period	Good preoperative planning
	Identification of vascular position and its relation to the pathology and the surgical corridor
	Knowledge of anatomy of the deformity
	Knowledge of the patient-related variables
Operative period	Mechanical and pharmacological prevention of venous thrombi in the lower limbs
	Careful positioning of the patient's legs
	Three-dimensional anatomic knowledge of the surgical area
	Gentle surgical manipulation
	Adherence to intraoperative EMG
	Avoid endplate violation during discectomy and implant insertion
Postoperative period	Thromboembolic prophylaxis
	Early patient mobilization

33.5.2 Operative Period

The operative steps to prevent vascular complications are:

1. Prevention of a venous thrombus in the lower limbs
2. Careful positioning of the patient's legs
3. Three-dimensional anatomic knowledge of the surgical area
4. Gentle surgical manipulation
5. Adherence to intraoperative EMG for real-time identification of the lumbar plexus within the psoas muscle
6. Avoiding endplate violation during discectomy and implant insertion by the use of fluoroscopic visualization during the procedure [21]

Proper patient positioning is essential for a successful procedure. The patient must be secured to the operating table in a manner that prevents movement during the surgical procedure, so that the orientation remains the same for the surgeon. Once the patient has been securely positioned, image intensifier-based views of the spine are obtained. It is important to obtain images in true lateral and AP projections.

To prevent or minimize vascular complications during XLIF, the surgeons must have an anatomic understanding of the relationship between the ventral nerve roots, the retroperitoneal vessels,

and the vertebral body. Although care is taken both on the ipsilateral and the contralateral side of approach, laceration of the vessels on the contralateral side can occur caused by unintentional breach of the fibrous annulus during the discectomy or by releasing the annulus to prepare the intervertebral space to accommodate a large cage.

Once the retroperitoneal space has been entered through the lateral incision, blunt finger dissection is used down to the psoas muscle itself. A table-mounted, split-blade retractor is used to maintain the exposure during disc-space preparation and cage insertion. When the lateral aspect of the annulus is visualized, a guidewire is inserted into the disc space. However, if the guidewire placement is too anterior, it can result in damage to the anterior longitudinal ligament or even to the great vessels during preparation of the disc space and placement of the interbody device.

The importance of secure patient positioning and adequate X-ray imaging cannot be overemphasized. The exposure is small and provides the surgeon with a limited view of the spine. It is relatively easy to become disoriented and stray outside the safe bounds of the surgical field. The segmental arteries lie at the midportion of the vertebral bodies. The exposure should stay close to the vertebral endplates to avoid inadvertent damage to and bleeding from these arteries. Likewise, excessively anterior dissection can result in damage to the inferior longitudinal ligament or even to the great vessels.

Arterial complications can be minimized by avoiding the use of fixed retraction systems on the large vessels and by limiting the degree of arterial mobilization in the setting of heavy vessel calcification. The manipulation of the inferior vena cava needs to be minimized in order to avoid transient vascular injury and relative venous stasis, increasing the risk of developing thromboembolic complications.

Permanent intraoperative left leg oxygen saturation surveillance via pulse oximetry can help detect embolic situations thereby allowing immediate treatment minimizing the leg ischemia or preventing limb loss [21].

Spine surgery is associated with a significant risk of postoperative pulmonary embolism and/or deep vein thrombosis, mainly because of long periods of immobilization [22]. The incidence of thromboembolic complications in the spine patient varies in the literature and can be as high as 15 % in deep vein thrombosis and 0.5–2.7 % in pulmonary embolism patients [23]. The preventive measure to venous thromboembolism is a combined mechanical and pharmacological approach.

Mechanical prophylaxis is performed through compressive devices. The intermittent pneumatic compression sleeves with or without elastic stockings are the primary mode of prophylaxis in patients undergoing all types of spinal surgery [24–26].

Pharmacological prophylaxis is widely used in patients with spinal cord injury, but there is no consensus on its role in degenerative spine surgery. The controversy is due to the risk of epidural hematoma particularly after laminectomy leading to the idea that the prevention of thromboembolic disease in patients undergoing spinal surgery is a two-edged sword [25]. Low-molecular-weight heparin prophylaxis seems to carry a very low hemorrhage risk when started 24–36 h after spine surgery [27]. An intermediate strategy is delayed low-molecular-weight heparin initiation for 48 h to minimize the risk of hemorrhage and retain benefits of dual prophylaxis. The authors use subcutaneous heparin initiated either preoperatively or on the same day surgery is performed. The heparin subcutaneous dose administered consisted of 5,000 U three times daily, except in older patients (>75 years) or weighing less than 50 kg, who received this dose twice daily [28].

Patients with proven thromboembolic disease of the lower extremity or patients with symptomatic emboli are best managed by insertion of a vena cava filter [29, 30].

33.5.3 Postoperative Period

After surgery, the patient must be closely monitored and mobilized as soon as he/she is sufficiently comfortable, usually on postoperative day 1. Thromboembolic prophylaxis with subcutaneous low-molecular-weight heparin is initi-

ated 48 h after the procedure or regular heparin on the same day surgery is performed until full patient mobilization.

33.6 Management of Vascular Injuries

The initial therapy adopted after a vessel injury is usually related to the prognosis (Table 33.2).

33.6.1 Venous Injury

Initial maneuvers following recognition of injury to a major venous structure (e.g., iliac vein or vena cava) are critically important and usually determine the outcome [31].

After injury to a major venous structure, surgeons should avoid (1) aggressive use of suction and/or traction at the venotomy site, since prior to gaining control, they can cause further damage to the injured vessel, and (2) encircling the iliac vein or applying vascular clamps, as this will generally result in further venous disruption and increased bleeding [31].

Table 33.2 Maneuvers that are recommended or not after intraoperative vascular injury

Vessel injury	Recommended	Not recommended
Venous injury	Gain proximal and distal control of the hemorrhage	Aggressive use of suction and/or traction at the venotomy site
	Adopt the Trendelenburg position	Encircling the iliac vein or applying vascular clamps
	Perform a primary repair with suture or vascular clips	
	Promote endovascular repair	
	Use topical hemostatic agents as adjuncts to direct repair or sole method of hemostasis	
Arterial injury	Perform a lateral suture repair with or without vascular clamps above and below the arteriotomy	Aggressive use of suction and/or traction at the arteriotomy site

After injury to a major venous structure, surgeons should:

1. Gain proximal and distal control of the hemorrhage, typically through the use of Kitner peanut dissectors, or sponge-sticks, or Wylie renal vein retractors.
2. Place the patient in Trendelenburg position.
3. Perform primary repair with 5-0 Prolene suture on a cardiovascular needle once adequate visualization of the venotomy has been obtained. If the minimal access incision does not permit formal suturing and tying, vascular clips may be placed at right angles to the long axis of the vessel in "railroad track" fashion.
4. Endovascular repair of the left common iliac vein with a covered stent is a viable therapy [32].
5. Topical hemostatic agents including Gelfoam® (Pfizer, New York, NY), Surgicel® Fibrillar™ and Surgiflo® (Ethicon, Somerville, NJ), and Tisseel (Baxter, Deerfield, IL) are important adjuncts to direct repair and in many instances can be effective as the sole method of hemostasis.

Successful repair of seemingly minor injuries of the iliac vein can result in thrombosis in the postoperative period [31]. Manifestations of leg swelling may not be readily apparent in the setting of bed rest and limited ambulation. Venous duplex scanning is notoriously unreliable in detecting thrombosis cephalad to the inguinal ligament. For this reason, iliac venous imaging by computed tomographic angiography or magnetic resonance venography is performed routinely following iliac venous repair [31]. Detection of iliac vein thrombosis in the early postoperative period typically mandates placement of a vena cava filter, as anticoagulation is generally not an option.

33.6.2 Arterial Injury

Arterial hemorrhage can be managed with traditional lateral suture repair. If necessary, the surgeon must apply vascular clamps above and below the arteriotomy to reduce the bleeding.

Arterial thrombosis can be more dangerous in patients with prior atherosclerotic disease. Continuous pulse oximetry of the lower extremity ipsilateral to the site of arterial retraction, typically the left, is a useful monitor to employ routinely. Management by catheter thrombectomy and repair of the culprit lesion sometimes requires adjunct methods of endarterectomy or bypass. Consideration should be given to leg fasciotomy, depending upon the degree and duration of extremity ischemia [31].

Conclusion

Injury to the retroperitoneal vessels during lateral approach to the lumbar spine is uncommon, but when it happens, it is a potentially catastrophic complication. The contributing factors are limited visualization of the surgical field and vascular anatomic variation. The measures adopted to prevent vascular injury are adequate preoperative planning, knowledge of the anatomy in three dimensions, expert surgical skills with attention to details, and close monitoring in the postoperative period.

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Managing and Preventing Soft Tissue Complications

34

Peng-Yuan Chang and Michael Y. Wang

34.1 Introduction

Minimally invasive surgery (MIS) techniques for lumbar fusion have been undergoing a development and evolution for the past two decades. As such, they are continuously being validated by clinical and radiological studies. Among various surgical methods, the approach to the anterior column of the lumbar spine with a lateral and transpsoas procedure was innovated and popularized by Pimenta in 2001, who described the procedure as an "extreme lateral interbody fusion" (XLIF) [1]. Whether it is called lateral lumbar interbody fusion (LLIF), direct lateral interbody fusion (DLIF), or XLIF, this surgical approach offers several advantages comparing to traditional methods for interbody fusion, including the avoidance of mobilization of great vessels, less operative time, and reduced blood. In addition, there is no requirement for retraction of the nerve roots or the need for an approach surgeon (such as with true anterior approaches). The application of such MIS techniques and its application as a more sophisticated procedure to treat adult deformity undoubtedly have been a powerful tool in the surgical armamentarium in the new millennium.

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As with other surgical or medical treatments, no intervention is totally free of complications. According to the latest systemic review study conducted by Jacob et al. in 2015, the overall complication rate of XLIF is 31.4 % [2]. Previous reports on complication rates ranged from 0 to 30.4 %, with major complication rates from 0 to 8.6 % [1–8]. The most commonly reported complications include temporary and permanent neurologic deficit, medical complications, hardware failure, and pseudarthrosis. However, since spinal surgeons are accustomed to preventing and managing these categories of complications, they are quite familiar. Soft tissue complications, however, are rarely seen by spinal surgeons and thus are in some ways more feared.

34.2 Injuries Within the Psoas Muscle Corridor

The direct lateral approach utilizes two surgical corridors: (1) the transpsoas access to the spinal column and (2) a created retroperitoneal space. Potential complications of such approach can be thus divided into these corridors. These are the most commonly encountered approach-related complications, including neuronal damage to the lumbar plexus located in the psoas muscle and psoas muscle weakness from mechanical stretch or manipulation.

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The incidence of approach-related complications varies from 1 % to more than 50 % in the literature (Table 34.1) [6–26]. It should be noted that the incidence of complications is likely underreported or under-detected [27], but the most commonly encountered complications reported in literature are ipsilateral thigh pain and psoas muscle weakness [4, 5, 28, 29]. In a large XLIF conducted by Rodgers and colleagues in 2011 [29] with 600 patients, the overall soft tissue complication rate was described as 1 %. In contrast, Anand et al.'s report from 2010 showed a 70 % soft tissue complication rate [30]. Cummock and colleagues also described a 60 % incidence of new thigh numbness dysesthesias, weakness, or pain [31]. Of note, that study included objective, patient reported data, as opposed to surgeons' descriptions of complaints. Following the Cummock study, most publications began dividing the neurologic deficits to different categories, including pain, numbness, and weakness [4, 6–10, 14–17, 19–24, 31].

Most of these neurologic deficits are self-resolving, and patients usually recovered in the long-term follow-up. Pumberger et al. [20] reported in 2012 that sensory deficit's rate at 6 weeks post-op was 28.7 % and this dropped to 1.6 % at 1-year follow-up. Similar patterns were recognized with other complications in the same study, including anterior thigh pain, psoas weakness, and lumbar plexus injury [20].

It is also worth noting that Rodgers et al. specifically addressed the issues of thigh pain and hip flexor weakness being almost universal, but always transient [29]. Some of these experiences may be considered part of the healing process after the surgery. The variation and discrepancy of complication rates among different studies might be explained by the difference in interpretation of postoperative experiences of the patients.

34.3 Retroperitoneal Injuries

Anterior approaches to the spinal column are most commonly performed with the assistance of an access surgeon. The approach surgeon is most commonly a vascular surgeon, but cardiac, urologic, gynecologic, and general surgeons also can serve in this role. Regardless of their subspecialty, the access surgeon is typically well-versed in five skill sets that spinal surgeons typically have less experience with. These skill sets include (1) access through the potential retroperitoneal space without entry into the peritoneal sac; (2) mobilization of the large retroperitoneal vascular structures; (3) repair of any damaged structures, including the major blood vessels, bowel, ureter, and kidney; (4) management of entry into the thoracic cavity, including postoperative chest tube management; and (5) wound closure techniques that minimize the risk of hernia formation.

Because the retroperitoneal corridor created with the lateral approach is typically performed by the spinal surgeon, there is the potential that injuries in this area are unfamiliar to the surgeon. Complications can thus occur from numerous causes. These include the failure to properly identify critical anatomical structures that spinal surgeons are less familiar. An example is the failure to see or know the likely location of the ureters. The surgeon may also fail to recognize that a complication has already occurred, missing the opportunity to quickly and effectively manage that problem before it becomes amplified. An example would be failure to detect a bowel perforation, which should be managed with direct repair or colostomy creation, thus avoiding the potentially fatal complication of sepsis. Finally, the surgeon may not be well-versed in the skill sets needed to manage a recognized complication. An example would be the inability to repair a major vascular injury, which can result in death within minutes from exsanguination. The inability to control bleeding quickly can be the result of not having a surgeon available within minutes for this rare but catastrophic problem.

As is typical, reporting of disastrous complications of this nature is initially uncommon and likely leads to an underestimation of their true prevalence. Underreporting is the result of lack of awareness of their occurrence (treatment at another facility than the index operation), surgeon fear and embarrassment, restrictions due to active litigation, and lack of follow-up. However,

Table 34.1 Soft tissue complication reports

Study	Total patients	Soft tissue complications	Rate
Anand et al. [9]	12	4	25 %
		4 neurologic deficits	
Knight et al. [10]	58	9	15.5 %
		8 neurologic deficits	
		1 psoas spasm	
Anand et al. [30]	28	20	71 %
		19 neurologic deficits	
		1 retroperitoneal hematoma	
Tormenti et al. [4]	8	11	[a]
		8 neurologic deficits	
		2 pleural effusions	
		1 bowel perforation	
Dakwar et al. [6]	25	3	12 %
		3 neurologic deficits	
Wang et al. [11]	23	8	34.9 %
		7 neurologic deficits	
		1 pneumothorax	
Oliveira et al. [12]	21	4	19.0 %
		3 neurologic deficits	
		1 psoas hematoma	
Rodgers et al. [5]	432	5	1.6 %
		4 neurologic deficits	
		1 incisional hernia	
Youssef et al. [32]	84	1	1.2 %
		1 neurologic deficit	
Isaacs et al. [7]	107	12	11.2 %
		8 neurologic deficits	
		1 pleural effusion	
		1 renal laceration	
		2 pneumothoraxes	
Rodgers et al. [29]	600	6	1 %
		4 neurologic deficits	
		1 incisional hernia	
		1 subcutaneous hematoma	
Dakwar et al. [13]	568	10	1.8 %
		10 neurologic deficits	
Moller et al. [14]	53	19	35.8 %
		19 motor deficits	
Cummock et al. [31]	59	37	62.7 %
		37 neurologic deficits	
Tohmeh et al. [15]	102	30	29.4 %
		30 motor deficits	
Pimenta et al. [16]	36	6	16.7 %
		6 motor deficits	
Sharma et al. [8]	43	16	37.2 %
		15 motor deficits	
		1 retroperitoneal hematoma	

(continued)

Table 34.1 (continued)

Study	Total patients	Soft tissue complications	Rate
Kepler et al. [17]	13	4	30.8 %
		4 neurologic deficits	
Houten et al. [33]	2	2 neurologic deficits	Case report
Papanastassiou et al. [18]	14	2	14.3 %
		2 psoas and renal injuries	
Berjano et al. [19]	97	17	17.5 %
		16 neurologic deficits	
		1 psoas hematoma	
Pumberger et al. [20]	235	114	[a]
		12 lumbar plexus injuries	
		70 sensory deficits	
		32 psoas deficits	
Sofianos et al. [21]	45	18	40 %
		18 neurologic deficits	
Cahill et al. [23]	118	7	5.9 %
		2 neurologic deficits	
		5 abdominal bulges	
Malham et al. [24]	30	7	23.3 %
		6 neurologic deficits	
		1 bowel injury	
Galan et al. [34]	1	1 incisional hernia	Case report
Le et al. [22]	71	14 neurologic deficits	19.7 %
Balsano et al. [26]	1	1 bowel perforation	Case report

[a]Unable to calculate due to overlapping of symptoms

reports of these complications are beginning to emerge, even if only as case reports.

While covered in a separate chapter, vascular injuries can be particularly problematic. This was highlighted recently in a case report by Heary and colleagues [35] that despite the advantage of bypassing the direct encounter of the great vessels as in the anterior approach, fatal outcome can still occur through XLIF. In this report, a patient underwent an XLIF procedure at outside hospital and suffered from extensive vascular injury presumably from the detachable retractor blade. A salvage operation was carried out after the patient was transferred, and the authors found that these injuries were distinctly recognized at distal posterior inferior vena cava, right common iliac vein, right internal iliac vein, right external iliac vein, and left common iliac vein. Even though hemostasis was obtained and the patient was discharged to acute rehabilitation facility, the surgery still resulted in retroperitoneal abscess 7 days after being discharged with subsequently fatal multiple organ failure. This event demonstrated the danger of great vessels from such approach despite of the advantage of bypassing them as opposed to the direct encounter in the anterior approach. It also demonstrates that multiple sites of vascular injury can occur when a less invasive approach is used with retractors which are not necessarily designed to retract blood vessels.

Another potentially catastrophic complication is bowel injury. In an earlier series in which Kanter et al. [4] utilized XLIF to treat patients with scoliosis, they encountered a bowel perforation in one out of eight patients in the study. The 11 % bowel perforation rate in the study was suggestive of the risk, especially when the procedure was performed in the setting of scoliosis. Malham et al. [24] also reported a patient with bowel perforation in a retrospective study of their first 30-case experience of XLIF. A similar scenario can also been seen in a recent case report by Balsano et al. Thus, it is critical for the surgeons to be alert of such risk, espe-

cially in patients with previous abdominal surgery and/or intestinal adhesion, and to take caution during and after the surgery.

The retroperitoneal space itself is a common source of complications, mainly from the manipulation of abdominal wall and thoracolumbar structures, insufficient closure of the deep fascia, and inadequate hemostasis in the corridor. Anand et al. [30] conducted a retrospective review of 28 patients in 2010, and one of the patients suffered from sustained retrocapsular kidney bleeding. This patient suffered 2,000 ml of blood loss from renal bleeding and luckily was salvaged by tamponade without sequelae. Renal laceration was also reported in another series of 107 patients by Isaacs et al. [7]. Wang et al. [11] reported a patient suffering from pneumothorax, which was identified after the surgery. The authors suspected that the event might be resulted from the exposure at T12. Compromise of the pleura occurred during the surgery, and it led to a prolonged stay in the hospital up to 20 days due to the placement of the chest tube. Manipulation of the pleural structures and the organ within might cause pleural effusion as described by Kanter et al. and Isaacs et al. [4, 7].

Last but not the least, improper closure of the deep fascia layer may result in the formation of incisional hernia after the surgery. This complication has been sporadically reported in the results of XLIF [5, 29, 34] and can be detrimental if it involves incarceration of the visceral organs, and in that case, surgical repair would be mandatory. It is crucial for surgeons to differentiate between hernia and pseudo-hernia. While hernia represents the compromise of peritoneal integrity with resultant protrusion of the visceral organs, pseudo-hernia, also known as abdominal wall paresis, presents as an abdominal mass mostly due to the violation of the abdominal wall innervation and the regional weakness of the affected muscles (Fig. 34.1). This phenomenon is recognizable in conventional abdominal surgeries and gynecological operations, but it was not described in the realm of minimally invasive, retroperitoneal spinal surgery until 2011 when Uribe et al. [13] conducted a retrospective study involving ten patients with such condition. Being largest series in reporting such complication, this study delineated the clinical description of pseudo-hernia, as well as regional abdominal anatomy and the avoidance of such unwanted event. It is worth noting that, besides clinical symptoms and signs, image tools such as CT scan may be necessary to differentiate a true hernia from a pseudo-hernia. In the study by Uribe, four patients underwent CT scan to exclude the presence of abdominal wall defect; all patients were treated conservatively, and eight of ten patients experienced total resolution of such event while no long-term sequelae was recognized in the study.



Fig. 34.1 Pseudo-hernia caused by stretching of the nerves supplying the abdominal wall musculature

34.4 Management of Complications

Most postoperative neuropathies, including motor deficits and sensory deficits, require no specific intervention. As previously mentioned, most of these complications tend to recover in long-term follow-up. However, permanent neurological deficits have also been reported [4, 7, 10]. In a recent review article involving 18 publications and 2,310 patients, Ahmadian and

colleagues [27] noted that most of the patients with postoperative lumbar plexopathy may recover within the first 3–6 months. They proposed a diagnostic protocol that allows a 6-week observation before the first diagnostic electromyography (EMG) to identify possible neuropathy and to define the degree of injury, followed by another EMG at 3 months [27]. A clinical indicator of possible recovery was also proposed in the same study: the prognosis for recovery is good if the patient's immediate postoperative motor decline on the motor scale is 2 or less. Even so, no specific management in terms of treating postoperative neuropathy is proposed.

The manifestation of vascular injury can be violent and unrectifiable. Any sudden drop in the hemodynamics during the surgery should raise the surgeon's concern about possible vascular injury, especially when the anterior longitudinal ligament (ALL) is violated by any abrupt or unusual movement of surgical instruments, as reported in Heary et al.'s article [4] where the retractor blade was detached and moved unexpectedly anteriorly to the ALL. The patient had an estimated blood loss of 9,200 ml and received 29 units of packed red blood cells, 7,300 ml of crystalloids, and 3,250 units of albumin. Generally speaking, the surgical salvage team is expected to incorporate neurosurgeons, general surgeons, vascular surgeons, a team of anesthesiologists, and a strong backup in the intensive care unit after the operation. The salvage surgery usually includes an assessment of arterial or venous endovascular treatment and the attempt for direct repair which might be easier in the setting of arterial injury. Given the limited space in XLIF, the surgical field for salvage tends to be created either from a new site or by further exploration, mostly depending on the location and extend of injury. Real-time in-field decision making and reactions that involve both spinal surgeons and vascular surgeons are critical to regain hemodynamic stability.

Intestinal perforation is an emergency and can also be devastating if not corrected in time [4, 24, 26]. The best way to detect these injuries is to examine the approach path after the cages have been placed. Keeping the retractor open with fiber-optic lighting in place, the surgeon slowly pulls the retractor out, watching the surrounding soft tissues to look for any evidence of hollow viscus perforation. Postoperatively, the surgeon should thus be alert whenever the patient presents with abnormally abdominal pain or peritoneal signs. Fever, abdominal distention, local abdominal pain, or ileus could be some of the initial presentations. Without proper evaluation and management, peritonitis and sepsis may follow. The condition should be able to be appreciated with physical exams if patients present with local tenderness, rebound tenderness, or abdominal rigidity. The radiographic assessment should also be performed whenever being suspicious. The presence of free peritoneal air is a strong sign of perforation, and emergent operation should be promptly carried out. All efforts should be made to prevent the development of sepsis, and the administration of antibiotics that cover the intestinal spectrum should never be hesitated. The surgical treatment usually involves laparotomy and large irrigation of the peritoneal cavity. Direct repair could be carried out in the setting of controllable bowel perforation; however, sometimes the treatment may require creation of a colostomy.

If the surgeon is unable to recognize the ureteral damage during the surgery, the patient may develop symptoms of mild fever, nausea or vomiting, abdominal dull pain, back pain, and/or urinary retention after the surgery. Due to the relatively aseptic environment, the onset could be insidious that typically presents in days to weeks. Physical exams may show abdominal distention and tenderness of lower abdomen. Bowel sounds usually become slow possibly due to the mass effect from fluid accumulation. Ultrasound and abdominal X-ray and CT scan should be promptly performed to confirm the presence of fluid accumulation, which should be differentiated among hematoma, abscess, lymphatic seroma, or urinoma, by utilizing needle aspiration and further biomechanical tests. Once being confirmed, the ureteral injury should undergo assessment cystoscopy, retrograde (antegrade if necessary) ureterogram, or ureteroscopy to delineate the location and extend of the injury. The first attempt to treat is usually ureteral stenting. If that fails, further interventions may require diverting nephrotomy procedure, end-to-end ureterostomy, ureteric reimplantation, or, rarely, autotransplantation. Other renal injuries include

renal hematoma and kidney laceration. Given the limited retroperitoneal space, the condition usually can be treated by local temponade as described in Anand et al.'s study [30]. In extreme cases, endovascular embolization may be needed for hemostasis [8]. Familiarity of the anatomy of the surgical corridor and careful surgical procedures with caution are the keys to avoid such iatrogenic complication [36, 37]. It should be noted that given the potential for risk to the urogenital and renal systems, the surgeon may select the side of approach as contralateral in patients with a solitary kidney.

Typical presentations of pneumothorax include dyspnea and chest pain and can be fatal if not corrected in time. The surgeon should be alert whenever the patients present with such symptoms. In the setting of XLIF or minimally invasive spinal surgery, the exposure to the thoracic spine, as being reported by Wang et al. [11] with special attention, should be made for detection of such complication. On physical exam, the patients may appear tympanic to percussion of the chest, and subcutaneous emphysema might be present. X-ray can be a quick and useful tool for diagnosis, and a chest tube placement should never be halted, especially if the lungs are collapsed or tension pneumothorax is present.

Both incisional hernia and pseudo-hernia present as abdominal wall protrusion or masses. Patients with incisional hernia may not experience pain. The hernia is usually near the incision and tends to be more prominent with increased abdominal pressure such as straining. However, if incarceration of the intestines or other visceral organ occurs, the patient may develop abdominal pain, distention, and/or ileus with bowel dysfunction. It can be treated with surgical repair, either by open surgery or with the assistance of laparoscope [34]. Patients with disturbing or cosmetically unappealing symptoms and the ones with visceral incarceration are recommended to have repair surgery. Pseudo-hernia, or abdominal wall paresis, unlike the incisional hernia, tends to occur away from the incision and takes place in the anterior abdominal wall on the same side of operation. Patients typically feel no remarkable pain, but abdominal fullness can be appreciated. CT scan may be obtained to exclude the possibility of abdominal wall defect or the involvement of visceral organs. Usually no specific treatment is needed if the diagnosis is made. In the series of ten patients with abdominal paresis reported by Uribe et al. [13], all patients were treated conservatively, and eight out of ten patients had complete recovery. No long-term sequelae were identified in the study.

34.5 Prevention of Complications

The development of electrophysiological technology has been widely adopted in the past decade to reduce the risk of neuropathy. Being the "third set of eyes" during the surgery, besides the surgeon's eyes and the fluoroscope, intraoperative neuromonitoring is already a necessary equipment in a lateral approach surgery. Real-time directional-stimulated, discrete-threshold EMG has been used to identify and avoid the nerve during exposure. The application of intraoperative EMG is also demonstrated to be associated with occurrence of postoperative lumbar plexopathy [15].

Despite of many advantages of deploying intraoperative EMG in the procedure, the technology does not provide an injury-free guarantee. Complications of nerve injury can still occur with no deleterious changes of electrophysiological signals through the procedure or the detection nerve proximity [33]. Houten and colleagues stated in the study that the challenges of such detection lie in the fact that small motor potentials are difficult to evoke in proximal muscles and that the quadriceps and iliopsoas muscles are multiply innervated by different roots. Other difficulties include the detection of sharp transection injury and risk caused by the shifting of soft tissue from positioning of the retractors [15, 33]. It is of utmost importance to note that gentle blunt dissection is recommended to separate the fibers of psoas muscle, which should be parted between the middle and anterior third of the muscle span. All the anatomical and electrophysiological efforts are made to avoid direct proximity and injury to the nerves. The theoretical measurement to prevent such damage is cautious placement of the retractor with direct stimulation and visualization. Additionally minimization of the opening of retractor and operation time also helps to reduce the risk of stretching injury to the nerves.

Unlike with posterior spine surgery, the surgeon must pay close attention to non-spinal structures on preoperative three-dimensional imaging. MRI and CT can show the proximity of hollow viscus and vascular organs that may be at risk in the approach, particularly the spine which is axially rotated or the anatomy which is abnormal. The trajectory and initial docking of working channel is the most critical step in terms of avoiding visceral damage. The position of the retractor may create peritoneal violation itself, and special attention should be made in an ectomorphic patient for the adipose content may be insufficient in the retroperitoneal space [26]. Either a two-incision technique or larger access with direct visualization is highly recommended to safely guide the instruments to the indicated lateral vertebral body, as described in the milestone article by Ozgur et al. which basically standardizes the procedure [1]. Slow and gentle movement with caution should be taken during the removal of the retractor in order not to violate the peritoneum. It is crucial to identify the possibility of bowel perforation with sensitive clinical sense by physical examination and image studies including X-ray and CT scan.

In order to avoid incisional hernias, the closure of the surgical corridor should be solid and complete. Several measurements were proposed to avoid such complication, including placing the incision as posterior as possible to utilize the transversalis fascia, blunt dissection during exposure to avoid denervation of the muscular structure [13, 34], and avoidance of postoperative strain and increased abdominal pressure [34]. Once the hernia was identified, it can be surgically repaired in patients with severe symptoms. Careful examination and studies may be needed to rule out the possibility of intestinal involvement and potential incarceration.

Conclusion

The lateral approach is a valuable minimally invasive procedure with inevitable risks of complications. Soft tissue complications of the procedure involve nerve injuries and other organic damages that cause symptoms. All efforts should be made with the utilization of gentle surgical senses, intraoperative neuromonitoring, and application of anatomical knowledge to avoid iatrogenic injury to the nerves despite that most of the reported postoperative neuropathies are self-resolved in nature. Other structural damages can usually be avoided with great care, yet it is crucial for surgeons to be alert and meticulous at all times from positioning, retroperitoneal dissection, and traversing the psoas muscle, the closure, and postoperative care, to minimize the risk of these complications. It should also be stated that although soft tissue complications can be quite serious, there remains the unique advantages of a lateral approach over anterior, posterior, and posterolateral access corridors. Thus, as with any surgical intervention, the selection of the approach is complicated, multifactorial, and nuanced.

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Ileus and Gastrointestinal Complications

35

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35.1 Definition of Ileus

Postoperative ileus (POI) is a pattern of bowel dysmotility following surgery characterized by delayed transit and the accumulation of stool, gas, and fluid secondary to a decrease in coordinated peristalsis. Historically, the term has been used to describe both the mechanical and functional loss of peristalsis, though in more recent parlance, the word is used to describe an expected physiologic response of the GI tract leading to accumulation of normal secretions in the postsurgical patient [1]. It should be stressed that decreased gastrointestinal motility is a normal and expected physiologic consequence of major surgery, especially surgery involving bowel manipulation and/or general anesthesia. Typically, intestinal motility returns within hours of surgery and colonic motility within 1–2 days postoperatively [2]. While the exact timing and clinical parameters which define a true ileus are ill-defined, postoperative ileus is considered pathologic when prolonged and in the opinion of the authors may be defined as a failure of return of bowel function by postoperative day 3 [3].

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35.2 Mechanisms of Postoperative Ileus

The vast majority of literature investigating postoperative ileus has been performed in the patient population undergoing intra-abdominal surgery as the effects of ileus are most profound following bowel manipulation. However, centrally mediated mechanisms and the effects of postoperative opioids on bowel motility can, in part, help to explain the incidence of ileus following posterior spinal surgery and lateral lumbar fusion – as well as other orthopedic procedures that do not involve significant bowel manipulation such as total joint arthroplasty [4].

35.2.1 Neural

Manipulation of the bowel following abdominal surgery or the approach to the anterior lumbar spine results in the activation of splanchnic nerves, an increase in sympathetic tone, and a resultant bowel hypomotility [5]. In addition to contributions from the sympathetic visceral nerves, abdominal skin incision and bowel

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manipulation have been shown to stimulate adrenergic inhibition in the gut [6]. Central mechanisms inhibiting gastric motility are moderated by corticotrophin-releasing factor (CRH) which is released from central structures – the hypothalamus, pons, and medulla – after bowel manipulation where it serves in turn to stimulate sympathetic preganglionic neurons [7]. Additional neuromuscular inhibitors have been investigated as possible contributors to POI including norepinephrine, nitric oxide, the secretin family of peptide hormones, and endogenous opioids [8]. It is accepted that no single mechanism is causative in the development of POI, and the overlap between these causes complicates the treatment and understanding of POI; however, the neurogenic mechanism is generally recognized as the greatest contributor to early postoperative ileus. Moreover, as demonstrated by the effect of adrenergic inhibition, the neurogenic mechanism of POI does not require bowel manipulation as simple skin incision can lead to bowel hypomotility and predispose the patient to ileus, as would be the case in XLIF. As Bauer and Boeckxstaens note in their review of mechanisms of POI, studies examining the neural contributions to bowel hypomotility are by and large performed immediately after surgery in animal models, supporting the notion that POI, which often lasts several days and may not be evident immediately postoperatively, has equally large contributions from the inflammatory and pharmacologic mechanisms [5].

35.2.2 Inflammatory

A number of studies examining immune cells in the muscularis externa of the bowel have shown that intestinal manipulation causes macrophages to release nitric oxide, cyclooxygenase 2, and prostaglandins as well as causes degranulation of mast cells in the muscularis externa in turn promoting inflammation and bowel wall edema and decreasing the contractility of bowel wall circular muscle [9, 10]. There is additional evidence supporting the synergistic interaction between the inflammatory and neuronal mechanisms of ileus, i.e., kinetically active substances released by the inflammatory cells in the bowel wall activate primary afferents to the gut and serve to perpetuate the neuronal contribution to POI [11].

35.2.3 Pharmacologic

While the abovementioned mechanisms of POI are dependent to some degree on manipulation of the bowel or activation of splanchnics through an abdominal incision, the pharmacologic mechanism of ileus is more broadly applicable to spinal surgery. It is well understood that activation of δ- and μ-opioid receptors decreases peristalsis, likely by stimulating the release of inhibitory neurotransmitters, and morphine is known to delay gastric emptying [12]. Similar to the interaction between inflammatory cells and neural mechanisms of ileus, activation of opioid receptors appears to stimulate NO release from immune cells in the bowel wall, further propagating the inflammatory mechanism of POI [13].

While the mechanism of POI following ALIF may be to some degree explained by the manipulation of the bowel associated with the approach [14, 15], mechanisms of POI following XLIF are less clear. Ileus following XLIF is likely mediated by neural pathways, and the increased incidence of ileus after surgeries performed at the L1–L2 level suggests that manipulation of the celiac plexus and resultant decrease in parasympathetic input to the GI smooth muscle may be a contributor.

35.3 Incidence of Ileus and GI Complications in Spinal Surgery

To date, there has been only one published study examining the incidence of and risk factors for POI following XLIF. However, with the increase in rates of lumbar fusion in the US population, there has been a burgeoning interest in defining the perioperative risk profile for developing ileus following spinal surgery [16, 17]. One of the first

studies to report specifically on ileus rates in ALIF was performed to examine the perioperative complications of ALIF when using a vascular "exposure" surgeon in a cohort of 405 patients over an 8-year period from 2000 to 2008. While the primary outcome was a major and minor vascular injury necessitating repair, the authors mention that six patients had "prolonged" ileus (1.5 %) though they neglected to define what was considered prolonged. Of note, they state that the mean duration of postoperative ileus was 0.77 days, which, based on the working definition of prolonged postoperative ileus, would be considered physiologic and expected POI rather than a complication [14].

A similar retrospective cohort analysis from 2012 by Asha et al. examining perioperative complication rates when using a vascular access surgeon during ALIF and anterior lumbar disc replacement (ALDR) reported an incidence of POI in 18 of 121 patients (14.8 %). In this study, all patients with POI were treated conservatively – i.e., made NPO and underwent nasogastric tube placement – and resolved within 2–6 days [15]. While the above studies do provide insight into the incidence of POI following spinal surgery, they also highlight the difficulties inherent in analyzing the literature and attempting to determine risk factors given that pathologic versus physiologic postoperative ileus has historically been poorly defined.

In 2013, Fineberg et al. examined rates of ileus in postoperative spine patients through query of the National Inpatient Sample database which represents approximately 20 % of all hospital discharges. The study identified 220,552 posterior, anterior, and combined circumferential lumbar fusions over an 8-year period from 2002 to 2009 with associated rates of ileus of 2.6 %, 7.49 %, and 8.41 %, respectively, as identified by the admission's association with the ICD-9 code for paralytic ileus (again, the duration of POI is not strictly defined in this study). Furthermore, patients with ileus had a significantly greater mean length of stay (LOS) than the non-ileus cohort regardless of the surgical approach and incurred significantly larger costs ranging from an average difference of $6,758 in patients undergoing PLF up to $7,857 in the combined anterior-posterior fusion cohort [17].

One study from 1995 looking at complications of ALIF in the thoracic and lumbar spine in adults at a single center from 1969 to 1992 reported on a number of complications common to anterior and posterior spine surgery. Their combined rate of ileus of 3.44 % (42 patients) is slightly lower than that reported in the current literature, which is understandable given their definition of POI as requiring a nasogastric tube for decompression for greater than 4 days postoperatively. In their sample of 1,223 anterior spine procedures performed in 1,152 adult patients, they also reported a number of additional GI complications they felt were common to anterior and posterior spine surgery, among them gastritis (four patients, 0.33 %), esophagitis (two patients, 0.16 %), duodenal ulcer (one patient, 0.08 %), and small bowel obstruction (one patient, 0.08 %). However, given the low incidence rates, these may or may not have been attributable to the procedure itself and may instead have been complication of hospitalization or the physiologic stress of surgery [18].

To the authors' knowledge, there is only one paper to report on the incidence of prolonged postoperative ileus following XLIF. In a study published in 2014, Al Maaieh et al. observed POI, defined as ileus for greater than 3 days postoperatively, in 42 patients of a cohort of 596 (7.0 %) who underwent XLIF at a single institution over a 6-year period, which is similar to the rate reported in the ALIF literature. Also similar to previously reported literature of POI after spine surgery was the increase in postoperative length of stay (9.9 ± 4.3 days in the POI cohort, 5.6 ± 4.1 days in the control group).

35.4 Risk Factors for Gastrointestinal Complications After Interbody Fusion

In order to control for bias introduced by a surgeon's learning curve, the aforementioned study of ileus in XLIF analyzed a matched

cohort of patients undergoing interbody fusion based on the month of surgery. By doing so, they were able to employ uni- and multivariate analyses to look for risk factors for ileus following XLIF. Among the risk factors identified were gastroesophageal reflux disease, combined lateral and posterior instrumentation, and XLIF at the L1–L2 level. Notably, in addition to GERD, the use of a proton pump inhibitor was also found to be a risk factor for POI after surgery. Shindo et al. have reported decreased levels of ghrelin in patients with nonerosive reflux. Moreover, there is an emerging body of evidence supporting the notion that ghrelin is a bowel promotilic [19–21]. While intriguing, this correlation merits further examination.

Additional risk factors for complications after anterior and posterior spine surgery have been identified based on a multivariate analysis of nearly 1,600 patients from the National Inpatient Sample. The study, which looked at complications in six organ systems, identified several GI complications including ascites, colitis, GI bleed, ileus defined by abdominal distension and no passage of stool or flatus (at a rate of 2.26 %), obstruction, pancreatitis, and perforation with a total adverse event rate of 3.9 %. Risk factors for developing a GI complication included age >40, specifically age >65, previous cardiac incident, hypertension, anemia, revision surgery, combined anterior and posterior approach, and larger surgery based on the surgical invasiveness index which accounts for the number of levels involved and the approach. Of these, age greater than 65 and elevated surgical invasiveness were significant risk factors for complications in all organ systems [22].

Fineberg et al. list several independent risk factors for POI following anterior or posterior lumbar spine surgery including male sex, African-American ethnicity, greater than three level fusion, preoperative vitamin deficiency, use of BMP, and chronic anemia. The risk factors with the highest odds ratios were preexisting fluid and electrolyte disorders (OR 3.1) and a recent history of weight loss (OR 3.1). While electrolyte disorders are a known risk factor for developing ileus, the association with weight loss is less clear [17].

The scope of risk factors contributing to GI complications and ileus in posterior spinal fusion and anterior and lateral interbody fusion is presented here primarily due to the dearth of research investigating the incidence of and risk factors contributing to POI and GI complications following XLIF. It is likely that these various procedures share many of the same risk factors. However, given their differences, namely, avoidance of direct bowel manipulation with the lateral approach and promise of improved pain scores after XLIF possibly leading to faster mobilization and decreased opioid requirement, it is possible that there are differences in risk factors and outcomes that may be elucidated with further study.

35.5 Management of Postoperative Ileus

Unfortunately, there are no proven standardized regimens for addressing POI in patients undergoing spine surgery, which is related in some degree to the lack of data describing incidence rates and a limited understanding of risk factors in this patient population. Methods of addressing postoperative ileus naturally aim to combat the known causes of ileus, namely, the neurogenic, inflammatory, and pharmacologic mechanisms outlined above. While the bulk of the literature evaluating the management of POI has been performed in patients undergoing intra-abdominal surgery, there are a number of methods that may be applicable to those undergoing spinal surgery.

Traditional, non-pharmacologic supportive care has involved keeping the patient NPO until return of bowel function, encouraging early ambulation, and occasional placing of nasogastric tubes for decompression. While early ambulation has not been shown to increase time to return of bowel function, it is recommended for its additional postoperative benefits including decreasing the risk of venous thromboembolism [23]. Similarly, the placement of nasogastric tubes for the treatment of POI is not supported

based on a Cochrane review from 2005 which found increased risk of pulmonary complications, decreased patient comfort, and increased length of stay in patients treated with NG tubes for POI after abdominal operations [24]. Limiting perioperative intravenous fluid to prevent bowel edema and using nonsteroidal anti-inflammatories, intravenous Tylenol, and atypical opioids such as tapentadol to reduce traditional opioid use have been shown to be effective means of decreasing the risk of developing POI [25–28]. However, treatment options are largely limited once a patient has developed prolonged ileus.

Opioids are commonly used after orthopedic surgery to combat postoperative pain, but the large doses administered via PCA, oral analgesics, and frequently via breakthrough injections have well-known gastrointestinal side effects [4, 29]. Complicating the use of opioids and their association with POI is the fact that while opioids achieve their analgesic effect in the CNS through their action on mu-opioid receptors, these same receptors exist in the gut, and their stimulation is the cause of the adverse GI side effects seen in opioid use [29].

Alvimopan , a peripherally acting mu-opioid receptor blocker which does not cross the blood-brain barrier, was created to theoretically block the adverse effects of opioids on the GI tract while still allowing for their use as a postoperative analgesic. In a meta-analysis of five studies comparing the drug to placebo, it was shown to decrease the time to bowel movement and toleration of solid food and ultimately decreased time to discharge when used in patients following abdominal surgery [30]. The drug, however, is approved only in the USA for GI recovery in patients undergoing upper or lower GI bowel resection surgery with primary anastomosis (need FDA reference). While it may be used off label in some centers, no such data exists to support its use in patients with POI following spinal surgery.

Methylnaltrexone is a peripherally acting quaternary mu-opioid receptor antagonist that acts primarily in the GI tract and, like Alvimopan, does not readily cross the blood-brain barrier. It is currently approved for treatment of opioid-induced constipation in patients with advanced illness receiving palliative care [31]. It has been shown to be useful in the treatment of chronic opioid-induced constipation [32] and Ogilvie's syndrome [33]. In a phase 2 study using methylnaltrexone for the treatment of acute opioid-induced constipation, significantly more patients receiving methylnaltrexone achieved laxation and in a significantly shorter time than those receiving placebo (33.3 % vs. 0 % at 2 h, 38.9 % vs. 6.7 % at 4 h). Further, there was no evidence of opioid withdrawal.

Invasive treatments such as enemas, nasogastric tubes, and colonoscopic decompression are primarily supportive therapies meant to decrease morbidity associated with ileus but do not address its root cause and in some cases may do more harm than good [24]. As such, many of the methods used in spine surgery aim to combat postoperative opioid-induced constipation through a variety of laxatives, ingestibles, and various pharmacologic agents. However, in a 2008 Cochrane review of prokinetic treatment of adynamic ileus, drugs including cerulein, cholecystokinin, cisapride, propranolol, vasopressin, and cholecystokinin were shown to be ineffective agents in the treatment of POI [34].

Chewing gum and sugar alcohols are thought to stimulate bowel motility via vagal stimulation, sham feeding, and release of pancreatic juices and saliva [35]. A Cochrane review from 2015 compiled results from 81 studies with 9,072 patients finding that the use of chewing gum reduced first time to flatus, time to bowel movement, and time to bowel sounds. Again, the bulk of the studies were performed in patients undergoing cesarean section or colorectal surgery [36]. Studies are ongoing which examine the effects of chewing gum on the return of postoperative bowel function after spinal surgery [37].

Neostigmine is a parasympathomimetic agent that competes with acetylcholinesterases to reversibly inhibit acetylcholine hydrolysis effectively stimulating bowel wall smooth muscle contraction [38]. Neostigmine has been used effectively to treat postoperative ileus [39] and Ogilvie's syndrome in postoperative spine patients [40]. In a meta-analysis of RTCs looking at the use of neostigmine to address acute colonic pseudoobstruction, it was found to be effective after a single dose of 90 % of the time with abdominal pain, sialorrhea, and vomiting. Bradycardia occurred 6.3 % of the time. Given the side effect profile, neostigmine is typically given in a monitored setting.

Preoperative bowel preparation has been assessed in patients undergoing spine surgery. In a randomized control trial of 55 patients with adolescent idiopathic scoliosis, patients who underwent a standard preoperative bowel prep showed a modestly shorter time to first bowel movement compared to matched peers who did not, though it had no effect on the length of hospital stay. Furthermore, given the discomfort associated with the prescribed bowel preparation regimen, the authors ultimately did not recommend this intervention [41].

Epidural analgesia holds the promise of a decrease in the use of systemic opioid analgesia and its accompanying risk profile. The use of thoracic epidural analgesia to effectively block the sympathetic innervation to the gut that has been shown to be a primary cause of early postoperative ileus has been tried with good success. A 2014 meta-analysis of RCTs comparing epidural analgesia with systemic opioid use following surgery found that epidural analgesia significantly decreased the risk of ileus and postoperative nausea and vomiting as well as improving speed to return of bowel function [42]. The subset of literature evaluating continuous epidural analgesia (CEA) versus patient-controlled analgesia (PCA) in patients undergoing spine surgery failed to show a difference in diet, ambulation, or length of stay in either group and noted its technical limitations and high cost. However, ileus and other gastrointestinal adverse events were not recorded outcomes in any of these studies, and the patient population underwent posterior instrumented spinal fusion rather than interbody fusion [43–45]. Klatt et al. randomized 66 patients with AIS undergoing PSIF to single CEA and double CEA or PCA, and while the study was not powered to evaluate POI, decreased incidence of constipation was noted with DCEA. There was, however, no difference in length of stay or time to ambulation [46].

35.6 Fiscal Consequences of POI

Effectively addressing POI has the potential for massive savings for insurers and hospital systems as minimizing the incidence of postoperative ileus would decrease length of hospital stay as well as additional costs incurred treating the entity [47]. The cost of POI to the healthcare system as estimated in 1990 approached $750 million, increasing to a staggering $1.46 billion in a 2007 estimate of costs related to POI following abdominal surgery alone which stemmed primarily from prolonged hospital stays, associated costs, patient morbidity, and hospital readmission [48]. While not as well studied as ileus following abdominal surgery, ileus following XLIF and other spinal surgeries is not inconsequential and has been shown to increase length of hospital stay [3, 17]. More studies focusing on the prevention and treatment of ileus following spinal surgery are merited given the immense potential to save healthcare costs and improve patient outcomes. Until that time, POI unfortunately remains an entity that is merely managed rather than effectively treated or prevented.

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Lumbar Plexus Injury: Lateral MIS Spinal Fusion

36

Jesse Skoch, Nikolay Martirosyan, and Ali A. Baaj

36.1 Introduction

One of the challenges of the lateral trans-psoas approach to the thoracolumbar spine is the potential for injury to the lumbar plexus running over and through the psoas muscle and the lateral aspect of the disc spaces. Improvements in technique, especially the increasing adoption of real-time neuromonitoring during the approach to the disc space, have begun to substantially minimize femoral nerve injury that can result in devastating motor deficits. However, injuries to other nerves in the lumbar plexus are almost certainly under-recognized and underreported. While there is largely a sense of optimism regarding the tolerability and recovery from injuries to the nerves of the lumbar plexus among surgeons performing lateral approaches, there is currently insufficient data to provide patients with reliable answers regarding the actual risks of sensory loss or painful neuralgias or to accurately describe the time course of recovery or the likelihood of permanent deficit. In general, we can appreciate that the vast majority of these injuries are well tolerated and are typically self-limited within a time course of several months. Nevertheless, adopting the lateral trans-psoas approach into one's repertoire of surgical techniques demands a degree of humility from spine surgeons that typically harbor only a limited knowledge of the anatomy and physiology of the lateral lumbar plexus as it courses through the psoas muscle in the retroperitoneum. To achieve the highest possible level of success and patient satisfaction with the lateral approach in its current state demands a familiarity with the lumbar plexus and importantly the ability to accurately diagnose plexus injuries as well as preparation to treat iatrogenic injury when indicated.

The lumbar plexus is the amalgamation of the ventral and dorsal divisions of the lumbar spinal nerves from L1 to L4 with a small contribution from the subcostal nerve (T12). The output of the lumbar plexus includes direct innervation of the psoas muscle which the plexus passes through as well as innervation of the anterior hip, perineum, and lower extremity. The anatomy of the plexus is typically studied from an anterior perspective, but lateral approaches to the thoracolumbar spine have prompted a number of high-quality anatomical diagrams illustrated from a lateral perspective in recent literature (Fig. 36.1). Knowledge of this anatomy and the relative zones of safest entry for each disc level is essential (Fig. 36.2) [1, 2].

The most common plexus-related complications observed with the lateral approach are related to neuropraxic injury to the more superficial branches resulting in thigh or hip numbness

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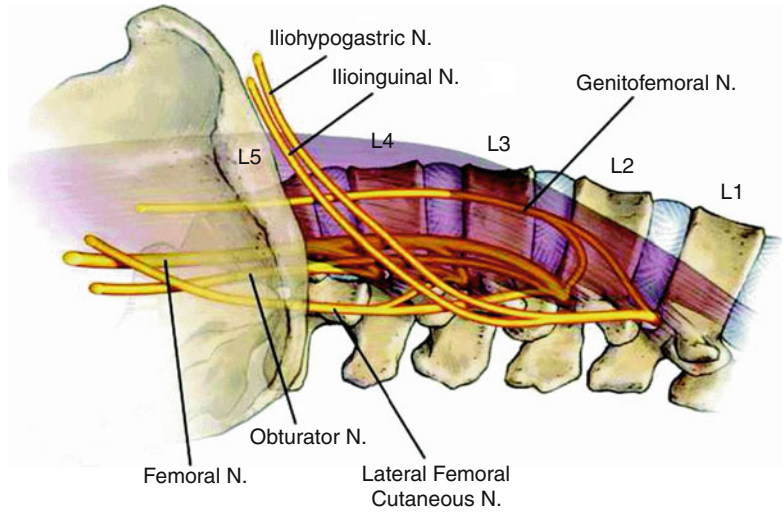


Fig. 36.1 Lumbar plexus from a lateral perspective relevant to the lateral trans-psoas approach [18]

and pain that is typically self-limited with the majority resolving by 1 month. Less commonly reported complications include thigh and hip pain, radicular pain, and quadriceps weakness. We believe that the following points specifically salient to the known possibility of plexus injury should be reviewed with patients during surgical consent:

- Thigh/hip/groin numbness, paresthesias, or pain
  - Nine to 60 % incidence – typically short lived (<1 month) [3–5]
- Quadriceps weakness related to femoral nerve injury
  - Rare and typically avoidable (1.7, 4.8 % at L4–L5 level) [6] – most will improve with time and therapy
- Psoas weakness
  - Nearly universal and transient on the ipsilateral side – typically attributed to direct muscular injury – but can occur from damage to some of the small nerve fibers from the plexus that innervate the muscle

The implications of lumbar plexus injuries related to the trans-psoas lateral approach typically involve a patient coping with minor sensory or motor deficits for a relatively short period of time during recovery from the neurapraxia. Reassurance and optimism from the physician are typically appropriate during the early postoperative assessments. Despite potential plexus complications, the majority of patients still demonstrate improved back and leg pain and decreased total disability scores after lateral procedures [3]. However, rare cases of persistent thigh or groin pain or debilitating proximal weakness can become more disabling than the presenting spine symptoms. We therefore advocate for recognition of these complications, careful avoidance, and aggressive treatment when appropriate.

36.2 Sensory Complications

Sensory complications related to stretch injury of the lumbar plexus during lateral trans-psoas approaches to the spine are common. L1–L3 sensory branches run with variable courses through the retroperitoneal fat, are challenging to visualize, and are not reliably detectable with SSEP recording. Because of the complex and overlapping dermatomal distribution of the iliohypogastric, ilioinguinal, and genitofemoral branches, differentiating numbness, pain, or paresthesias from these nerves can be challenging. The relative novelty of upper lumbar plexus anatomy to most spine surgeons and the typically self-resolving transient nature of injury to this region probably contribute to underreport-

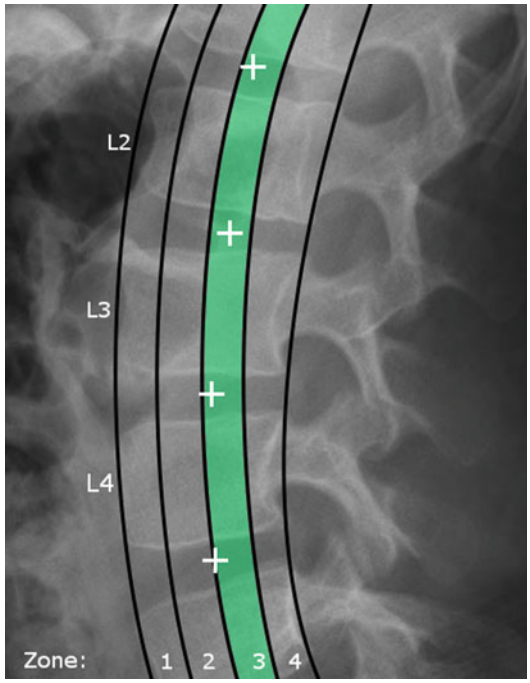


Fig. 36.2 Lateral radiograph of the lumbar spine with overlay dividing the vertebral column into four zones. A generalized "safe zone" is depicted by the highlight in zone 3. Optimal safe trajectories are depicted for each level with white crosses

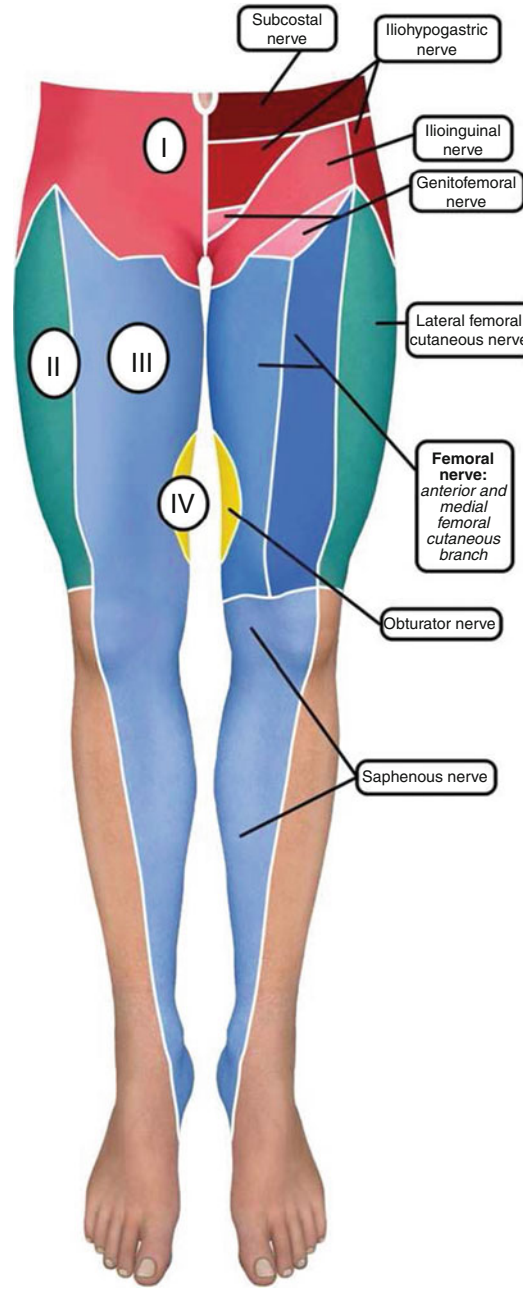


Fig. 36.3 Sensory dermal zones (SDZs) of the lumbar plexus. *Left side* – zones to simplify reporting of sensory complications. *Right side* – approximate dermatomes [17]

ing of sensory complications associated with lateral approaches. While even permanent sensory loss from damage to lumbar plexus sensory branches can be very well tolerated, the difference between the etiology of local anesthesia and a painful neuropathy is not well understood mechanistically, and therefore, we advocate for efforts aimed at accurately characterizing and minimizing injury to sensory portions of the plexus. In this section, we will review the function and anatomy of each sensory branch in the context of the lateral approach. Ultimately, to simplify reporting of sensory deficits relative to postoperative complications of the lateral approach, we recommend the sensory dermal zone (SDZ) classification system (Fig. 36.3) that classifies lumbar plexus sensory deficits into four simplified anterior zones. Pain in any of these zones typically resolves rapidly, but may persist chronically in up to 5.5 % of patients that experience it postoperatively [5]. In patients with a chronic painful neuropathy, a more detailed workup including EMG and selective blocks is warranted to identify candidate nerves for definitive therapy. Table 36.1 reviews the

Table 36.1 Lumbar plexus nerve innervation, complications, and treatment options for consideration

Nerve	Cutaneous	Motor	Complications	Treatment
Iliohypogastric	SDZ1 – lat. buttock, suprapubic	Transversus abdominis, internal oblique	Increased risk of direct hernia, pain	R/o direct hernia, paravertebral or superficial blocks, neurectomy, dorsal root ganglionectomy
Ilioinguinal	SDZ1 – external genitals, medial thigh	Transversus abdominis, internal oblique	Groin pain	Paravertebral or superficial blocks, neurectomy, dorsal root ganglionectomy
Genitofemoral	SDZ1 – external genitals, anteromedial thigh	Cremaster	Groin pain	Differentiate from ilioinguinal injury, neurectomy or blocks
LFCN	SDZ2 – lat. thigh	None	Meralgia paresthetica	Medications, nerve block, neurectomy
Femoral	SDZ3 – anteromedial thigh/leg	Iliopsoas, pectineus, sartorius, quadriceps	Weakness – hip flexion, knee extension, and rotation. Numbness or pain	Early rehabilitation, obturator nerve transfer
Obturator	SDZ4 – inferomedial thigh	Adductor longus, adductor magnus, obturator externus, gracilis, pectineus	Adductor weakness – rare/unlikely	Early rehabilitation

Neuropathies may warrant a trial of medical management such as Tegretol or Neurontin. Thorough workup to localize a pain generator is necessary and treatment can vary considerably on a case by case basis
R/o rule out, *lat.* lateral

innervation of lumbar plexus nerves, complications associated with lateral trans-psoas procedures, and treatment options.

36.2.1 Iliohypogastric Nerve (T12, L1): SDZ1

The iliohypogastric nerve emerges from the posterolateral border of the psoas muscle at the L1 level and crosses obliquely behind the kidney, anterior to the quadratus and iliacus muscles, toward the anterior iliac crest. Just above the iliac crest, it divides into lateral and anterior branches with the lateral branch piercing the oblique muscles as it heads cutaneously and the anterior branch running between the transversus abdominis and internal oblique as it heads medially before piercing the internal and external obliques. These branches provide sensory innervation to the lateral buttock and the hypogastric suprapubic regions, respectively (Fig. 36.3).

The dermatomes of the iliohypogastric nerve often have redundancy with other sensory nerves, and isolated injury to this nerve should rarely produce a significant regional numbness. Given its long course through mobile retroperitoneal fat, tethering in multiple muscle and fascial layers, and the inability to reliably detect any changes with electrophysiological monitoring, injury to the iliohypogastric is likely common during the early stages of the lateral lumbar approach [7]. Most injuries are largely asymptomatic and transient and go undetected. The rare painful neuropathy warrants closer investigation if it persists. A potential localizer (which can represent either iliohypogastric or ilioinguinal damage) borrowed from abdominal surgery literature involves searching for a particular hyperalgesic pressure point 2–3 cm medial to the edge of the anterior

superior iliac spine (ASIS) with possible relief from local anesthetic administered at this point [8]. Avoiding techniques that utilize a secondary incision for retroperitoneal palpation is recommended as these likely increase the risk of iliohypogastric or ilioinguinal injury [9].

36.2.2 Ilioinguinal Nerve (L1): SDZ1

The ilioinguinal nerve is a pure L1 branch that typically runs parallel and anteroinferior to the iliohypogastric nerve. After passing medial to the ASIS, it traverses the internal oblique and enters the inguinal canal emerging from the superficial inguinal ring. While its dermatome overlaps largely with the anterior branch of the iliohypogastric nerve, importantly it typically extends more medially providing sensation to the groin and proximal external genitalia.

Injury is often paired with injury to the iliohypogastric due to their similar courses. The ilioinguinal nerve can be involved in the afferent arm of the cremasteric reflex, but this is of limited diagnostic value. While injury to the ilioinguinal nerve (or genitofemoral) can result in significant groin pain that may be continuous or intermittent, even gross ilioinguinal neurectomy has been shown to produce little to no detectable sensory loss [10, 11].

36.2.3 Genitofemoral Nerve (L1, L2): SDZ1

Traveling within the psoas muscle obliquely from L1 and L2 roots, typically crossing the L2–L3 disc space, and emerging from the muscle at the L3–L4 level, the genitofemoral nerve then descends over the psoas major, anteriorly over the L4–L5 lateral interspace, and into the inguinal ring. It then divides to provide sensory innervation to the inguinogenital region and anterior medial thigh (SDZ1).

Due to its distinct emergence from the mid-psoas, the genitofemoral nerve can occasionally be localized by direct visualization from a lateral approach; however, it has been described as difficult to locate even in some cadaver dissections and has the highest standard deviation in course of any nerve in the lumbar plexus [10, 12]. The oblique and variable course of this nerve puts it at risk at all levels during lateral trans-psoas lumbar procedures [2]. In cases of severe injury in male patients, the ipsilateral cremasteric reflex should be absent since this nerve acts as the efferent; however, EMG and selective blocks may be needed to differentiate genitofemoral neuropathies from ilioinguinal in cases of persistent pain [13]. Such a workup is warranted in cases of refractory pain since genitofemoral neuralgia can be amenable to neurectomy [10, 13].

36.2.4 Lateral Cutaneous Nerve (L2, L3): SDZ2

The lateral cutaneous nerve is a pure sensory plexus branch with a uniquely identifiable dermatome (SDZ2). It emerges from the posterolateral border of the psoas at the L3–L4 level and courses obliquely across the iliacus toward the ASIS and then through or below the inguinal ligament after which it divides into anterior and posterior branches that innervate the lateral thigh. As with the iliohypogastric and ilioinguinal nerves, damage can occur during dissection through retroperitoneal fat, and injury can produce symptoms akin to meralgia paresthetica for which this nerve is best known. In a prospective study aimed at complication detection in lateral interbody fusions, injury to this nerve was detectable in 10 % of patients [14]. Treatment considerations should follow second-line therapies for meralgia paresthetica.

36.3 Motor Complications

The feared motor complication of the lateral trans-psoas lumbar spine approach is injury to the femoral nerve. Fortunately, triggered dilator-

based intraoperative EMG and femoral nerve SSEP recordings can usually reliably localize the femoral nerve before the capacity for injury exists. While there is the potential for femoral nerve injury when approaching any lumbar interspace, it is important to recognize that the risk may be nearly three times higher at the L4–L5 level [6]. Significant non-femoral nerve motor injuries involving the lumbar plexus are very rare. It is possible that abdominal muscle weakness from damage to the iliohypogastric or ilioinguinal nerves could cause an increased propensity for direct inguinal hernia, but this should not be confused with the more common pseudohernia or flank bulge produced when the subcostal nerve (T11, T12, not part of the lumbar plexus) is injured [15].

36.3.1 Femoral Nerve (Dorsal L2–L4)

The dorsal divisions of the ventral rami of L2 through L4 merge in the lumbar plexus to form the femoral nerve. The femoral nerve is large and courses deep within the substance of the psoas major where it gives off numerous small branches. At the L4–L5 disc space, the nerve begins to exit the lateral aspect of the psoas and courses over the disc space continuing inferiorly between the psoas and iliacus (which it also innervates via small fibers) and under the inguinal ligament into the anterior thigh. It then widely branches into an anterior cutaneous sensory branch (SDZ3), anterior motor branch (sartorius, pectineus), and posterior motor branches that innervate the quadriceps.

The fairly consistent course of the femoral nerve (standard deviation relative to bony landmarks – 0.9 cm compared to genitofemoral nerve 2.3 cm) within the psoas along the posterior aspect of the vertebral bodies typically permits avoidance by following trajectories of standardized safe zones (Fig. 36.2) [10]. However, variant anatomy puts this nerve at significant risk during this unvisualized portion of the muscular dilation, and routine use of SSEP and triggered EMG is recommended [6, 16]. If injury does occur, it is recognizable as weakness when mobilizing the knee joint; sensory loss (SDZ3) and loss of patellar reflex may be present as well but should not occur in isolation with injury at the psoas level. Mild neurapraxia is expected to have a rapid and robust recovery, while loss of antigravity strength or plegia at the knee joint may demonstrate a more protracted course [17].

36.3.2 Obturator Nerve (Ventral L2–L4) and Lumbosacral Trunk (L4, L5)

The obturator nerve forms from the ventral divisions of the ventral rami of L2 through L4. It descends through the psoas and exits medially and posteriorly around the L5–S1 level prior to coursing laterally against the pelvic brim and behind the iliac vessels before entering the thigh via the obturator canal. It provides sensory innervation of the mid-medial thigh (SDZ4) and motor innervation to the thigh adductors.

The lumbosacral trunk is the most caudal aspect of the lumbar plexus and joins the lumbar plexus with the sacral plexus. It consists of the anterior division of the fifth and a portion of the fourth lumbar nerves and runs parallel and just medial to the obturator nerve along the lateral aspect of the L5 body proximally. It continues caudally to meet the first sacral nerve and join the sacral plexus where it contributes primarily to the sciatic and gluteal nerves.

There are currently no significant complications reported related to the obturator nerve or lumbosacral trunk. There is a theoretical risk particularly at the L4–L5 interspace, but following the more anteriorly located safe zone at this level intended to protect the femoral nerve should also spare these more posterior branches.

Conclusions

Despite the minimally invasive nature of lateral trans-psoas approaches to the lumbar spine, the nerves of the lumbar plexus course variably through even the statistically optimal anatomical trajectories at times, and surgery at

any interspace from L1–L2 to L4–L5 bears the potential for plexus injury. For the femoral nerve, cautious avoidance with diligent lateral positioning, optimized fluoroscopy, and triggered dilator-based EMG is a safe and realistic strategy. Axonotmesis of the femoral nerve should be extremely rare with these precautions, and neurapraxic injury should be recognized and treated with therapy expecting typically excellent outcomes.

Presently, techniques for detection and avoidance of the primarily sensory aspects of the plexus are limited. With enough procedures performed, encountering these types of injuries becomes a certainty. Therefore, the strategy for adequately managing sensory complications should focus on recognition, patient education, and aggressive treatment strategies including neurectomy when refractory painful neuralgias are identified.

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