Frank M. Phillips
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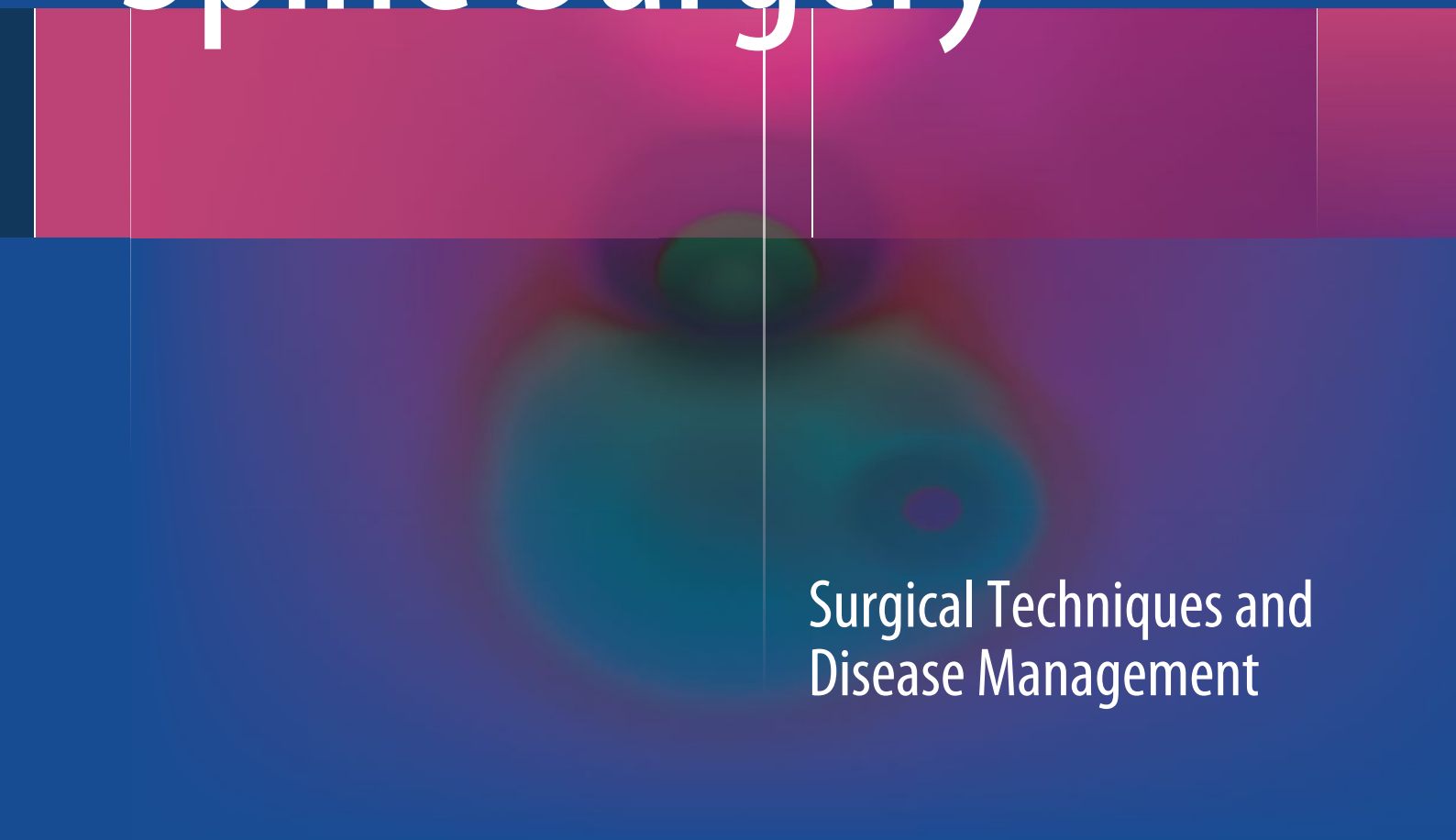
Editors

Minimally Invasive Spine Surgery



Surgical Techniques and Disease Management

Springer

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Preface

Despite the rapid evolution of minimally invasive spine (MIS) surgery over the past decade, there exists little consensus among spine surgeons regarding the precise definition of this field. Is minimally invasive spinal surgery defined by the length of the incision, the minimizing of damage to collateral structures, expedited recovery, or reduced surgical risks and complications? In reality, all of these are worthwhile goals that surgeons should strive to accomplish without sacrificing the ultimate aims of the procedure. Many quality studies have indeed shown reduced perioperative morbidity, blood loss, surgical time, and length of hospital stay, while at the same time showing economic value to a number of established MIS procedures. In today's health-care environment, assessing the value of surgical procedures has become a critical metric increasingly relied on by surgeons, payers, policy makers, and patients for informed decision-making.

Although advanced enabling technologies have resulted in minimally invasive spine surgery becoming more reliable, reproducible, and safe, there remains a difficult learning curve. Being facile with open surgical procedures does not necessarily translate into minimally invasive skills. It is important to realize that MIS surgery need not be an all-or-none phenomenon and is rather a progressive journey of acquiring knowledge and skills. In *Minimally Invasive Spine Surgery*: *Surgical Techniques and Disease Management*, we have attempted to address many of these challenges. In addition to highlighting surgical techniques and procedures, we have also focused on decision-making and application of the varied MIS techniques to address common and rare spinal conditions. We have assembled experts and thought leaders in the field to critically appraise various techniques of MIS surgery. We have encouraged discussion of the evidence base for the recommended procedures.

Our goal with this book is to provide a comprehensive text covering more established as well as innovative techniques of MIS surgery. This has only been possible because of the collective expertise and wisdom of the outstanding contributors to this book, many of whom have played significant roles in the development and advancement of the field. We hope this book will serve as a resource for trainees as well as experienced spine surgeons.

Chicago, IL — Frank M. Phillips
Plano, TX — Isador H. Lieberman
Minneapolis, MN — David W. Polly Jr.

Acknowledgments

I would like to express my deep gratitude to Denise, Gina, and Jay, who have supported, inspired, and loved me along this journey.

I dedicate this book to the many talented young spine surgeons that I have had the honor of educating. Your insights, enthusiasm, and search for the "truth" have kept it real and motivate us all to search for answers that will improve outcomes for our patients.

Frank M. Phillips

To Deeci, Rachelle, Josh, and Danielle, who continue to support and inspire me day after day.

Isador H. Lieberman

Contents

Part IV Surgical Techniques: Fusion

Part V Disease-Specific Approaches

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Part I

Introduction

History and Evolution of Minimally Invasive Spine Surgery

1

Omar N. Syed and Kevin T. Foley

Introduction

The development of minimal access approaches to the spine has revolutionized the arsenal of the contemporary spine surgeon. Traditional open approaches to the spine, although familiar to spine surgeons, are associated with approach-related morbidity. The tissue injury that occurs during the surgical approach can result in increased blood loss, increased postoperative pain, lengthened recovery time, and impaired spinal function. Thus, less invasive techniques that can achieve the same goals as traditional approaches while minimizing the approach-related morbidity are desirable [1].

Advances in surgical technique and technology have enabled the "reinvention" of several commonly performed spinal procedures through the adoption of minimally invasive approaches. Such advances in microscopy, tissue retractors, and specialized instruments have allowed surgeons to perform procedures through smaller incisions [2].

Minimally Invasive Spine Surgery

Benefits

The use of small surgical corridors to approach pathology is seen in various surgical subspecialties. One such example is the use of laparoscopic cholecystectomy as the primary operative treatment for symptomatic gall bladder disease. This approach has been associated with less surgical-related morbidity, better long-term postoperative outcomes, and decreased costs largely due to shorter postoperative hospital stays [3, 4]. In orthopedics, arthroscopy of joints such as the knee, shoulder, and hip has significantly reduced the approach-related morbidity and improved outcomes [1].

With respect to lumbar spinal surgery, morbidity is related to the significant iatrogenic muscle and soft tissue injury that occurs during routine exposure. Biochemical reaction and morphological alteration have clinically significant implications with reduction in muscle strength, decreased endurance, and increased pain [5]. Kawaguchi and colleagues proposed that muscle injury is due to a crush mechanism related to the use of forceful self-retaining retractors [6, 7]. Elevated serum levels of creatine phosphokinase MM isoenzyme, a marker of muscle injury, are directly related to the retraction pressure and duration. In fact, studies show increased levels of several circulating markers of tissue injury including aldolase, interleukin-6 and interleukin-8, and glycerol [2]. Stevens et al. [8] and Tsutsumimoto et al. [9] studied MRIs in patients with traditional open approaches to the lumbar spine and compared them with patients undergoing mini-open approaches. These studies showed decreased intramuscular edema and decreased atrophy in the mini-open approach patients. Styf and Willen determined that retractor blades increase intramuscular pressure to levels of ischemia [10]. Rantanen et al. concluded that patients with poor outcomes after lumbar spine surgery are more likely to have persistent selective type-2 muscle fiber atrophy and pathological structural changes in the paraspinous muscles [11]. Sihvonen has demonstrated that local denervation atrophy due to damage of dorsal rami after lumbar spine surgery is associated with an increased risk of failed back syndrome [12].

Another key concept of minimally invasive spine surgery is to limit the amount of tissue resection to minimize postoperative spinal instability, specifically by limiting the disruption of the facet joint and the midline interspinous ligament-tendon complex [2]. A finite element analysis showed that minimizing bone and ligament removal resulted in greater preservation of normal motion of the lumbar spine after surgery [13].

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Limitations

As with any new surgical technique, a learning curve is necessary to become proficient in minimally invasive surgery. Spine surgeons are familiar and comfortable with the anatomy when it can be directly visualized. However, minimally invasive exposures are generally limited to the area of surgical interest and certain key anatomic landmarks within this limited field of view. Familiarity with the anatomy allows the surgeon to safely perform the surgery without exposing structures that are not being treated surgically. Minimally invasive spine techniques are also more technically demanding, as surgeons must be facile when working through small channels and longer distances, often employing the use of bayoneted instruments. McLoughlin and Fourney analyzed the depth of the learning curve involved in minimally invasive lumbar microdiscectomies and found that it took about 15 cases for spine surgeons to become comfortable with, and proficient at, the technique. Operative times and complications for minimally invasive microdiscectomy were reduced as the surgeon became more experienced with the technique [14, 15]. Additionally, while loupe magnification and endoscopy can be used, the use of the operative microscope can greatly enhance illumination and visualization. Recent developments have allowed stereoscopic high-definition visualization of the field of view in real-time on three-dimensional (3D) flat panel displays in the operating room. This technology is also useful for recording 3D surgical video for educational purposes and presenting on-demand and streaming 3D surgical video content. The technology has significant implications for surgeon education.

Minimally invasive techniques will oftentimes require the use of intraoperative fluoroscopy or image guidance. The surgeon needs to master the use of these systems in order to complete the surgery in a safe, effective manner. For example, the interpretation of fluoroscopic images can be challenging for surgeons who have not had significant experience using two-dimensional images to determine their three-dimensional surgical position.

Finally, while minimally invasive spinal techniques have been used for the past decade, only now are long-term results being reported [16, 17]. More studies are necessary to validate many of these techniques.

Minimally Invasive Surgery in the Lumbar Spine

Percutaneous Techniques

The first report of a percutaneous approach to the lumbar spine is generally credited to Pool. In 1938, he described the use of a modified, battery-operated cystoscope to visualize the cauda equina, a technique he termed "myeloscopy" [18]. The technique was employed for diagnostic purposes.

Smith reported the use of chemonucleolysis for the treatment of symptomatic herniated nucleus pulposus in humans by percutaneous injection in 1964 [19]. Chymopapain was discovered and isolated in 1941 by Jansen and Balls from the latex of the fruit of *Carica papaya* [20]. Chymopapain is a proteolytic enzyme that can reduce the water content of the nucleus pulposus and cause reduction in disc height and bulge [21]. Despite approval by the Federal Food and Drug Administration in 1982, surgeon interest in this modality has diminished, as the efficacy of this technique for disc pathology remains speculative. As well, it has been associated with anaphylaxis, epidural scarring, and transverse myelitis [22].

The first percutaneous nucleotomy was performed by Hijikata in 1975. He employed a posterolateral approach using a 2.6 mm diameter cannula to fenestrate the annulus and partially resect the nuclear substance. The procedure reportedly reduced intradiscal pressure and obtained relief of irritation of the nerve root or the pain receptors around the disc [23]. In 1983, Kambin and Gellman performed a discectomy through a posterolateral approach using a Craig cannula and small forceps after an open laminectomy [24]. In 1986, Schreiber described "discoscopy," in which he added an arthroscope to percutaneous nucleotomy for direct visualization [25].

A similar percutaneous technique employing an endoscope was subsequently described by Mayer and Brock in 1993 [26]. Faubert and Caspar also described their technique of percutaneous discectomy using a 5.4 mm diameter cannula (with a 4.6 mm internal diameter) and a fluoroscope, but with no direct visualization [27]. Various automated disc removal instruments were added to the approach as described by Onik and Maroon [28, 29]. They described a percutaneous nucleotomy procedure which employed a blunt-tipped, suction-cutting probe (nucleotome) in a procedure termed automated percutaneous lumbar discectomy (APLD). Principles of its mechanism involved rhythmic irrigation, aspiration, and cutting to retrieve disc material from inside the annulus [30]. Around this time in the early 1980s, the idea of using a laser in the treatment of lumbar disc herniations arose. Ascher and Heppner, in 1984, were the first to use lasers to treat lumbar disc disease [31]. Theoretically, the application of laser energy, as delivered percutaneously through a cannula, would evaporate water in the nucleus pulposus resulting in a reduction of intradiscal pressure. This was postulated to cause the herniated disc material to recede towards the center of the disc, thus leading to reduction of nerve root compression and relief of radicular pain [32, 33]. After a series of in vitro experiments, Choy and colleagues performed the first percutaneous laser discectomy on a human patient in 1986 [34, 35]. In the 1990s, Saal and Saal introduced intradiscal electrical thermocoagulation (IDET). This technique also employs a percutaneous approach,

similar to nucleotomy or APLD; however, heat is applied using a thermoresistive coil [36]. It is specifically designed to treat pain from internal disc disruption and annular tears.

Historically, the indications for percutaneous discectomy have generally been limited to contained lumbar disc herniations. Lumbar radiculopathy secondary to large, free fragment (noncontained) disc pathology, migrated disc fragments, and bony compression of the nerve root have been contraindicated to percutaneous lumbar discectomy [37]. The efficacy of percutaneous nucleotomy and laser discectomy has been questioned. In a recently updated Cochrane review, Gibson and Waddell concluded, "At present, unless or until better scientific evidence is available, automated percutaneous discectomy, coblation therapy, and laser discectomy should be regarded as research techniques" [38]. However, despite the facts that conclusive evidence is lacking, randomized multicenter trials do not exist, and many of these procedures are labeled as experimental [33, 38], intradiscal therapies and percutaneous mechanical disc decompression techniques continue to increase [33, 39].

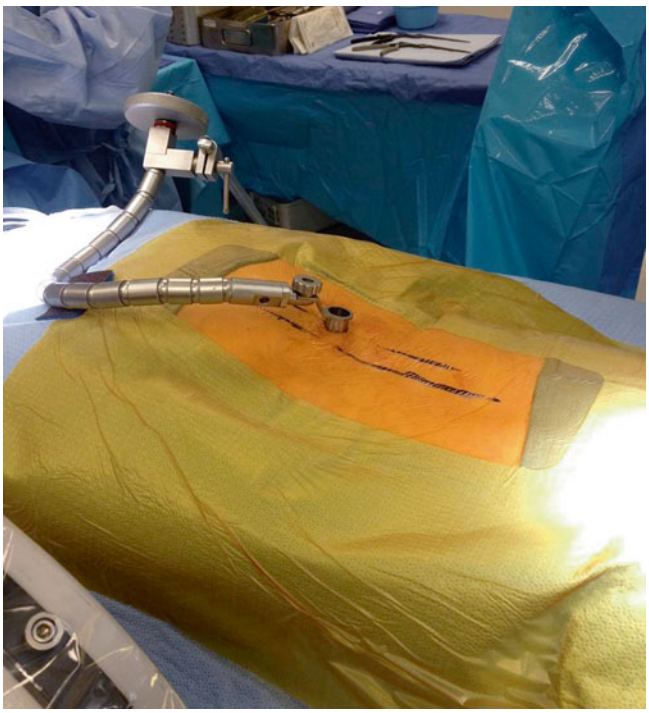

Fig. 1.1 A 16 mm diameter tubular retractor has been inserted for performance of a lumbar microdiscectomy

Lumbar Decompression Using Tubular Retraction

The use of a tubular retractor system for lumbar surgery was described by Foley and Smith in 1997 [37]. The microendoscopic discectomy (MED) system was specifically designed by the senior author (K.T.F.) to address the limitations of percutaneous nucleotomy and percutaneous endoscopic transforaminal approaches. Concerns regarding prior minimally invasive approaches to discectomy included the inability to adequately visualize the relevant anatomy and pathology and ergonomic issues related to small cannulae and tiny instruments. Lastly, in the senior author's personal experience with nucleotomy, failure to adequately decompress the nerve roots resulted in reoperation in several patients. Therefore a tubular retractor system was specifically designed to address these issues while remaining a minimally invasive procedure that utilized a muscle-sparing, percutaneous approach. The system consists of a series of concentric dilators and thin-walled retraction tubes of varying lengths. The spine is accessed via serial dilation of the natural plane between muscle fascicles, instead of a traditional muscle-stripping approach. The use of a tubular retractor, rather than blades, allows the retractor itself to be thin-walled (0.9 mm) and circumferentially defines a surgical corridor through the paraspinous muscles. The tube is held in place by an articulated, repositionable arm that also connects to the operating table. Unlike expanding bladed retractors, which rely on muscle tension to stay in position, tubular retractors minimize and evenly distribute the pressure on the surrounding paraspinous tissues. All of the midline supporting musculoligamentous spinal structures are left intact with this technique. An appropriately sized working channel is created that permits spinal decompression and fusion. Surgery can be performed using the operating microscope, loupes, an endoscope, or a combination of techniques, depending on the preference of the surgeon [5, 40]. The system has been used to provide minimally invasive access for a broad range of cervical, thoracic, and lumbar pathologies. Figure 1.1 illustrates a 16 mm diameter tubular retractor in place during microdiscectomy. Figure 1.2 shows the healed skin incision after completion of the microdiscectomy.

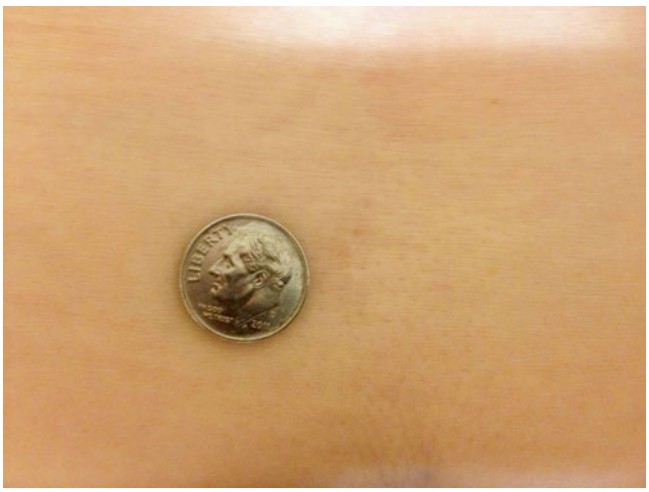

Fig. 1.2 A small, healed incision is visible following a lumbar tubular microdiscectomy

The tubular retractor system for microdiscectomy of herniated discs is the most common minimally invasive spine surgery performed in the United States [2]. However, limitations with the initial MED system included the fact that the endoscope was not reusable, image quality was inconsistent, and the working space within the tubular retractor was limited [41]. The lack of depth perception and stereoscopic visualization associated with the use of the endoscope prolonged the learning curve of the procedure [21]. To address these limitations and as surgical applications for this technology expanded, the MED system evolved into a more versatile tubular retractor system. Compared with the initial system, the modified system has additional advantages, including improved image quality, three-dimensional visualization, decreased endoscopic diameter, variable tubular retractor size, increased available working room within the tubular retractor, and decreased per case cost [41]. Unlike prior percutaneous approaches, the use of tubular retractors allows surgeons to address not only contained lumbar disc herniations but also sequestered or migrated disc fragments and lateral recess stenosis [41].

Data from six prospective randomized controlled trials comparing minimally invasive discectomy with tubular retractors to open discectomy (with a total of 837 patients) were pooled in a recent meta-analysis by Dasenbrock [42–48]. Incidental durotomies were reported significantly more frequently during minimally invasive discectomy, which may be due to the learning curve associated with this procedure. However, the total incidence of complications did not differ between the open and minimally invasive approaches. The current evidence suggests that both open and minimally invasive tubular retractor discectomy lead to a substantial and equivalent degree of short-term and long-term improvement in leg pain, the primary symptom of most patients with lumbar radiculopathy [42].

Tubular retractor systems have been used to address spinal pathology other than herniated discs. Guiot and colleagues, Khoo, and Palmer described a technique of bilateral decompression via a unilateral tubular approach for lumbar spinal stenosis [49–51]. After a standard unilateral decompression is performed, the working channel of the tubular retractor is angled medially, allowing for a central and contralateral decompression. The dural tube can be gently retracted, and the ligamentum flavum and the medial portion of the contralateral articular processes can be resected to achieve a bilateral decompression using a drill, Kerrison punches, and curettes [49, 50, 52]. The Tubular retractor systems have also been applied to address far lateral disc herniation [53], recurrent disc herniation [54], synovial cysts [55, 56], tethered cord syndrome [57], and intradural tumors [58, 59] among other applications [60].

Minimally Invasive Fusion and Fixation Techniques: Posterior

Efforts to minimize the approach-related morbidity of lumbar fusion can be traced to Watkins. In 1953, he reported a paraspinal approach between the planes of the sacrospinalis and the quadratus lumborum to expose the transverse processes for posterolateral lumbar fusion [61]. Subsequently, Wiltse described a modified transmuscular approach for spondylolisthesis using a longitudinal separation of the sacrospinalis group between the multifidus and longissimus [62].

Effective lumbar fusion, both open and minimally invasive, has generally relied upon effective means of internal fixation. Thus, the development of techniques for minimally invasive lumbar fusion has paralleled the development of techniques for minimally invasive lumbar fixation. Current options for percutaneous lumbar fixation include facet screws and pedicle screws. Facet screws fix the spine in situ and should be used only when the posterior spinal elements are intact (e.g., following an ALIF). Percutaneous pedicle screws, on the other hand, can be used following a posterior decompression or when the posterior elements are deficient (e.g., lytic spondylolisthesis). As well, pedicle screws can be used to apply corrective forces to the spine and to compress interbody grafts. For these reasons, we prefer pedicle screws for minimally invasive lumbar fixation.

Magerl described the use of percutaneous lumbar pedicle screws with long shafts (Schantz screws) and an external fixator in 1982. Initially, his system was used for external skeletal fixation of the lower thoracic and lumbar spine in spinal fracture cases [63]. The limitations of this technology included the risk of infection, patient discomfort associated with the external instrumentation, and the need to remove the instrumentation at a later date. However, it allowed for the evolution of techniques for minimally invasive lumbar fusion. Using Magerl's external fixator, Leu described a staged procedure for single-level percutaneous lumbar fusion in 1993 [64]. The technique did not allow for bony decompression and was limited to single segments. In a first procedure under general anesthesia, a Magerl external pedicular fixator was applied to the patient. In a second procedure at a later date, bilateral 7 mm diameter cannulae were inserted via a posterolateral, percutaneous approach 9–11 cm off the midline. The cannulae were passed through the annulus into the interbody space, where a nucleotomy was performed and the end plates were abraded with special instruments. Iliac bone graft that had been harvested through a separate incision was then inserted into the disc space through the cannulae. Finally, in a third procedure approximately 3 months later, the external fixator was removed. Leu reported 33

patients who had been operated upon using this technique from October 1988 to January 1991. The reported fusion rate for these cases was 84 %.

Mathews first described and performed a wholly percutaneous lumbar pedicle fixation technique in which he used plates as the longitudinal connectors in 1995 [65]. In his procedure, pedicle screws with long, smooth shafts above the threaded portions (similar to Magerl) were employed, but the screw shafts were connected with subcutaneous plates that were passed between the two screw incisions, applied to the screw shafts under direct vision, and then secured under direct vision utilizing nuts. In 2000, Lowery described a similar technique in which subcutaneous rods were used to connect the long screw shafts rather than plates [66]. With both the Mathews and Lowery procedures, the longitudinal connectors were placed superficially, just beneath the skin [65, 66]. This had several potential disadvantages. First, the superficial hardware could be irritating and required routine removal [66]. Second, longer screws (and thus longer moment arms) were required, producing a less effective biomechanical stabilization than that achieved using standard pedicle fixation systems and leading to a higher potential for implant failure.

In 2001, Foley and colleagues described a system for percutaneous pedicle screw/rod insertion to address the limitations of the prior techniques for percutaneous thoracolumbar fixation [67, 68]. The design criteria included the ability to percutaneously insert a biomechanically sound pedicle screw and rod construct into a standard, subfascial anatomic position similar to that of traditional open techniques. A key design element was the use of "extenders" that were removably attached to standard-sized pedicle screws. Once the screws had been percutaneously inserted through the pedicles, the extenders allowed the surgeon to align the screw heads remotely for subsequent percutaneous delivery of a rod.

The combination of the tubular retractor and the ability to place standard pedicle screws in a minimally invasive fashion led to rapid advances in minimally invasive fusion. In 2001, Foley published the results from the first cases performed using this system [67, 68]. This included the first tubular posterolateral onlay fusion with percutaneous pedicle screw and subfascial rod placement performed in 2000. The first tubular posterior lumbar interbody fusion (PLIF) with percutaneous pedicle screw and subfascial rod placement was performed by Foley in 2001, presented at the Congress of Neurological Surgeons annual meeting in 2001, and published in 2002 [5]. He reported on the results of tubular PLIF in seven patients. The first tubular transforaminal lumbar interbody fusion (TLIF) with percutaneous pedicle screw fixation was performed in 2001 and reported by Foley, Holly, and Schwender in 2003 [40].

Short-term and midterm outcomes of minimally invasive TLIF have been reported [16, 69]. We recently studied the long-term outcome in patients who underwent minimally invasive transforaminal lumbar interbody fusion for spondylolisthesis or spondylosis with or without radiculopathy with a minimum of 5 years' follow-up [17]. Only those patients who completed a preoperative Oswestry Disability Index questionnaire (ODI) and Visual Analog Score questionnaire (VAS) were included in the study. A total of 37 patients underwent a single-level minimally invasive TLIF. All patients had bilateral pedicle screw fixation and placement of a polyether ether ketone (PEEK) interbody device with autograft and appropriately dosed rh-BMP2. The mean age of the cohort was 63 years (37–80) with a mean follow-up of 72.6 months (60–90 months). Of the 37 patients, 25 had surgery at L4–5 and 12 at L5-S1. All patients had evidence of radiographic fusion at 2 years with none requiring revision surgery. There were 24 patients with low-grade spondylolisthesis (Meyerding Grade I and Grade II), 1 patient with Meyerding Grade III spondylolisthesis, and 12 patients without spondylolisthesis. One out of these 12 suffered multiple recurrent disc herniations at the same level warranting a fusion; the remaining 11 had spondylosis with associated mechanical low back pain and radicular symptoms. Thirty-three patients had a unilateral decompression and four patients had a bilateral decompression. Improvements in average visual analog scale-back pain, visual analog scale-leg pain, and Oswestry Disability Index (preoperative to last follow-up) scores were 50–12, 56–16, and 53–17, respectively. This is the first study with a greater than 60-month follow-up demonstrating long-term durability of minimally invasive TLIF results. The significant improvements in disability, back pain, and leg pain seen in this study suggest that minimally invasive TLIF is capable of producing sustained relief of symptoms and improvement in patient function.

The senior author also described a technique for minimally invasive TLIF that permits the surgeon to reduce spondylolisthesis percutaneously, utilizing translational screw extenders. Figure 1.3 is a schematic showing how reduction is achieved. Figure 1.4 depicts lateral fluoroscopic images showing reduction of a spondylolisthesis using the reduction screw extender [70]. Forty patients who underwent minimally invasive TLIF for symptomatic spondylolisthesis utilizing this approach were studied. Thirty cases involved a degenerative spondylolisthesis while the remaining ten were isthmic. The minimum follow-up was 24 months with a mean of 35 months. The mean preoperative Oswestry Disability Index score was 55 and decreased to a mean of 16 postoperatively. The mean preoperative leg and back pain visual analog scale scores were 65 and 52, respectively, improving to means of 8 and 15, respectively. Reduction of

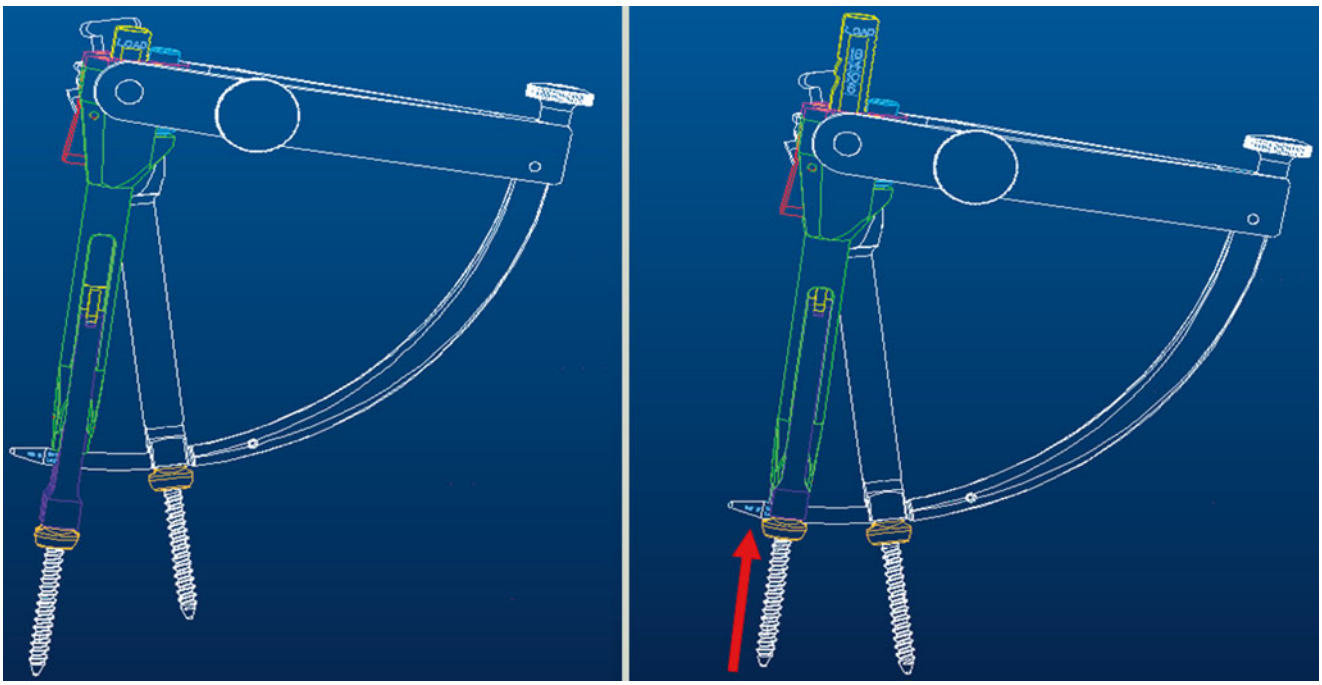

Fig. 1.3 Spondylolisthesis reduction is accomplished by shortening the length of the extender. When the set screw of the standard extender is provisionally tightened, this locks the angle between the rod and the pedicle screw. Turning the drive screw of the reducible extenders shortens its length and pulls the slipped vertebral body towards the rod

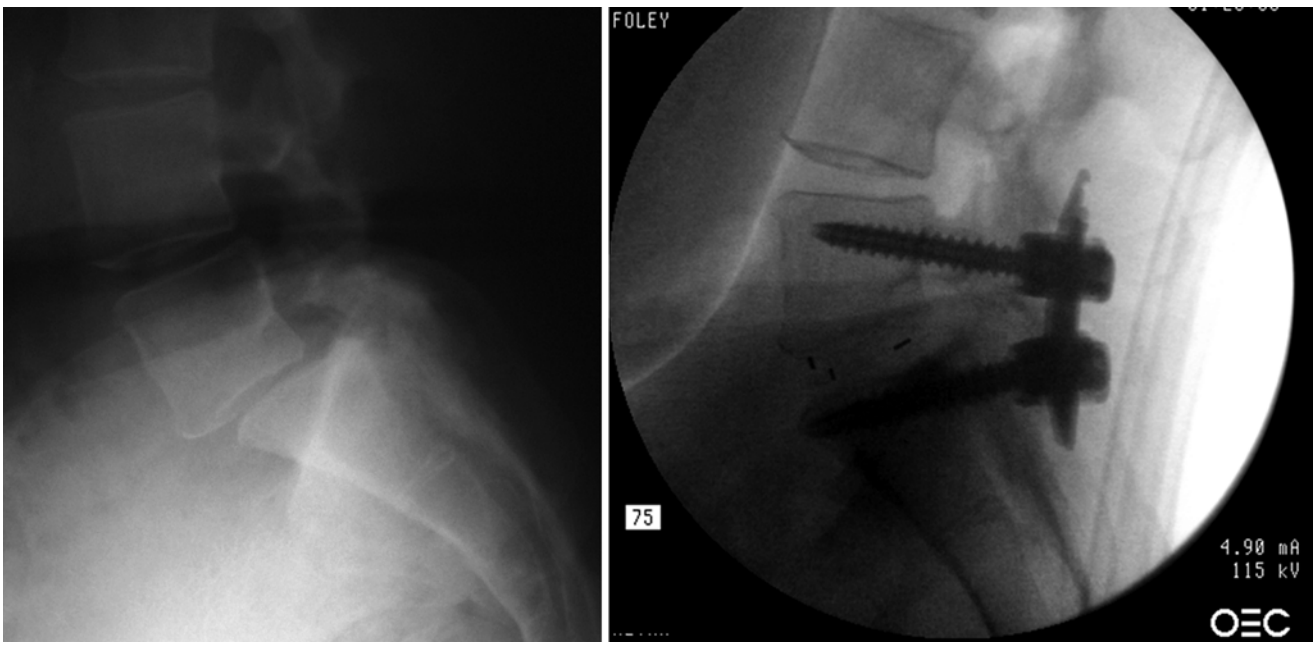

Fig. 1.4 Lateral fluoroscopic images show the spondylolisthesis before and after minimally invasive reduction

the spondylolisthesis was achieved in all cases, with a mean decrease in forward translation of 76 %. The authors conclude that minimally invasive TLIF for symptomatic spondylolisthesis appears to be an effective surgical option with results that compare favorably to open procedures.

During the last decade, the indications for percutaneous pedicle screw fixation and device options for placing them have expanded, permitting surgeons to routinely use percutaneous fixation in multilevel thoracolumbar cases. Currently, percutaneous pedicle screws are used in a variety of spinal

disorders, including trauma, spinal neoplasia, infection, revision surgery, and deformity [71].

Recently, a new class of posterior spinal fixation devices called interspinous spacers has been introduced. Theoretically, the insertion of an interspinous spacer provides for indirect decompression by maintaining flexion of a stenotic spinal segment. Ideal candidates for this surgery include patients with neurogenic claudication that is relieved with flexion [72]. These devices can be inserted under local anesthesia in a less invasive fashion than conventional lumbar surgery. The idea dates back to Knowles in 1957; he placed a steel "plug" between the spinous processes to hold the spine in a flexed posture. Unfortunately these devices loosened and were dislodged easily [73]. Currently there are many designs of interspinous spacers. They can be categorized as either static/noncompressible or dynamic/compressible. The first interspinous spacer to be used in the United States for the treatment of patients with neurogenic intermittent claudication due to spinal stenosis was approved by the Food and Drug Administration in 2005. A recent systematic review of the clinical evidence by Kabir concluded that this form of interspinous process spacer may improve outcome when compared to nonoperative treatment in a select group of patients over 50 years old, with lumbar stenosis and neurogenic claudication, who have improvement of their symptoms in flexion. While studies on multiple interspinous devices have shown promising initial clinical results, prospective randomized controlled trials are lacking. Further, good quality trials are needed to clearly outline the indications for their use [72, 74]. A recent report by Epstein raised concerns about high complication rates, reoperation rates, poor outcomes, and high costs for interspinous devices [75].

Minimally Invasive Fusion Techniques: Lateral

The lateral retroperitoneal transpsoas approach is a novel minimally invasive procedure that provides a surgical corridor to the anterior lumbar spine to perform interbody fusion [76]. In 1997, Mayer [77] first reported the technique of a less invasive, retroperitoneal, direct lateral approach to the lumbar spine, which was later refined by McAfee in 1998 to include the use of an endoscope and placement of lateral threaded fusion cages [78]. Subsequently, in 2006, Ozgur, Aryan, Pimenta, et al. described a further evolution of the lateral interbody fusion technique [79]. In this approach, the patient is placed in the lateral decubitus position. Dissection occurs through the retroperitoneal anatomical fat plane, directly down to the psoas muscle. Dilators and a modified tubular retractor are then placed under fluoroscopic guidance to provide access to the appropriate spinal level. To guide dissection through the psoas muscle, intraoperative neuromonitoring is necessary to prevent injury to the lumbosacral plexus. Once the lateral aspect of the disc space has been localized and exposed, discectomy and fusion are performed using standard techniques [30]. An advantage of this approach is that it does not require a second access surgeon. Other advantages are reduced incidence of ileus compared to open anterior approaches, maintained integrity of the anterior and posterior longitudinal ligaments, reduced operative time in comparison to other anterior approaches, and reduced postoperative hospital stay and analgesic requirements [76]. Morbidity for this approach includes transpsoas swelling causing hip flexor weakness, genitofemoral nerve irritation causing numbness or pain of the thigh and groin area, and lumbar plexus injury [80, 81].

Minimally Invasive Fusion Techniques: Anterior

Anterior lumbar interbody fusion (ALIF) has been used for spinal degenerative disorders since 1932, when Carpenter first described the technique for treatment of spondylolisthesis [82]. ALIF was originally performed through an open retroperitoneal approach. In the mid-1980s, reports were published which described a simultaneous combined anterior and posterior approach for spinal fusion [83]. The procedure was characterized by a 25-cm incision extending from the midline to the lateral border of the rectus abdominis, 400–600 cc of intraoperative blood loss, a surgical duration of 3.25 h, and hospitalizations typically lasting 10–14 days [83, 84]. The incorporation of laparoscopy-assisted techniques by gynecologic, urologic, and general surgeons paved the way for these technologies to provide access to the anterior lumbar spine. In 1991, Obenchain reported the first use of a laparoscopic approach to the lumbar spine for a discectomy [85]. In the mid-1990s, mini-open retroperitoneal [77, 86], mini-open transperitoneal [77], laparoscopic transperitoneal [87, 88], and laparoscopic retroperitoneal [78] approaches were developed for ALIF.

A novel method for instrumentation of the lumbosacral spine is through the paracoccygeal transsacral corridor, first reported by Cragg in 2004 [89]. A small paracoccygeal incision is used to develop a corridor in the presacral space. Custom instruments can be directed under fluoroscopic guidance along the midline of the anterior sacrum to the surface of the sacral promontory, where an axial bore can be created through the remaining sacrum into the lower lumbar vertebral bodies and discs. A discectomy can be performed, bone graft can be inserted into the interspace, and an axial threaded screw for fixation can be placed. This procedure is usually accompanied by posterior fixation although it can be performed as a stand-alone under certain circumstances [30]. A recent study by Tobler in 2011 evaluated the 2-year clinical and radiographic outcomes in 156 patients who underwent an L5-S1 interbody fusion and fixation using this approach.

Clinical improvements were realized in back pain severity and functional impairment through 2 years of follow-up, and the overall radiographic fusion rate at 2 years was 94 % (145 of 155) [90].

Minimally Invasive Surgery in the Thoracic Spine

Traditional access to the thoracic spine includes anterior- and posterior-based approaches. Such approaches include posterior transpedicular, costotransversectomy, lateral extracavitary, anterolateral transthoracic, and sternotomy. These techniques, while familiar to the spine surgeon, carry significant morbidity.

One of the first developments applicable to minimally invasive approaches to the thoracic spine was video-assisted thoracoscopic surgery (VATS). A Swedish physician, Hans Christian Jacobaeus, is credited as the pioneer of this technique in 1910 [91]. The development of endoscopic video cameras and improvements in surgical instrumentation further broadened applications of thoracoscopy. The first use of thoracoscopy for the treatment of spinal disease was developed simultaneously by Mack [92] in the United States and Rosenthal [93] in Germany [94]. VATS has been used for infectious processes, including biopsies and drainage, tumor biopsies, thoracic disc herniations, sympathectomies, and anterior releases for deformity correction [95].

The application of tubular retractors to the thoracic spine has been described by Jho and Perez-Cruet [96, 97]. This technique, as for the lumbar spine, involves a series of muscle dilators, a tubular retractor, and an endoscope for visualization, which can reduce much of the morbidity associated with traditional approaches. Recently, lateral approaches to the thoracic spine employing the use of tubular and expandable retractors have been used for tumor removal and traumatic spinal pathologies, including corpectomies and the placement of expandable cages with anterior plating [98, 99].

Minimally invasive thoracic pedicle screw fixation has recently been described. In 2003, Holly and Foley evaluated the accuracy of percutaneous thoracic pedicle screw placement in three cadavers. Fifty-nine of sixty-four screws were placed completely within the pedicles (92 %); the remaining screws violated the pedicle walls by less than 3 mm [100]. In 2006, Ringel and colleagues placed percutaneous posterior pedicle screws in the thoracic and lumbar spine via a transmuscular approach using two-dimensional fluoroscopy alone in 104 patients [101]. The use of cannulated pedicle screws using neuronavigation has also been recently reported by Kakarla [102]. Minimally invasive percutaneous instrumentation has been used for traumatic vertebral body fractures and neoplastic, infectious, and degenerative diseases of the thoracic spine in a safe manner with acceptable rates of accuracy and morbidity [102].

Minimally Invasive Surgery in the Cervical Spine

While there have been tremendous advances in minimally invasive approaches and techniques for the thoracolumbar spine, the same cannot be said for cervical spine surgery. The anterior cervical approach to the spine is a commonly performed procedure and enjoys a relatively low morbidity. Therefore, the impetus to search for alternative cervical options is reduced unless long-segment posterior decompression or stabilization across the occipitocervical and cervicothoracic junctions is necessary [103].

Progress in imaging techniques has allowed for much more thorough preoperative assessment and characterization of the specific indications for posterior cervical approaches. Specifically, with posterolateral cervical nerve root decompression, such as for an intraforaminal disc herniation or cervical foraminal stenosis, a posterior cervical foraminotomy can be effective. The tubular retractors that had success in the lumbar spine were used in the cervical spine. The first application of the microendoscopic discectomy system (MED) for minimally invasive posterior cervical foraminotomy was described by Roh in cadaveric specimens in 2000 [104]. Adamson and Fessler and colleagues described their initial clinical experience with this technique in 2001 and 2002, respectively. The technique was found to be safe and effective [105, 106]. Wang and colleagues described their initial experience and 2-year follow-up on short segment lateral mass fixation using a tubular retractor system [107, 108]. Their technique involved a midline incision followed by placement of tubular retractors that were directed rostrally and laterally ("up and out") in a trajectory very similar to that used for traditional open cervical lateral mass screw placement. The major limitation of this method remained the need for rod passage and the need for a mini-open exposure of the lateral masses [108]. Wang and colleagues also explored minimally invasive applications for cervical laminoplasty. They reported their initial cadaveric study in 2003, along with recent clinical experience documenting the technique's feasibility in 2008 [109, 110]. Recently, Ahmad and colleagues described their initial experience with percutaneous trans-facet screw instrumentation in the subaxial cervical spine. This technique is particularly attractive because it avoids the need for an interconnecting plate/rod. It has been used primarily to supplement anterior fusion surgeries where the risk of pseudoarthrosis or kyphosis is high [103].

Early clinical experiences with minimally invasive posterior approaches to the cervical spine are promising. However,

these techniques are challenging and carry a steep learning curve. Ultimately, patient-driven outcome assessment and randomized, prospective studies will be needed for validation of these approaches.

Conclusion

The future for minimally invasive spine surgery appears promising. New technologies will allow surgeons to effectively perform more complex spinal procedures using techniques that minimize tissue injury. These procedures hold the promise of decreased iatrogenic soft tissue injury and approach-related morbidity while allowing the surgeon to perform the operation as effectively as the conventional open surgery.

Preliminary results suggest that many minimally invasive spinal procedures can be performed safely and effectively, and at this time long-term outcomes are starting to be reported in the literature. The long-term improvement of patient-derived outcomes has positive implications for cost-effectiveness of these techniques. Studies assessing cost savings and cost-effectiveness are essential, as rates of spine surgery have increased dramatically over the past decade, with the most dramatic increase noted for lumbar fusion [111]. In fact, recent studies have demonstrated the cost-effectiveness of minimally invasive lumbar fusion [112–114]. Although minimally invasive spinal techniques have a logical basis and are appealing to patient and surgeon alike, only prospectively conducted, long-term studies will clearly determine their advantages and disadvantages compared with conventional open surgeries.

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Philosophy and Biology of Minimally Invasive Spine Surgery

2

Paul D. Kim and Choll W. Kim

Philosophy of Minimally Invasive Surgery (MIS)

The goals of minimally invasive spine surgery are to accomplish the same goals of traditional open spine surgery whether it is decompression, fusion, or correction of deformity. The key concepts that guide MIS approaches are as follows: (1) decrease muscle crush injuries during retraction; (2) avoid detachment of tendons to the posterior bony elements, especially the multifidus attachments to the spinous process and superior articular processes; (3) maintain the integrity of the dorsolumbar fascia; (4) limit bony resection; (5) utilize known neurovascular planes; and (6) decrease the size of the surgical corridor to coincide with the area of the surgical target site. Recent advancements in instrumentation, combined with refinement of surgical techniques, have allowed treatment of an ever broader array of spinal disorders.

Recently, there are reports purporting the clinical benefits of MIS of the spine. These early outcomes point to improvements in infection rates, decreased hospital stay, and less blood loss/transfusion [1, 2].

Preservation of Muscle Tissue

Minimally invasive spine surgery techniques strive to minimize muscle injury during surgery. By eliminating the use of self-retaining retractors, intramuscular retraction pressure is reduced and thereby leads to less crush injury. In addition, focusing the surgical corridor directly over the surgical target site allows for less muscle stripping which may otherwise disrupt muscle attachments or damage their neurovascular supply. There are multiple studies that demonstrate the muscle preservation associated with MIS approaches. Kim et al. [3] compared trunk muscle strength between patients treated with open posterior instrumentation vs. percutaneous instrumentation. Patients undergoing percutaneous instrumentation displayed over 50 % improvement in extension strength, while patients undergoing open surgery had no significant improvement in lumbar extension strength. Extension strength correlated with preservation of multifidus cross-sectional area which was measured on magnetic resonance imaging (MRI). In a similar study, Stevens et al. [4] assessed the postsurgical appearance of the multifidus muscle using high-definition MRI sequences. In patients treated via an open posterior transforaminal lumbar interbody fusion (TLIF) technique, marked intermuscular edema was observed on postsurgical MRI 6 months after surgery. In contrast, patients in the MIS TLIF group had a normal appearance on postsurgical MRI. Also, Hyun et al. [5] retrospectively assessed a group of patients that underwent unilateral TLIF with ipsilateral instrumented posterior spinal fusion via a standard midline approach. Contralateral instrumented posterior spinal fusion was also performed at the same level employing a paramedian, intermuscular (Wiltse) approach. Postoperatively, there was a significant decrease in the cross-sectional area (CSA) of the multifidus on the side of the open approach, while there was no reduction in the multifidus CSA on the contralateral side. Figure 2.1 demonstrates the MIS TLIF approach with the use of lighted tubular retractors.

Decreases in tissue trauma not only have local effects but have systemic effects as well. Markers of skeletal muscle injury (creatine kinase, aldolase), pro-inflammatory cytokines (IL-6, IL-8), and anti-inflammatory cytokines (IL-10, IL-1 receptor antagonist) were measured in a study of patients undergoing open vs. MIS fusions [6]. A two- to seven-fold increase in all markers was observed in the open surgery group. The greatest difference among the groups occurred on the first postoperative day. Most markers returned to baseline in 3 days for the MIS group, whereas the

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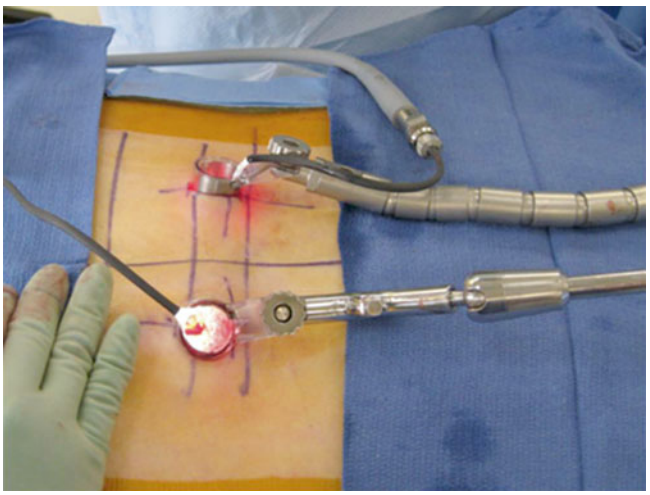

Fig. 2.1 The minimally invasive translumbar interbody approach using lighted tubular retractors

open surgery group required 7 days. IL-6 and IL-8 are known cytokines that participate in various systemic inflammatory reactions [7–9]. It is possible that such elevations in inflammatory cytokines have direct effects beyond the surgical site.

Preservation of the Bone-Ligament Complex

Excessive facet resection leads to altered motion and hence spinal instability [10]. Furthermore, a laminectomy leads to loss of the midline supraspinous ligament complex which can contribute to flexion-extension instability [11, 12]. In cases where significant bony resection is required, or when there is an underlying relative instability (such as in spondylolisthesis), concomitant fusion is often recommended following a decompressive laminectomy. Efforts to limit such potentially destabilizing surgery have been pursued via unilateral laminotomies in which the spinous processes and corresponding tendinous attachments of the multifidus muscle and the supraspinous and interspinous ligaments are preserved. When this technique is combined with minimally invasive tubular retractors, bilateral decompression for stenosis can be achieved with good clinical results [13, 14]. The long-term outcome of such MIS procedures and their effect on spinal stability have yet to be shown clinically. However, biomechanical studies suggest that such MIS techniques do maintain spinal stability [13].

Fessler and co-workers compared three decompressive techniques to treat 2-level spinal stenosis: open laminectomies vs. interlaminar midline decompression (which retains the spinous process but sacrifices the interspinous/supraspinous ligaments) vs. MIS unilateral laminotomies [15]. Standard open laminectomy produces marked increases in flexion, extension, and axial rotation. For flexion-extension, there is a greater than two-fold increase in motion which leads to increased stress on the annulus. No changes in flexion were noted when the interlaminar or MIS models were studied. Axial rotation increased by 2.5-fold in the open and interlaminar groups but only 1.3-fold in the MIS group. These findings lend further support to the concept that MIS techniques have relevant effects on spinal motion and stability.

Correlation of Muscle Injury with Clinical Outcomes

The end result of postsurgical muscle damage remains to be determined. There, however, appears to be a correlation between paraspinal muscle damage and long-term postoperative pain. Sihvonen et al. found severe denervation of the multifidus muscle in patients with failed back syndrome [16]. Muscle biopsies showed signs of advanced chronic denervation consisting of group atrophy, marked fibrosis, and fatty infiltration. Moreover, fiber type grouping, a histological sign of reinnervation, was rare. They hypothesized that the denervation injury resulted from direct damage to the medial branch of the posterior rami during muscle retraction associated with the posterior midline approach. The lack of reinnervation was thought to result from the absence of intersegmental nerve supply to the multifidus. Severe denervation of the paraspinal muscles correlates with poor outcome of postsurgical patients. They also showed that poor clinical outcomes are associated with abnormal EMG patterns 2–5 years after surgery. Although a correlation between the degree of muscle atrophy following surgery and the incidence of failed back syndrome was found, it is not clear what specific pathogenic factors are responsible.

Biology of Minimally Invasive Spine Surgery

Posterior Paraspinal Muscle Anatomy

The posterior lumbar paraspinal muscles are part of a larger biomechanical system that includes the abdominal muscles and their fibrous attachment to the spine through the lumbosacral fascia. This network of muscles is responsible for generating movements of the spine while maintaining its stability (Fig. 2.2). In addition to maintaining spinal posture in its neutral position, the paraspinal muscles guard the spine from excessive bending that would otherwise endanger the integrity of the intervertebral discs and ligaments [17]. Panjabi et al. have proposed that the paraspinal muscles apply minimal resistance inside the neutral zone (NZ), but increase their stiffness exponentially once the range of motion falls outside this NZ [18–20]. This dynamic stabilizing system is controlled by an interconnected chain of mechanoreceptors

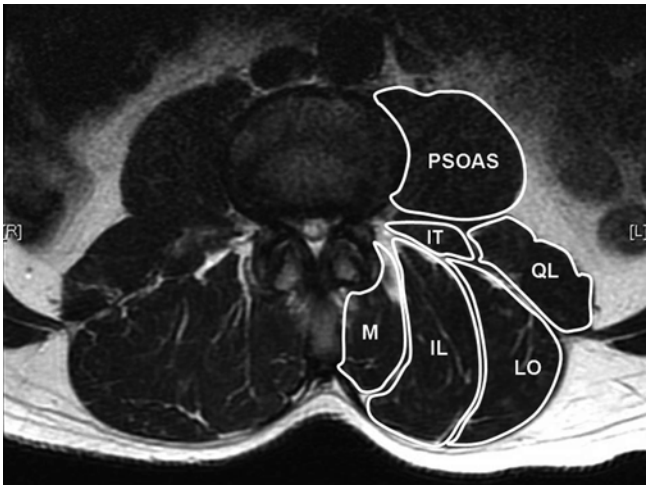

Fig. 2.2 The posterior lumbar paraspinal muscles (*IT* intertransversarii, *QL* quadratus lumborum, *M* multifidus, *IL* iliocostalis lumborum, *LO* longissimus), *PSOAS* muscle

imbedded in the muscle fascicles, the disc annulus, and the spinal ligaments [21]. Functional EMG studies reveal that spinal stability is achieved by the simultaneous contraction of several agonistic and antagonistic muscles [17]. Architectural studies suggest that the individual paraspinal muscles may have different primary roles at different times as either movers or stabilizers of the spinal column [22].

Multifidus Muscle

The posterior paraspinal muscles are composed of two muscle groups: the deep paramedian transversospinalis muscle group, which includes the multifidus, interspinales, intertransversarii, and short rotators, and the more superficial and lateral erector spinae muscles that include the longissimus and iliocostalis. These muscles run along the thoracolumbar spine and attach caudally to the sacrum, the sacroiliac joint, and the iliac wing. The multifidus is the most medial of the major back muscles and is the largest muscle that spans the lumbosacral junction. It is believed to be the major posterior stabilizing muscle of the spine [17, 23]. Compared to other paraspinal muscles, the multifidus muscle has a large physiologic cross-sectional area (PCSA) and short fibers. This unique architectural anatomy is designed to create large forces over relatively short distances. Furthermore, the multifidus sarcomere length is positioned on the ascending portion of the length-tension curve. When our posture changes from standing erect to bending forward, the multifidus is able to produce more force as the spine flexes forward. This serves to protect the spine at its most vulnerable position.

The multifidus is the only muscle that is attached both to the posterior parts of the L5 and S1 vertebrae and is, therefore, the sole posterior stabilizer that both originates and inserts to this segment. The morphology of the lumbar multifidus is complex [24]. Unlike the other paraspinal muscles that have specific origins and insertions, the multifidus muscle is formed by five separate bands, each having its own origin and several different insertion sites. Each band consists of several fascicles arising from the tip of the spinous process and the lateral surface of the vertebral lamina. Caudally, the different fascicles diverge to separate attachments into the mammillary processes of the caudal vertebrae two to five levels below their origin and downward through each vertebra to the sacrum. For example, fibers from the L1 band insert into the mammillary processes of the L3, L4, and L5 vertebrae, to the dorsal part of S1, and to the posterior superior iliac spine. Biomechanical analysis, based on the multifidus muscle anatomy, has shown that it produces posterior sagittal rotation of the vertebra, which opposes a counterrotation generated by the abdominal muscles. The multifidus can further increase lumbar spine stability through a "bowstring" mechanism in which the muscle, positioned posterior to the lumbar lordosis, produces compressive forces on the vertebrae interposed between its attachments [22–25].

Erector Spinae Muscles

The erector spinae muscles are composed of the longissimus, the iliocostalis, and the spinalis in the thoracic area (Fig. 2.2) [26, 27]. In the lumbar spine, the longissimus is positioned medially and arises from the transverse and accessory processes and inserts caudally into the ventral surface of the posterior superior iliac spine. The laterally positioned iliocostalis arises from the tip of the transverse processes and the adjacent middle layer of thoracolumbar fascia and inserts into the ventral edge of the iliac crest caudally. Unilateral contraction of the lumbar erector spinae laterally flexes the vertebral column; bilateral contraction produces extension and posterior rotation of the vertebrae in the sagittal plane. In addition to their role as the major extensor muscles of the trunk, the iliocostalis and the longissimus also exert a large compressive load as well as lateral and posterior shear forces at the L4 and L5 segments. While these forces increase the stiffness and stability of the normal vertebral column, the shearing forces could also exacerbate instability and deformity in a malaligned spine [28]. In contrast to the multifidus muscle, micro-architectural studies reveal that these muscles are designed with long muscle fascicles with relatively small PCSA. This anatomic morphology suggests that they serve to move the trunk to extension, lateral bending, and rotation. With this type of design, they are less likely to act as primary stabilizers of the vertebral column [29].

The Interspinales, Intertransversarii, and Short Rotator Muscles

The interspinales, intertransversarii, and short rotator muscles are short flat muscles that lie dorsal to the intertransverse ligament (Fig. 2.2). The intertransversarii and interspinales run

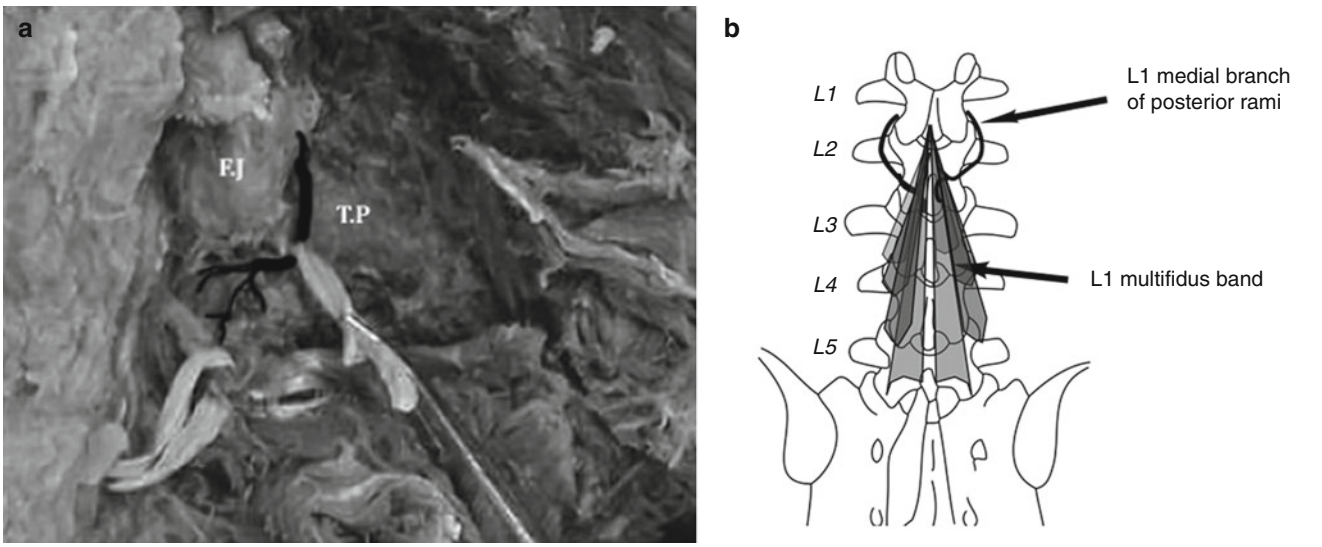

Fig. 2.3 (**a**, **b**) Multifidus innervation by the medial branch of the dorsal rami

along the intertransverse and the interspinous ligaments of each segment. The short rotators originate from the posterior superior edge of the lower vertebra and attach to the lateral side of the upper vertebral lamina. Because of their small PCSA, they are not able to generate the forces needed for movement or stability of the spinal column. More likely, they act as proprioceptive sensors rather than force-generating structures.

Innervation of the Posterior Paraspinal Muscles

The innervation of all of the posterior paraspinal muscles is derived from the dorsal rami. The iliocostalis is innervated by the lateral branch, while the lumbar fibers of the longissimus receive innervation from the intermediate branch. The multifidus is innervated by the medial branch of the dorsal rami (Fig. 2.3). The medial branch curves around the root of the superior articular process and passes between the mammillary and accessory processes to the vertebral lamina where it branches to supply the multifidus muscle, the intertransversarii and the interspinales muscles, and the zygapophysial joints. During its extra-muscular course, the medial branch is strongly attached to the vertebral body in two locations. The first attachment is to the periosteum lateral to the zygapophysial joints by fibers of the intertransverse ligament. The mamillo-accessory ligament provides the second attachment in the lumbar spine. This strong ligament covers the medial branch and is often ossified. These attachments to the vertebra are of clinical importance as they expose the medial branch to possible damage during a midline posterior surgical approach.

Direct damage to the nerve is also possible during insertion of pedicle screws [30]. Insertion of a pedicle screw in the area of the mammillary process can injure the medial branch arising from the cephalic level nerve root causing denervation injury followed by atrophy to the multifidus fascicles that arise from the adjacent cephalic level. For instance, pedicle screws placed at L2 may damage the L1 nerve, which denervates the multifidus bands that originate at L1 and inserts into the vertebrae caudally. Moreover, the mono-segmental innervation of the multifidus makes it particularly susceptible to atrophy as it lacks a collateral nerve supply from adjacent muscle segments [24]. It is intriguing to hypothesize that dysfunction of this muscle could contribute to adjacent-level disc degeneration.

Characteristics of Paraspinal Muscles in the Postsurgical Spine

Spinal surgery inherently causes damage to surrounding muscle [31]. This injury can be followed by atrophy of the muscles and subsequent loss of function. Among the different surgical approaches to the spine, it appears that muscle injury is greatest when using the classic midline posterior approach [32]. The multifidus muscle is most severely injured when using this approach. Muscle atrophy coincides with decreased muscle cross-sectional area which in turn correlates with decreased force production capacity of the muscle [25, 33]. Figure 2.4a demonstrates postoperative changes associated with the traditional midline approach, and Fig. 2.4b demonstrates preservation of muscle architecture with the paramedian approach.

Muscle biopsies obtained from patients undergoing revision spinal surgery exhibit an array of pathologic features that include selective type II fiber atrophy, widespread fiber type grouping (a sign of reinnervation), and "moth-eaten" appearance of muscle fibers [34]. Although these pathologic changes can occasionally be found in biopsies from normal individuals, the pathologic changes are more prevalent after surgery.

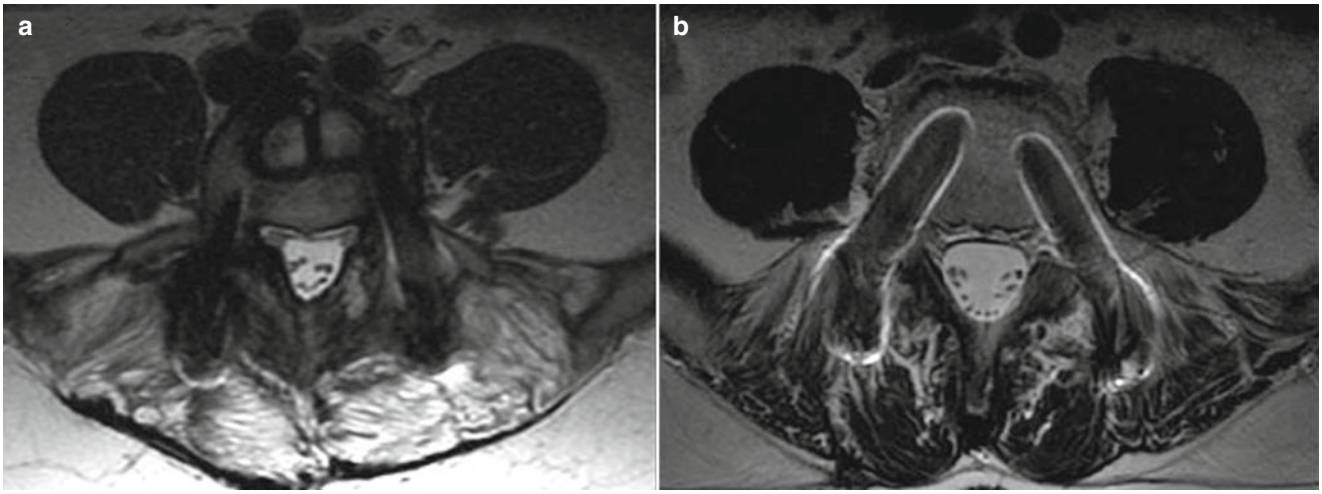

Fig. 2.4 (**a**) Postoperative MRI changes associated with the traditional midline approach and (**b**) demonstrate preservation of muscle architecture with the paramedian approach

Atrophy of the paraspinal muscles can readily be seen in postsurgical back patients, and reductions in the cross-sectional area (CSA) of the paraspinal muscles are the greatest following a midline approach for a posterolateral fusion [31, 35]. Little to no reduction in CSA was found following single-level laminectomy or laminotomy with discectomy.

The Mechanism of Paraspinal Muscle Injury During Surgery

The factors responsible for muscle injury during surgery have been well studied in both animals and humans. Muscle damage can be caused by several different mechanisms. Direct injury to the muscle is caused by dissection and stripping of tendinous attachments from the posterior elements of the spine. Additionally, extensive use of the electrocautery causes localized thermal injury and necrosis to the tissues. Another significant factor responsible for muscle injury is the use of forceful self-retaining retractors. Kawaguchi and co-workers quantified the factors responsible for muscle necrosis following a standard open midline posterior approach [36–39]. They proposed that injury is induced by crush mechanism similar to that caused by a pneumatic tourniquet during extremity surgery. During the application of self-retaining retractors, elevated pressures lead to decreased intramuscular perfusion [40, 41]. The severity of the muscle injury is closely correlated to the degree of the intramuscular pressure and the length of retraction time. A pressure-time parameter can be calculated by multiplying the intramuscular pressure and the length of time of the surgery. A high pressure-time product was shown to be tightly correlated to muscle necrosis. They concluded that muscle damage can be reduced by intermittent release of the retractors during prolonged surgery combined with a relatively longer incision that allows reduced retraction pressures.

Denervation is yet another mechanism that leads to muscle degeneration and atrophy following surgery. Injury to muscle innervation can occur in a discrete location along the supplying nerve or be located in several points along the nerve and the neuromuscular junction. As previously described, nerve supply to the multifidus is especially vulnerable to injury because of its mono-segmental innervation pattern [22]. Muscle denervation is also possible through damage to the neuromuscular junction following long muscle retraction and necrosis. A shorter retraction time or an intermittent release of muscle retraction every hour was shown to significantly decrease degeneration and denervation of the muscles [39]. Bogduk et al. [28] examined the relationship between retraction time and postoperative damage to the paraspinal muscle, by measuring postoperation signal intensity of the multifidus muscle, using T2-weighted MR imaging. Long retraction time during surgery was found to correlate with high signal intensity in the multifidus muscle even at 6 months postsurgery. They proposed that these findings reflect chronic denervation of the muscle caused by damage to the neuromuscular synapses in the muscle.

Conclusions

Minimally invasive spine surgery is entering an exciting era of new technology, and more recent outcomes report on the benefits of MIS of the spine techniques. The goals of surgery remain the same as open spine surgery with reduced patient morbidity and better long-term outcomes. The classic midline spine approach has its utility, but we must recognize also the morbidity associated with this approach. Preserving the soft tissue envelope and understanding the anatomy and biology of the posterior spinal musculature remain the key concepts in MIS of the spine.

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Economics of Minimally Invasive Spine Surgery

3

Y. Raja Rampersaud and Kevin Macwan

Introduction

In most countries the cost of health care has progressively increased at a rate greater than the respective national economic growth [1]. Consequently, health-care delivery in its present state is unsustainable and in many countries has already resulted in increased taxation as well as decreased government funding of other vital societal services. From a macroeconomic perspective the economic impact of health-care interventions is critically important to all stakeholders. As stakeholders in health-care management and delivery attempt to mitigate increasing expenditures, greater demands are made upon all therapies to describe their proven indications, report adverse events, and delineate their outcomes [2].

With increasing costs, it also becomes necessary for health providers and payers to assess the value (defined as the relative worth, utility, or importance) of an intervention compared to alternative interventions. These needs have been highlighted by the Institute of Medicine (IOM) as comparative effectiveness research (CER). As per the IOM "*Comparative effectiveness research is the generation and synthesis of evidence that compares the benefits and harms of alternative methods to prevent*, *diagnose*, *treat*, *and monitor a clinical condition or to improve the delivery of care. The purpose of CER is to assist consumers*, *clinicians*, *purchasers*, *and policy makers to make informed decisions that will improve health care at both the individual and population levels*" [3–5]. Physicians have traditionally understood and taken the perspective of safety and clinical efficacy of an intervention. However, physicians often lack the perspective and language of purchasers and policy makers, which also includes the health economic aspect of not only the intervention of interest to a specific health provider, but also its impact and relevance to other relevant interventions and health-care delivery as a whole.

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Health Economic Evaluations (HEEs)

The Importance of Health Economic Evaluations

From the perspective of musculoskeletal surgery, the increasing demands for surgical services will only continue to increase [6–13]. It is estimated that by the year 2030, over half of the adults in the US population will be aged over 65 years. The economic effects of degenerative disorders such as arthritis of the spine (i.e., spinal stenosis), hip, and knee within this aging population will have profound implications on the future affordability and availability of quality spine care [6–13]. Within spine surgery, the SPORT studies [14–17] have documented the sustainable efficacy and cost-effectiveness of interventions using traditional open surgery techniques for lumbar disk herniation, spinal stenosis, and degenerative spondylolisthesis compared to nonsurgical care at the 4-year mark. However, CER within the spine surgery literature from an economic perspective is generally lacking and requires further research. Although the need for economic data in the current health-care climate is increasingly important, less than 1 % of articles published on lumbar spine fusion between 2004 and 2009 include a cost-effectiveness analysis (CEA) [18]. In addition, societal perceptions regarding spine surgery and its benefits, risk, and associated costs may also have an impact on the perceived value of spinal intervention, regardless of whether it demonstrates cost-effectiveness or not. Unfortunately, as a result of heterogeneity of spine surgery, particularly around the surgical management of low back pain, spine surgical interventions are perceived to be high risk, high cost, often

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ineffective, and often seen as a last resort. In addition, the high variability in results along with differences in clinical indications and techniques used further confounds existing opinions regarding spine surgery and surgical techniques [8]. Furthermore, from the non-spine surgeon perspective, much of what is done in spine surgery (good and bad) is lumped into one seemingly homogenous category that typically equates to the management of low back pain.

With these aforementioned challenges in mind, it is critically important for a spine surgeon to understand that the value of spine intervention for degenerative conditions must also be looked at from a big-picture perspective (i.e., societal and payer perspective). As health-care resources contract, resource allocation for competing pathologies including cancer and chronic conditions such as cardiovascular disorders, diabetes, cancer, and arthritis currently demands the largest portion of available funds. In a paper by Martin et al. that looked at expenditures and health status among US adults with back and neck problems, the authors noted significantly escalating cost with no appreciable improvement in health status compared to non-back/neck individuals [19]. Furthermore, the estimated annual US expenditures for back and neck problems ($86 billion) have reached levels comparable to diabetes ($98 billion), cancer ($89 billion), and non-spine arthritis ($80 billion). These are all second to heart and stroke expenditures which are estimated at $260 billion. A discussion of societal and payer prioritization regarding relative health-care resource allocation is clearly a complex issue which is not within the scope of this chapter, but is worthy of mention to enable the reader to keep the broader perspective of payers and policy makers in mind as they increase their personal understanding of CER.

The Language of Health Economic Analysis

A detailed description of HEE is not within the scope of this text and thus only fundamental concepts relevant to a surgeon, from the perspective of a clinician/surgeon will be provided [20]. A common misconception from physicians and surgeons is that all HEEs are the same (as many health economists may erroneously perceive all spine surgery to be the same) and only consider the bottom line (i.e., cost). The reality is that there are several types of HEE that are not interchangeable and require a better understanding when a clinician is considering the merit of an HEE. Some HEEs only consider cost and make the assumption that the clinical efficacy is equal between the intervention of interest, whereas others consider both the relative cost and efficacy of the intervention. Furthermore, it is critical to understand the perspective of the costing data source(s) and whether it only considers some or all health-care cost (direct and/or indirect[e.g., overhead]) attributable to a specific intervention and whether societal cost, such as productivity, has been included [20, 21]. Another important aspect of an HEE is the time horizon in which the analysis has been considered (e.g., perioperative period only or estimated over the lifetime of the patient) and whether the assumptions and variability associated with critical analytic parameters are accurate and accounted for. For HEEs where the outcome effects and cost are estimated for the lifetime of the patient, future costs and utilities are typically discounted to adjust for society's relative value placed on immediate costs and benefits compared to those in the future, a concept known as time preference [21]. Commonly, resources in the present are preferred over future resources since benefit can be derived from present resources in the interim. Most importantly when comparing interventions within the same analysis or across different analyses, it is critical to ensure that compatible clinical, costing, analytic model assumptions and overall economic analysis and perspective were employed between groups. Variations in these critical parameters can profoundly impact the outcome and interpretation of an HEE. Consequently, an important part of an HEE is the inclusion sensitivity analysis within the methodology. This enables relevant and realistic variation of important clinical and economic parameters to assess the robustness of the HEE findings and allows the reader to interpret the results based on alternate parameters that may be more consistent with their local health-care system [21].

As HEEs can be accomplished in a number of ways and customized to specific objectives, the outcome will be potentially interpreted differently based on the perspective taken by different stakeholders (i.e., value is in the eye of the beholder). For example, from the perspective of a private payer, the primary goal might be to obtain the greatest return on their investment. From a physician's perspective, patient outcomes and clinical outcomes such as procedural time or adverse events, regardless of the economic aspect, might be the major issues of consideration. From the patient's or a societal viewpoint, personal factors such as quality of life post-surgery, recovery time, and ongoing costs along with activity factors such as days of work missed and productivity losses may be most relevant.

Definitions of HEEs

The most basic type of economic analysis is cost analysis (CA) which compares the cost of health-care interventions and does not consider differences in health outcomes [20]. This type of analysis is obviously very "payer" focused; it evaluates interventions based on their costs only, and from a clinical perspective this type of analysis is not useful for CER, but represents the most common analysis in the spine surgical literature. Another type of economic analysis is cost-minimization analysis (CMA) which determines and evaluates the least expensive interventions among the interventions that have demonstrated the same outcomes. This type of analysis may be tedious to complete because

one must truly demonstrate that the resulting outcomes between interventions are in fact the same, quite a feat for health-care issues which are often multifactorial and dynamic. A CMA can be effective at any level where reducing expenditure is a priority and therapeutic equipoise from high-quality evidence has been established between two interventions for the same diagnostic/clinical scenario. A cost-benefit analysis (CBA) refers to an HEE where both the cost of the interventions and their outcome are assessed in terms of dollars. It is reflected as the ratio of the difference in outcome (e.g., cost difference of length of stay between two interventions) over the difference in cost. A CBA ratio greater than 1 suggests a cost-benefit of the intervention under evaluation. From a CER perspective, a cost-effectiveness analysis (CEA) which simultaneously considers both the comparative clinical effectiveness and cost of intervention is the HEE method of choice [20]. Thus, being cost-effective does not necessarily mean an intervention is less expensive up front.

Cost-Effectiveness (CEA) and Utility (CUA) Analyses

The primary premise of a CEA is the measurement of the incremental cost and effects that result from choosing one intervention option over another [22, 23]. The purpose is to assist key decision makers in determining how to allocate resources across a defined number of competing needs to optimize health outcomes, while adhering to budgetary constraints [23]. CEA is distinct from the aforementioned economic analyses such as a CA or CBA, as it simultaneously consider clinical effectiveness and cost. Within health care, CEA is utilized in scenarios where assigning a monetary value on a health effect might be inappropriate. A CEA is typically calculated using an incremental cost-effectiveness ratio (ICER), which equals the cost of a new strategy less the cost of current practice, divided by the clinical change in outcome of the new strategy, minus the current practice [24].

$$\text{ICER} = \frac{\text{Cost}_{\text{new strategy}} - \text{Cost}_{\text{current practice}}}{\text{Effect}_{\text{new strategy}} - \text{Effect}_{\text{current practice}}}$$

The ICER analysis typically makes the assumption that the new strategy is likely to cost more but has a clinically greater effect and is hence used to determine the cost per incremental difference in outcome.

Components of a CEA

As stated previously, economic analysis can be a very complex task, especially when cause and effect relationships are not very easily discerned. Another aspect which increases difficulty is the sheer volume of variables that can contribute to the overall costs of a health intervention. Often, it can be beneficial to break down the analysis into two smaller analyses: factors that directly contribute to cost against factors which indirectly affect it.

Direct Costs

Direct costs are tangible costs such as the cost of medical tests, implants, operating room time, rehabilitation, or out of pocket cost for payment of services that an individual may no longer be able to perform as a direct result of a disease state.

Proponents [25–31] of minimally invasive procedures frequently cite the advantage of MIS versus open surgery is its ability to lower postoperative morbidity. In a recent review, Allen and Garfin outline the factors in open procedures that may increase cost relative to MIS [32]. Factors such as increased blood loss (and transfusion rates), extended OR time, and the use of open posterior approach to the spine significantly increase the likelihood of an infection and other related morbidity (e.g., pain) and adverse events [32–34]. For example, the costs surrounding a unit of blood transfused are estimated to be just under $1,200, and this measure is often associated with increased LOS and resource utilization [32]. Kalanithi et al. reported that each inhospital complication for spine patients was associated with an increased cost of 10,000 USD and rising to over three times the cost of procedure if any readmission and revision surgeries were performed [33]. Khan et al. reported that a single complication may increase hospital costs for a patient in general surgery (except cardiac) by up to 79 % [35]. Broken down further, the median costs per complication resulted in costs of 4,278 USD (range, 2,511–25,168 USD) and as a result increased LOS by 11–297 % [35]. When complications occur, significant increases in LOS, mean total charges, and inhospital mortality are observed [33]. Consequently, taking steps to decrease the probability of adverse events and reduce LOS by using MIS techniques as well as other available interventions may help lower these associated costs substantially.

Indirect Costs

By definition these costs are more subjective and consequently much more variable depending on what is considered to be indirectly associated with a given disease state or intervention. Consequently, the determination of indirect cost is typically much more difficult. In their simplest form, indirect cost can be those associated with direct medical cost (e.g., the estimated institutional overhead to provide a particular service). More commonly, indirect costs refer to societal cost such as lost productivity. However, it is also important to consider that many indirect costs from a societal perspective may also be very closely related to direct costs,

further increasing complexity. For example, postoperative complications such as infections following surgery may result in longer hospital stays, greater recovery time, and additional medication costs contributing to an overall decline in health. These direct costs also have an effect on societal indirect costs as the individual may be out of the work force for a longer time, thereby decreasing their productivity. Thus, isolating and analyzing costs independently of each other can be very difficult, and results must be interpreted within a defined context and in relation to other factors as opposed to individually.

From a macroeconomic perspective, the societal costs of low back pain can be substantial. LBP has become the second most common reason for patients to visit primary care providers [36]. A recent systematic review of studies on the cost of low back pain noted that costs resulting from lost productivity and early retirement were the largest component of total costs, representing a median of 85 % of overall costs [37]. Consequently, indirect cost, particularly from a societal perspective, is an important measure of postoperative ongoing cost beyond discharge from hospital and provides a more comprehensive allocation of the costs associated with any intervention. In a 2004 study, Fritzell et al. reported that treating an individual with open lumbar fusion surgery was less expensive (and thus more beneficial) than to have the person not contribute to societal productivity while receiving conservative care treatment [38, 39]. In theory, those indirect benefits would increase if the surgical intervention resulted in less morbidity, faster recovery, and resumption of functional activity (e.g., work); in other words the promise of MIS should result in reduced cost.

Effectiveness

Effectiveness can be measured in a variety of ways depending on the most relevant outcome of the interventions assessed. For example, if mortality rate was the best outcome measure for a new therapy, the cost-effectiveness could be represented as the incremental cost per additional life saved or cost per adverse event avoided if the outcome of interest is morbidity. For elective surgical procedures the most common form of a CEA is a cost-utility analysis (CUA), which measures effectiveness using a generic health utility score that allows the comparison of different health outcomes by measuring them all in terms of a single unit—the quality-adjusted life-year (QALY). A QALY is a generic measure of the burden of a disease on life and encompasses both the quality and quantity of life lived [18, 21]. Thus, for HEEs it represents both the effect size and durability of a given intervention.

A QALY is an index number that is calculated by multiplying the utility score of that treatment by the duration of treatment effect. The utility score represents the health-related quality-of-life value in a range from 0 to 1, with 0 representing death and 1 representing the best or perfect health state. The utility score used to calculate the QALY of an intervention has been derived from several existing generic health-related measures, including the EQ-5D, Health Utilities Index, Quality of Well-Being Scale, and SF-36 (expressed as SF-6D) [40–48]. Consequently, the QALY is an outcome measure that enables decision makers to compare the effectiveness of interventions across many different areas of medicine and disease states. For this purpose decision makers utilize CEAs (and specifically CUAs) to identify the costs associated in achieving a single QALY (i.e., the relative value of a given intervention). It is important to note that currently available health utility scores are not interchangeable as they often generate different values from within the same population, and thus the cost/QALY values may differ depending on which utility score was utilized [40, 47, 48].

Equally important to the QALY effect size of an intervention on the health utility determination of an individual or population is the ability of an intervention to maintain that improved health state (i.e., the durability of the treatment effect) [14, 18, 21]. Tosteson et al. have recently demonstrated this concept in the spine literature [14]. In their report of the 4-year cost-effectiveness of surgery versus nonoperative treatment from the SPORT studies, the authors demonstrated sustainable superior results (QALYs gained) from surgical compared to nonsurgical treatment. This corresponded to an improvement in the cost/QALY ratio (ICUR) at 4 years compared to 2 years for all three subpopulations studied. For spinal stenosis, the 2- and 4-year ICUR for surgery compared to nonoperative treatment was $77,600 and 59,400. For the treatment of intervertebral disk herniation, the ICUR decreased from $34,355 at 2 years to $20,600 at 4 years. The greatest improvement was seen for the degenerative spondylolisthesis cohort, where the ICUR went down to $64,300 at 4 years compared to $115, 600 at 2 years. In more traditional economic models, where the QALY is estimated over the lifetime of the patient based on reference case data, the ICUR will typically reduce below $10,000/QALY for musculoskeletal interventions such as hip and knee replacement or 1–2-level spinal stenosis surgery [49].

Finally, when faced with a cost per QALY evaluation, recommendations exist regarding the threshold for which an intervention is considered cost-effective. Generally, an ICUR greater than $100,000 per QALY is considered too costly for the utility gained [50, 51]. This number can vary from country to country and typically ranges 50–100 K USD/QALY [21]. Furthermore, the number may vary depending on the clinical context that is being considered based on the local societal value of the given intervention (e.g., life-extending cancer surgery vs. improvement on quality of life).

Table 3.1 Principle approach to determining the need for a formal cost-effectiveness analysis (CEA)

Effectiveness of new strategy	Costs of new strategy	
	Costs more	Costs less
More effective	CEA relevant	**New strategy is dominant—adopt**
Less effective	**New strategy is ineffective—abandon**	CEA relevant

Clinician's Approach to HEE for MIS of the Spine

Table 3.1 demonstrates the possible relationships between cost and effectiveness and can be utilized to better discern when a CEA might be worthwhile [20]. Simply put, if a new intervention provides better outcomes and reduced cost, it has greater value than the current treatment and should be adopted. Conversely, if a new procedure is less effective and cost more, it should not be supported in its current form. All other scenarios typically will require a formal CEA to determine the relative value of an intervention compared to its alternatives [20]. From this fundamental approach, the first step would be the need to answer the question of whether or not MIS of the spine is clinically more or less effective compared to open surgery.

In the last 2 years, an increasing number of cohort studies comparing open versus MIS posterior lumbar fusion techniques for degenerative conditions have been published. Details of outcomes for specific techniques are available in chapters specific to certain MIS techniques. We are currently in the process of a systematic review assessing the comparative effectiveness of MIS versus open posterior fusion for degenerative lumbar conditions. To date, we included 16 English language publications meeting our inclusion criteria (same center comparative cohorts, with at least ten patients in each group and at least one of the following outcomes: patient-reported outcome measure(s), perioperative data (blood loss, surgical time, length of hospital stay), radiographic outcomes, complications, and economic evaluation) [25–31, 52–60]. Using the GRADE system, the quality of evidence was low (6) to very low (8) in the majority and moderate in two and high in only one paper [61]. As demonstrated in Table 3.2, the patient-reported clinical outcome at the specified time intervals suggests, at least qualitatively, comparable outcomes between the MIS and open cohorts at 1 and 2 or more years of follow-up. No study demonstrated an inferior patient-reported outcome with the MIS cohorts.

Additionally, our review also compared the specific perioperative outcomes of EBL, LOS, transfusion rate, and OR time. As demonstrated by others, the MIS cohorts performed significantly better than the open group in these aspects. In other literature reviews encompassing transforaminal and posterior lumbar interbody fusion (TLIF and PLIF) as well as extreme and direct lateral interbody fusion (XLIF/DLIF) techniques, Karikari et al. and Youssef et al. have demonstrated results regarding perioperative outcomes favoring the MIS techniques compared to open cohorts or historical controls [62, 63]. Karikari et al. specifically demonstrated that in all studies reviewed ($n=7$) the MIS subgroup performed significantly better than the open group in perioperative measures (e.g., EBL, LOS, and OR time) [62]. In a recent meta-analysis performed by Wu et al. (2010), the authors assessed the fusion rate of MIS versus open TLIFs [64]. Using 16 studies for open TLIF ($n=716$ patients) and 8 MIS studies ($n=312$ patients), they reported no difference in the fusion rate between open (90.9 %, 95 % CI; 86.4–94.0 %) and MIS TLIF (94.8 %, 95 % CI; 85.4–98.3 %). They also noted that the reported complication rates trended toward a lower rate in MIS (7.5 %, 95 % CI; 3.0–17.3 %) versus open (12.6 %, 95 % CI; 7.5–20.3 %) TLIF. The authors appropriately cautioned that there was significant variability in reporting and a lack of clear definition as to what constituted a complication. In another recent review, Parker et al. assessed the infection rate between MIS and open TLIF and reported a significantly reduced rated for MIS (0.6 %) versus open (4.0 %) TLIF [65].

Considering the current available literature, one could conservatively conclude that MIS fusion in the lumbar spine demonstrates superior perioperative quality and clinical process outcomes and comparable midterm (1–2 year) radiographic and patient-reported outcomes. However, from an economic perspective there are several up-front additional costs associated with MIS fusion such as increased operative time during the learning curve, implant and disposable costs, dependence on the use of intraoperative imaging and associated resources, education and training, and a possible higher reoperation rate required for the removal of prominent or symptomatic implants. In the context of CER, the next logical step is to examine the CEA of MIS versus open fusion. In other words, one must determine the incremental cost of the demonstrated short-term perioperative benefits of MIS fusions.

Economic Comparison of MIS Versus Open Fusion

In an excellent review of this topic, Allen and Garfin note the increasing importance of CEA in our current health-care environment. However, the authors point out the general lack of HEEs in the currently available literature [18, 32]. In addition, the authors importantly note that a "consistent method of exactly which cost to include, and how to accurately measure direct and indirect cost is yet to be defined in spine care, and existing cost analyses of spine care vary widely in their methods of measurement" [32]. As noted previously in the

Table 3.2 Summary of comparative literature presenting patient-reported outcomes for posterior MIS versus open lumbar fusion techniques

Study author Study origin	Principle diagnosis	Mean follow-up 6–12 weeks Outcome	 6 months Outcome	 1 year Outcome	 2 year + Outcome
Park et al. [27] Korea	Mixed		MIS	MIS	
Scheufler et al. [28] Switzerland	Mixed	MIS	MIS	MIS	
Dhall et al. [60] USA	Mixed				Equivalent
Starkweather et al. [26] USA	Instability	MIS			
Kasis et al. [25] UK	Mixed				MIS
Tsutsomimoto et al. [52] Japan	Degenerative spondylolisthesis	Equivalent		Equivalent	Equivalent
Peng et al. [53] Singapore	Mixed		Equivalent		Equivalent
Gahreman et al. [54] Australia	Isthmic or degenerative spondylolisthesis (<50 % slip)			Equivalent	
Ntoukas et al. [55] Germany	Mixed	MIS		Equivalent	
Wang et al. [56] China	Degenerative spondylolisthesis				Equivalent
Wang et al. [29] China	Mixed	MIS	MIS		MIS
Kotani et al. [30] Japan	Degenerative spondylolisthesis	MIS	MIS	MIS	MIS
Rampersaud et al. [31] Canada	Isthmic or degenerative spondylolisthesis (<50 % slip)			MIS	
Adogwa et al. [57] USA	Degenerative spondylolisthesis				Equivalent
Lee et al. [58] Singapore	Mixed		Equivalent		Equivalent
Mobbs et al. [59] Australia	Mixed			Equivalent	

Note: Mixed diagnoses refer to varying combinations of degenerative disk, stenosis, spondylolisthesis, and other instability

section covering HEE, when assessing a CEA the main drivers that need to be considered are the relative cost (direct cost of index procedure) as well as ongoing cost and indirect (e.g., productivity) and effect size and durability of the outcome gained.

In other surgical specialties, cost-effectiveness has been demonstrated comparing MIS and open surgical techniques. An excellent example is provided by Bijen et al. in a systematic review of the cost and effects of abdominal versus laparoscopic hysterectomy [66]. In this study the authors demonstrated that although the total procedural costs were greater for MIS intervention (6.1 % in this particular procedure), decreased length of hospital stay, fewer complications, and lower indirect cost compensated for the greater initial cost. Whether the perioperative benefits demonstrated for MIS fusion compensate for the aforementioned higher cost, associated MIS fusion is yet to be determined in any comprehensive manner. To date, no high-level prospective or randomized studies have included a CEA in the comparison of MIS techniques to open surgery or nonsurgical treatment of spinal disorders. More recently, economic considerations have been included in a handful of MIS versus open fusion retrospective cohort studies [29, 31, 56, 65, 67]; however, as noted in our current systematic review, the quality of evidence is generally low and the economic perspective and methodology of these studies are varied. If, as suggested by the current comparative literature, MIS fusion does in fact consistently provide significant short-term benefits and at least equal clinical outcomes, demonstration of overall cost neutrality or cost saving from the perioperative benefits is paramount in justifying the additional up-front cost.

Current MIS Versus Open Lumbar Fusion Studies with Economic Considerations

In a retrospective comparative study, Wang et al. performed a CA (i.e., cost analysis independent of clinical outcome)

utilizing hospital charges (not actual cost) for 1- and 2-level MIS (performed in patients with unilateral symptoms) and open (performed in patient with bilateral symptoms) posterior interbody fusion for lumbar spondylotic disease, disk degeneration, and spondylolisthesis [56]. During a 14-month period, 74 patients were treated (59 1-level [75 % MIS] and 15 2-level [53 % MIS] fusions). The mean LOS for patients undergoing single-level surgery was 3.9 and 4.8 days in the MIS and open cases, respectively ($p=0.017$). For those undergoing 2-level surgery, the mean LOS was 5.1 for MIS versus 7.1 for open surgery ($p=0.259$). Single-level MIS procedures were associated with average charges of $70,159 compared with $78,444 for open surgery ($p=0.027$). For 2-level surgery, mean charges totalled $87,454 for MIS versus $108,843 for open surgery ($p=0.071$). The primary drivers for these significant differences in hospital charges were noted to be complications and associated increased length of stay. Interestingly, for single-level surgeries, 5 and 20 % of patients undergoing MIS and open surgery, respectively, were discharged to inpatient rehabilitation. For 2-level surgeries, the rates were 13 and 29 %, respectively. The economic impact of this is another potential benefit of MIS; however, the associated charges were not accounted for in this study. Due to the rather large variation in hospital charges among the small cohorts, it is difficult to make any comparisons to other institutions or reports. In a subsequent study, Wang et al. reported on a cross-sectional retrospective analysis of acute hospital cost following MIS versus open lumbar interbody fusion [29]. Using the Premier Perspective administrative database, the authors identified a cohort 6,106 patients undergoing 1- and 2-level lumbar interbody procedures ($n=1,667$ MIS cases). The analysis was from the perspective of the hospital inpatient visit and included case costing data categorized into specific cost centers (emergency room, laboratory, operating room, pharmacy, professional fees, radiology, respiratory, room and board, central supply, therapy, cardiology, other and total cost). In this data set, the largest cost contributors were the central supply, operating room, and room and board. The adjusted analysis demonstrated a nonsignificant difference in cost for 1-level fusions (MIS $29,187 vs. open $29, 947, $p=0.55$). For 2-level procedures, the total cost was on average $2,106 less for MIS procedures (MIS $33,879 vs. open $35,984, $p=0.0023$). Minimally invasive surgeries were associated with greater central supply cost (i.e., implants and disposables) and typically less cost in most other categories compared to open. For 2-level surgeries, greater variance in cost associated with prolonged LOS was a significant driver of increased cost for the open cohort.

In their editorial, Deluzio et al. reported on a retrospective CA of 211 patients roughly half of whom received 2-level open posterior lateral interbody fusion (PLIF, $n=102$), while the remainder had been operated via a minimally invasive approach for degenerative conditions (specific diagnoses not reported) [2]. The MIS technique involved a lateral approach at L1–L5 and a transsacral fusion at L5–S1. The costing data was from the perspective hospital and included direct cost from the index procedure, the initial hospital stay, transfusions, reoperations, and residual events that occurred up to 45 days following discharge from hospital (ER visits, readmissions to hospital, rehabilitation). The average length of stay for the MIS group was 49 % lower than the open group (1.2 vs. 3.2 days). Overall the MIS group saved on average 2,563 USD per patient versus the open surgical group. The majority of cost saving resulted from reduced length of stay and residual events associated with the MIS cohort.

In a recent retrospective study, Pelton et al. analyzed intraoperative, immediate postoperative, and financial outcomes (cost analysis) in worker's compensation and non-worker's compensation patients undergoing either an open or MIS TLIF. Sixty-six consecutive patients undergoing a single-level TLIF (open/MIS) were analyzed (33 in each group) [67]. Twenty-four total worker's compensation (WC) patients were identified (11 MIS, 13 open). All patients had a diagnosis of either degenerative disk disease or spondylolisthesis and stenosis. WC status did not significantly impact perioperative outcome parameters in either the MIS or open groups. However, there were significant differences favoring MIS (WC and non-WC) compared to open (WC and non-WC) TLIFs in perioperative (operative time, blood loss, and hospital length of stay) and clinical outcomes (6-month pain score). Costing was determined using administrative databases and was isolated to the perspective of the hospital (direct and indirect cost including blood, imaging, implants, lab, pharmacy, allied health, room and board, and surgical services). There were statistically significant differences in total cost amounts between WC MIS TLIF and WC open TLIF ($28,060 vs. $33,862, respectively; $p=0.0311$) and non-WC MIS TLIF versus non-WC open TLIF groups ($29,429 vs. $32,998, respectively; $p=0.0001$). Although, for the minimally invasive surgeries, implant cost represented a higher percentage of total hospital cost (approximately 10 % higher), the difference in other health-care resource utilization compensated for this difference and resulted in an overall cost savings.

In their 2011 retrospective cohort study, Rampersaud et al. compared the direct economic impact of 1- and 2-level fusion for grade I or II degenerative or isthmic spondylolisthesis via an MIS TLIF technique compared with conventional open posterior decompression and instrumented fusion [31]. A total of 78 consecutive patients were reviewed (37 MIS and 41 open). The economic perspective of the study was from that of the hospital with direct case costing data that included operative costs, nursing (including postanesthetic care, step-down unit, intensive care unit, and ward), medical imaging, laboratories, pharmacy, and allied

health services. Costs of preoperative or postoperative rehabilitation or other outpatient health system costs were not collected. Institutional, patient, or societal indirect costs were also not collected. The groups were comparable in terms of age, sex, preoperative hemoglobin, comorbidities, and body mass index. Groups significantly differed ($p<.01$) regarding baseline ODI and SF-6D scores, as well as number of 2-level fusions (MIS, 12; open, 20) and number of interbody cages (MIS, 45; open, 14). Blood loss (200 mL vs. 798 mL), transfusions (0 % vs. 17 %), and length of stay (6.1 days vs. 8.4 days) were significantly lower in the MIS group. Reported complications were also fewer in the MIS group (4 vs. 12, $p<.02$). Both groups had significant improvement in 1-year outcome ($p<0.001$). However, the overall changes in ODI and SF-6D scores trended in favor of the MIS group at 1 year ($p=0.08$). Multivariate regression analysis showed that LOS and number of levels fused were independent predictors of cost. Age and MIS were the only predictors of LOS. Baseline outcomes and MIS were independent predictors of 1-year outcome. The mean total direct cost of an open fusion was 1.28 times greater than that of an MIS fusion ($p=.001$).

The cost analysis of these aforementioned comparative studies (retrospective cohorts) has all demonstrated lower perioperative cost associated with MIS from the limited perspective of the hospital and the perioperative time horizon. These studies demonstrate that the additional cost associated with the index MIS procedures seems to be compensated for by reduced resource utilization in the perioperative period. The most reproducible cost saving is associated with an overall reduction in LOS and utilization of other acute postoperative resources afforded by the MIS techniques. These studies only presented hospital cost for the index procedure and did not provide ongoing health-care cost or cost of revision surgery in either cohort. Furthermore, these studies (with the exception of Rampersaud et al. [31]) did not take the clinical outcome into account and thus represent cost analysis. If we consider the current comparative evidence on clinical outcome presented in Table 3.2 and make an assumption of clinical equipoise, these data can be considered as cost-minimization analyses (from the limited perspective of the hospital) that demonstrate cost savings in the perioperative period.

In addition to a cost analysis, Rampersaud et al. also performed a CUA to assess both cost and clinical outcome using the SF-6D at 1 year to determine the QALYs gained by each group [31]. The mean total direct cost was $14,183 CAD for the minimally invasive group compared with $18,663 CAD for the open group. The pre- and postoperative change in health utility was significant for both groups ($p<0.0001$ for MIS and $p<0.003$ for open) at the 1-year mark with a gain of 0.113 (SD = 0.10) and 0.079 (SD = 0.08) QALYs for the MIS and open groups, respectively. The cost/QALY was $128,936 for MIS and 232,912 for open (unadjusted for differing number of levels between cohorts). The authors did not perform an assessment of the incremental cost-utility (ICUR) between MIS and open fusion on the basis that a CEA (ICER/ICUR) typically makes the assumption that the new strategy is likely to cost more but has a clinically greater effect. In this case because the new strategy (MIS) costs less or is at least equivalent (using sensitivity analysis) and has a greater yet statistically and likely clinically insignificant difference in effect on the outcome, the MIS technique would be at the very least cost neutral [20]. However, due to the limited 1-year time horizon, the cost-utility of both techniques was over the $100,000 per QALY threshold to be considered reasonable value. The authors provided an estimate of the cost-utility for each group if the outcome was sustainable at the 2- and 4-year mark. As expected for the method of QALY determination, the cost/QALY significantly decreased for both groups to a more favorable value (MIS, $37,720; open, $67,510). In a recent study, Rouben et al. reported the outcomes of 169 consecutive patients with a minimum of 3-year follow-up after 1–2-level MIS TLIF for a variety of spinal diagnoses [68]. At a mean of 49 months, the average improvement of the ODI (41 %) score was sustained. In addition the reported revision rate was 14.2 % (7.6 % for symptomatic instrumentation, 1.8 % for adjacent segment disease, 0.6 % for infection in one patient, and 0.6 % for a pseudoarthrosis in another patient). Although for different indications, this revision rate is similar to that reported for the SPORT trial data at 4 years [15–17]. A current longer-term series from the principal author (manuscript in preparation) has demonstrated similar findings that support the results reported by Rouben et al. [68]. Simon and Rampersaud have recently presented a cohort of 66 patients with a minimum of 2-year follow-up after MIS TLIF for low-grade degenerative or isthmic spondylolisthesis. In 27 patients with 5-year follow-up (90 % follow-up rate), the improvements in ODI and SF-36 seen at 2 years were maintained at the 5-year mark [69]. These results support the inference of the projected CUA performed by Rampersaud et al. [31].

In addition to procedural durability, a more accurate HEE requires the capture of other ongoing cost following discharge from hospital. No current study has assessed ongoing resource utilization beyond the perioperative period following MIS versus open spine surgery. As demonstrated in the recent CEA analysis from the 4-year SPORT data, ongoing cost, especially indirect cost, is significant following intervention for spinal disorders [14]. This was particularly noted for the degenerative spondylolisthesis (DS) subpopulation, where the largest ongoing cost occurred in the nonoperatively treated patients. Sustained clinical superiority and reduced ongoing cost enabled the ICUR for the surgically treated DS group to improve from $115,600 at 2 years (above 100 K cost-effectiveness threshold) to $64,300 per QALY at 4 years compared to nonoperative treatment. If the clinical

outcomes are similar as in the case of MIS versus open surgery, then one has to make the invalidated assumption that ongoing health-care utilization may be similar, until data supporting this assumption is obtained. In the interim, more costly adverse events such as deep surgical site infections and revision surgery (in the short or long term) for other causes (e.g., instrumentation-related pain, pseudoarthrosis, or adjacent segment degeneration) should, at the very least, be accounted for in MIS versus open lumbar fusion HEE models. Two recent reviews suggest that ongoing medical cost may in fact favor MIS. In the first study, Parker et al. aimed to determine the incidence of surgical sight infections (SSI) in patients undergoing MIS versus open TLIF reported in the literature and the direct hospital cost associated with the treatment of SSI following TLIF [65]. Ten MIS TLIF cohorts (362 patients) and 20 open TLIF cohorts (1,133 patients) reporting incidences of SSI were identified. The cumulative incidence of reported SSI was significantly lower for MIS versus open TLIF (0.6 % vs. 4.0 %, $p=0.0005$). At the institutional level, 120 open TLIF procedures, SSI occurred in six (5.0 %) patients. The mean hospital cost associated with the treatment of SSI following TLIF was $29,110 in these six cases. The authors determined that the 3.4 % decrease in reported incidence of SSI for MIS versus open TLIF corresponds to direct cost savings of $98,974 per 100 MIS TLIF procedures performed. In the second study, Wu et al. performed a meta-analysis looking at fusion rates between MIS and open TLIFs [64]. As noted earlier, the authors demonstrated equal fusion rates between MIS (94.8 %) and open (90.9 %) TLIFs. The authors also reported a difference in reported adverse events favoring MIS (7.5 %) versus open (12.6 %).

The assessment of indirect cost and in particular productivity (e.g., return to work and reduced out of pocket expenses for care givers and house work) is grossly absent in the MIS fusion literature. Given the aforementioned findings, if additional economic benefits exist for MIS of the spine, the impact on improved productivity and other indirect economic benefits (i.e., from the societal perspective) is where we should be able to demonstrate it. With a demonstration of cost savings in the perioperative period, the promise of reduced morbidity from MIS of the spine to enable quicker return to activity, while many believe it to be true (the principal author included), needs to be objectively assessed and the economic impact quantified. It is here where the true cost-effectiveness of MIS of the spine may garner the greatest support.

Conclusion

Health-care systems are constantly changing and introducing necessary reform in an attempt to meet clinical demands, while keeping growing financial concerns in check. Regardless of what changes occur in health reform, resource allocation will likely favor those interventions that demonstrate the best value. In order for clinicians to contribute to meaningful reform, insight into the decision-making language (e.g., HEE, cost per QALY gained) of the government, payers, and policy makers is crucial. For the diagnostic categories of lumbar disk herniation and spinal stenosis without and with spondylolisthesis, open spine surgery procedures have shown both clinical efficacy and cost-effectiveness at 4 years compared to nonoperative treatment. Current comparative data (albeit of overall low evidentiary quality) suggest that MIS lumbar fusion provides at least equivalent clinical outcome in the midterm (1–2 years) and consistently demonstrates quality and cost-benefits in the perioperative period compared to open fusion. The initial increase in direct procedure-associated cost of MIS fusion appears to be offset by the perioperative benefits which produce an overall net cost savings. However, the evidence is sparse and of poor quality to enable any strong conclusions of superiority of MIS versus open. Going forward, more comprehensive HEE comparing the outcome effect size over time, the potentially lower post-surgery ongoing medical resource utilization and perhaps most importantly the difference in indirect cost such as earlier return to activity (i.e., productivity) of MIS versus open spine surgery are required to support a broader adoption of MIS of the spine from a societal and payer perspective.

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Part II

Enabling Technologies for Minimally Invasive Spine Surgery

Microscopes and Endoscopes

4

Harel Deutsch

Introduction

Microscopes were first developed in the 1600s and their first use was in the study of living tissue. Microscopes allowed visualization of small structures invisible to the eye. The application of the microscope in surgery was limited until several technical problems were solved by the 1970s. New diagnostic imaging allowed for an increasing understanding of microscopic pathology. New technology allowed easier microscope movement and angulations in the operating theater. Once, the technical problems were solved, the operative microscope became an essential tool in the operating theater. The application of the endoscope in medical practice preceded the microscope. Urologists routinely used endoscopes in the 1800s. New technology has vastly increased the utility of endoscopes in many clinical settings.

The microscope and endoscope both allow for magnification of small structures and better visualization and dissection. In spine surgery, most nerves and spinal column elements are macroscopic, but the magnification improves surgical safety where small movement may lead to significant neurological damage. The endoscope also adds the ability to look around corners through the use of angled objectives and flexible scopes. The rapid adoption of endoscopic surgery in general surgery in the 1980s translated to the increased research and application of endoscope technology in spine surgery. New high-definition cameras and monitors have also increased the endoscope's utility.

Several spine procedures such as lumbar discectomies allow for the use of either a microscope or an endoscope. Each has relative advantages and disadvantages. The microscope allows for three-dimensional visualization while traditionally endoscopes have only delivered a two-dimensional video image. Binocular endoscopes have been developed, but they require cumbersome headsets, and they have not been widely adopted. Endoscopes have angled objectives allowing the surgeon to look around corners while the microscope only functions in a direct line of site.

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Microscope

Among the early inventors of the microscope were Galileo. Galileo described the first compound microscope in 1624. The first compound commercial microscopes were developed by Karl Zeiss in 1847. In 1922, Gunnar Holmgren, an ear, nose, and throat physician, used a binocular microscope to overcome the lack of depth perception, and he attached a light source to the microscope [1].

In the 1950s, motorized zooms were added and movable stands with counterweights were developed.

Julius Jacobson, a vascular surgeon, contacted the Zeiss Corporation to design a microscope to allow an assistant to view the operative field. The subsequent design manufactured in 1964 incorporated beam-splitting technology. The microscope was thus named the "diploscope" [2].

Julius Jacobson suggested the use of the operative microscope to his neurosurgery counterparts at the University of Vermont. Dr. Donaghy and Dr. Jacobsen performed the first microvascular neurosurgical procedure in 1960. Dr. Yasargil travelled to the United States in 1965 and started working in Dr. Donaghy's lab and specifically helped develop in the extracranial-intracranial bypass operation made possible with the use of the microscope. In 1972, Yaşargil and Malis suggested constructing a system of adjustable multi-axis weights to counterbalance the microscope in order to make it more maneuverable. In addition a mouth switch was developed to release the brakes and control motion and focus. In 1976, Carl Zeiss Inc. developed a commercial suspension system based on Yaşargil's ideas [1, 3].

In 1975, Hankinson et al. described the use of the operating microscope in anterior cervical discectomy surgery and noted the improved visualization increased the procedure's safety and allowed addressing cervical myelopathy not

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previously adequately addressed by the anterior cervical procedure [4]. Yasargil described the use of the microscope in cervical spinal cord tumors and vascular malformation [5]. In 1977, Yasargil described the use of the microscope in lumbar herniated disc surgery [6]. In 1979, Wilson et al. described the use of the microscope in lumbar discectomies and concluded the microscope allows for superior results to a standard lumbar discectomy [7].

Microscopes used in surgery today are compound microscopes. Lenses are used to collect light from the field and separate lenses are used to focus the light into observer's eye or camera. The eyepiece or ocular consists of two or more lenses in a cylinder. Operative microscopes have two eyepieces to allow for stereoscopic vision. The movement of one eyepiece lens relative to the other lens allows the light to be brought into focus for the viewer. The ocular is located at the observer's end of the microscope. A diopter adjustment is also possible on the eyepiece to allow for correction for a surgeon's near or farsighted vision. The objective lens is the larger fixed lens which provides the greater magnification and is located on the patient side of the microscope. The eyepiece magnification is usually about 10× and combined with the objective lens usually provides between 3× and 27× magnification. A beam splitter in the optic path can divert some of the light for recording on a camera and video projection.

The microscope was rapidly adopted in neurosurgical practice, and operation of the operating microscope became standard training. The modern operative microscope has several common components and specifications. Microscopes generally use either a halogen light source or a xenon light source. Light source output is measured in Lux. A bright room is 400 Lux, while a very bright day is 100,000 Lux. Most microscope light sources have 30,000–50,000 Lux. These light sources allow for a very bright image without excessive heat. The microscopes can be focused between a distances of 200–400 mm. Motorized lens systems allow for varying the magnification and focal length to optimize the field of view.

An observer scope was a key advance in the design of the operative microscope, and it allows for an assistant in surgery. The assistant can be positioned side to side with the surgeon or across on the other side of the patient. An attached camera is standard today and allows for others in the room to view a two-dimensional image on a high-definition screen. The camera also allows for image capture and video capture.

The microscope base has a system of counterweights allowing the objective to be moved with minimal effort and to remain balanced despite assuming different positions and angulations. Early microscopes required manual balancing, but today, the balancing system is increasingly automated. The microscope has handgrips with switches allowing for movement of the microscope. Some systems employ a mouth switch to also allow for further control. Focusing and movement may also be controlled by foot switches to free up the surgeon's hands for other uses (Fig. 4.1).

Microscopes can be either floor mounted or suspended from the ceiling. Ceiling mounted microscopes save floor space but they cannot be moved between rooms. New technology has also integrated neuronavigation with the operative microscope (Fig. 4.2).

Endoscopes

History

The first endoscopes were developed by in 1853 by Desormeaux for examination of the bladder and urethra. The technique was used for esophagoscopy in 1867 by the German physician Kussmaul. Thomas Edison's invention of incandescent light bulbs helped improve illumination for endoscope use. The light sources were still limited and intense heat at the distal endoscope end often resulted in burns. Walter Dandy was an early user of endoscopes for neurosurgical procedures. He used endoscopes for ventricular endoscopy in 1932.

The Japanese Professor Kenji Takagi used a cystoscope in 1918 to view the inside of the knee. His goal was the diagnosis and treatment of tuberculosis of the knee. In 1921, the Swiss physician Eugene Bircher performed one of the first arthroscopies. Takagi's protégé, Masaki Watanabe, integrated new advances in optics and electronics to develop the first modern arthroscopy instrumentation in 1959. Watanabe also pioneered the first use of the arthroscope for treatment in addition to diagnosis. Robert Jackson observed Dr. Watanabe in Japan and returned to introduce the endoscope in North America. His first students included Dr. John Joyce III, Ward Casscells, and Jack McGinty. Dr. Richard O'Connor studied with Jackson and developed instrumentation to perform the first partial meniscectomies in 1974. Dr. Lanny Johnson developed the first motorized shaver instrument in 1976 [8]. Takagi described hip arthroplasty for tuberculosis in 1938, but the adoption of hip arthroplasty did not occur until the 1970s with descriptions of the procedure by Dr. Richard Gross, Lanny Johnson, and James Glick [9].

The 1952 introduction of the fiberglass tube allowed for the proximal light source to be outside the body cavity and improved endoscope safety. Initial endoscopes were empty tubes with a lens at the end but Hopkins devised filling the endoscope with glass rods, greatly improving image quality, and reducing the endoscope size. In 1965 Carl Storz Inc. licensed the idea of an external light source coupled with a rod lens optical system. In 1969 Bell Laboratories developed a lightweight image sensor camera, the charge coupling device (CCD).

In 1986 the video computer chip was developed to allow for the projection of the magnified endoscopic picture on a

Fig. 4.1 Carl Zeiss OPMI operative microscope

television screen. The first reported laparoscopic cholecystectomy was performed in 1987 by the French physician Mouret. Laparoscopic techniques were rapidly adopted and by 1992, more than half of cholecystectomies were done with the help of an endoscope [10]. The endoscope's possibilities were quickly noted and adopted in spine surgery and other surgical fields.

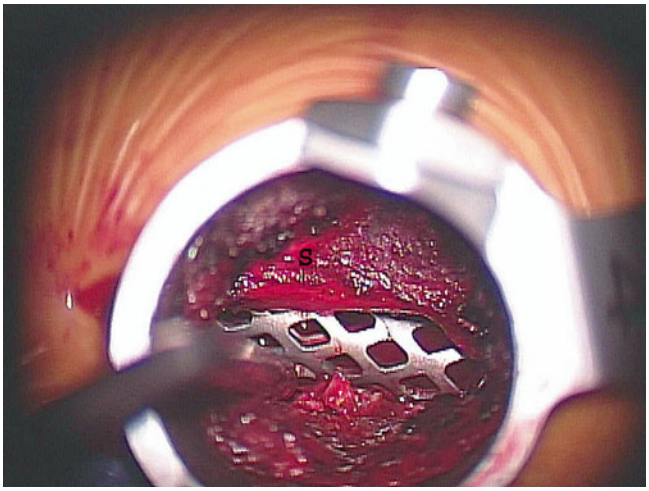

Fig. 4.2 The microscope operative view through a Medtronic MetrX retractor demonstrates the thoracic spinal cord and an anterior corpectomy device. (**s**) spinal cord

The Endoscope

The endoscope visualizes deep hidden structures. A typical endoscope system has three components. They include the endoscope, video camera and monitor, and the light source. The endoscope has an objective lens, an eyepiece, and a transmission system.

Endoscopes are either rod-lens endoscopes or flexible fiber optic endoscopes. The rod-lens rigid rod-lens scope offer better optic qualities. The rod-lens endoscope has three parts: a mechanical shaft, glass fiber bundles for light illumination, and the optics. Angled objectives allow for a varied distal angulation. The most commonly used are 0°, 30°, and 45°. Angled objective lenses require a prism as the most distal lens. The objective lens usually has between two and nine lenses. An irrigation system is often integrated into the endoscope to help clean and defog the lens. Diameter of rod-lens endoscopes vary from 1.9 to 10 mm. The scopes can be used free hand or with a scope holder (Fig. 4.3). Flexible fiber

Fig. 4.3 Karl Storz endoscope system designed for spinal surgery use and the endoscope tower and video screen

optic endoscopes usually have between 3,000 and 50,000 optical fibers with each fiber representing one pixel. The large number of fibers necessary required a fairly large endoscope.

The CCD camera revolutionized modern endoscopes. The "camera on a chip" allowed for light weight and accurate imaging. Initial cameras had a single CCD chip but color rendition was often poor. The cameras used today are typically three CCD cameras and allow for a high-definition output. The miniaturization of the CCD now allows for the chip-on-the-tip endoscope technology. Light transmission is not necessary since the CCD converts the image to electrical signals transmitted through wires. The chip-on-the-tip endoscope allows for every smaller scopes and better depth of field requiring less refocusing.

Each CCD chip picks up red, green, or blue light. Three-dimensional cameras are available and use two CCD images. Separate binocular images are formed, but typically a headset allowing for each eye to see the separate image is necessary. Three-dimensional systems have not been widely adopted because of difficulty with the use of such headsets and limited clinical usefulness.

The video monitors allow for at least 720 horizontal lines of resolution. The light source allows for cold light transmission. The glass fibers transmit heat poorly and the risk of burning tissue with the endoscope is reduced. Light sources are typically xenon or halogen sources.

The Endoscope and Spine Surgery

The use of the endoscope in spine surgery was first described as extension of percutaneous discectomy procedures and automated discectomy devices. In 1992, Kambin reported the use of a 2.7 mm glass endoscope and compared his results to other nucleotomy techniques [11]. The use of the endoscope was also described for anterior lumbar fusions [12]. The approach generally required a transperitoneal approach. The approach failed to be widely accepted because of the increased technical skills and complications associated with a transperitoneal approach versus an open retroperitoneal approach. Higher rates of retrograde ejaculation were reported with transperitoneal surgical approaches [13]. The endoscope was also used to replace the microscope for lumbar discectomies [14]. Most surgeons have continued using the microscope in traditional lumbar microdiscectomy surgeries because the microscope allows for three-dimensional imaging and the advantages of the endoscope over the microscope are not evident. Continued development of endoscope instrumentation, ports, and endoscope holders may influence more surgeons to adopt endoscopes for lumbar discectomies in the future.

The use of endoscopes in the cervical spine is limited. Roh et al. described a posterior cervical laminotomy using an endoscope instead of a microscope [15]. Transoral approaches to the odontoid utilizing an endoscope have also been described [16].

Currently, endoscopes are not used routinely in spine surgery but research in their use continues [17]. Advances in endoscopic technology increasingly improve the usefulness of endoscopes. Orthopedic surgeons and neurosurgeons increasingly are able to apply endoscopic skills from other procedures to spine procedures.

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Intraoperative Neurophysiology Monitoring

5

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Introduction

Spinal surgery involves procedures requiring access to pathology in and around the central and peripheral nervous system, blood vessels, and the skeleton. Manipulation of these structures is common when performing surgical procedures introducing risk of injury. Despite these risks modern surgery has a high expected rate of success and low expected rate of complications.

Minimally invasive spinal surgery (MISS) employs percutaneous techniques with fluoroscopy and other technologies to reduce tissue disruption and by design generally limits the surgeon's ability to directly visualize the pathology, spinal anatomy, or any associated neural structures [1]. When used appropriately, intraoperative neurophysiology monitoring (IONM) offers additional information to the surgeon providing the opportunity to improve results, reduce complications, and decrease surgical approach-related challenges. IONM can assist in identifying neural elements, provide a general idea of their proximity, and detect inadvertent injury from either direct or indirect compression, stretching, or unintended ischemia [2, 3].

The three most common methods or modalities of neuromonitoring used for spinal procedures include the following: electromyography (EMG), spontaneous (SpEMG) and triggered (TrEMG), somatosensory-evoked potentials (SSEP), and motor-evoked potentials (MEP) illustrated in Fig. 5.1. A fourth modality, dermatomal somatosensory-evoked potentials (DSEP), has also been employed although less commonly than the first three [4]. Figure 5.1 provides a general description of the stimulation and recording locations for each of these IONM modalities. While each has their own strengths and weaknesses, the surgeon's ability to understand each, their indications for use and their value in combination or multimodality monitoring, can contribute to optimal patient care and outcomes [3, 5, 6].

The type and location of surgery as well as the surgical approach determine which neural structures are most at risk and thus influence the monitoring modality(s) best suited for a given procedure. Peripheral structures generally benefit from TrEMG and recordings of SpEMG. Central tracts at risk benefit most from SSEP and/or MEP monitoring, but these modalities may also give valuable information about peripheral pathology.

Anesthesia Requirements and Preparation for IONM

All monitoring modalities can be affected to one degree or another by different aspects of the anesthetic technique. Thus, effective and accurate intraoperative neurophysiologic monitoring requires careful collaboration with the anesthesia team [7–9]. Baseline measurements of each monitored modality are taken at the beginning of the surgery and subsequent readings are compared to that baseline as the procedure progresses to determine if significant changes occur.

Muscle relaxants directly affect the accuracy of muscle recordings from EMG or MEPs. Therefore during the intubation process, small amounts of rapidly cleared muscle relaxants may be used; however, ideally these should be cleared prior to incision and before baseline modalities that measure muscle activity are run. One way to evaluate muscle relaxant(s) clearance is by repetitive stimulation of a nerve and measurement of the sequential muscle responses. This

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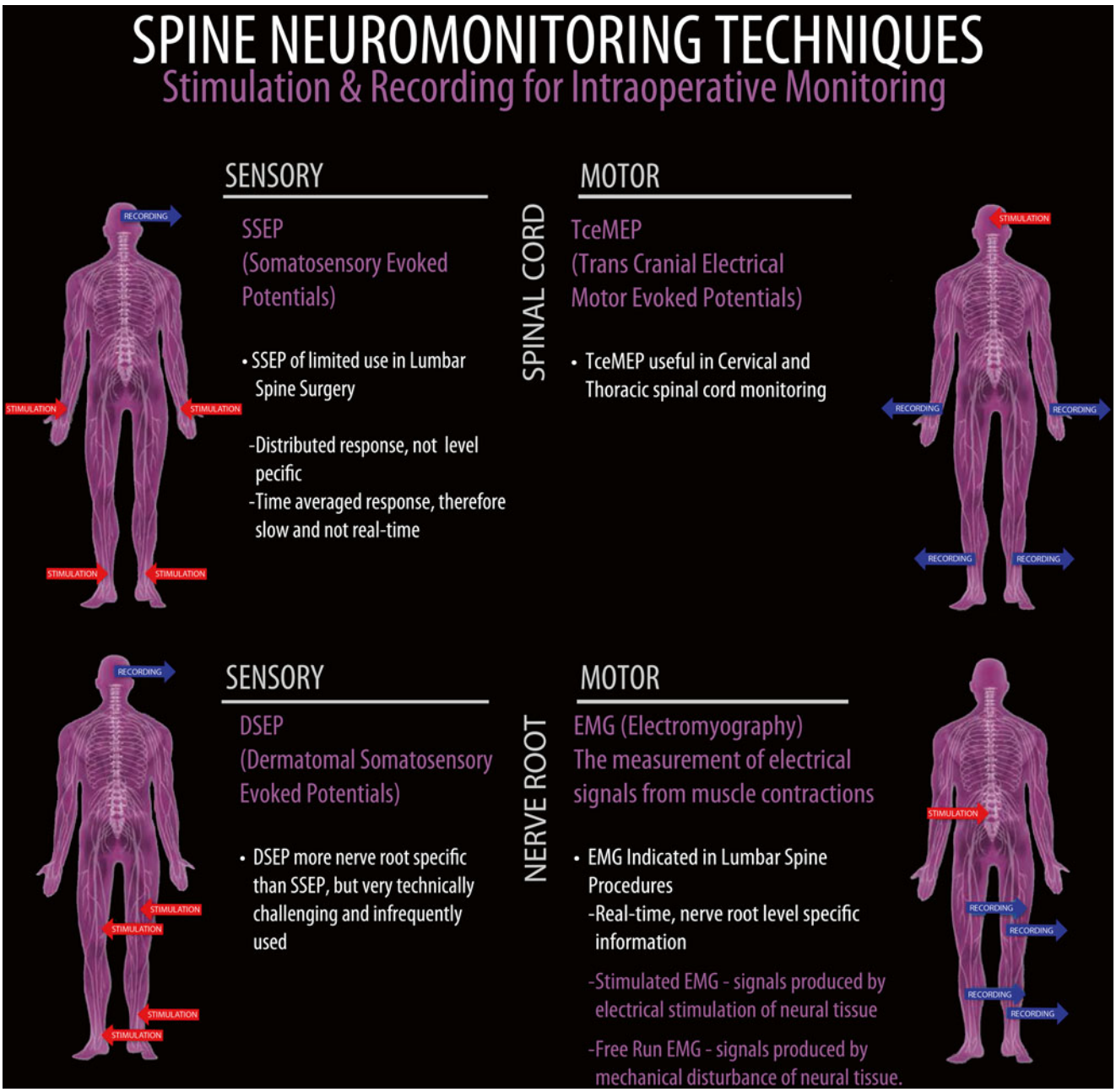

Fig. 5.1 Schematic illustration of the pertinent modalities of IONM for MISS showing location of stimulation (*red arrow*) and recording (*blue arrow*) (Copyright NuVasive, Inc.; used with permission)

so-called twitch test or train-of-four neuromuscular junction transmission testing is in wide use [10] and typically involves stimulating a peripheral nerve at 2 Hz for four stimuli and recording muscle responses. If each of the four stimuli evokes a corresponding muscle twitch without a significant drop in amplitude over the series, the neuromuscular blocking agents are considered to have been sufficiently cleared from the patients system. Since neuromuscular blocking agents may be differentially cleared from parts of the body, testing results may vary somewhat depending upon the location used for testing. Intraoperative monitoring personnel typically favor a peripheral extremity where clearance may lag rather than the face which is the usual location favored by the anesthesiologist. In addition, peripheral stimulation allows easier avoidance of the possibility of direct muscle stimulation which may bypass the neuromuscular junction and yield factitiously good readings.

By virtue of the efficiency afforded by lateral access surgery, the anesthesia team is asked to confirm the return of twitches before the skin is incised. After the intubation any

further muscle relaxants are withheld during the lateral access exposure portion of the surgery. It is important to emphasize this requirement with each anesthesia provider prior to and during surgery.

TcMEP has been used for MISS procedures in the thoracic regions but will be affected by the use of paralytic agents, particularly in the lower limbs. TcMEPs are also affected by inhalation anesthetic agents. The typical recommendation is for use of total intravenous anesthesia (TIVA) to avoid these issues [11, 12]. In addition, when using TcMEP, a mouth guard/bite block is indicated to help prevent inadvertent tongue or mucosal bite from jaw closure.

SSEPs, while immune from the effects of paralytics, may be quite sensitive to inhaled agents, particularly the waveforms representing the cortical responses. Peripheral or cervical recordings are less affected [13, 14].

Intended use of IONM should be discussed with the patient so that they are aware of the risks and benefits. Generally risks are minimal; however it is useful to mention if subcutaneous needle electrodes are going to be used, so that there are no surprises. The very low incidence of tongue bite when using TcMEPs and electrode burns should also be mentioned. Surface stick-on electrodes may be applied preoperatively; however needle electrodes are typically applied after induction.

Introduction to IONM Modalities

Spontaneous or Free-Run Electromyography (SPEMG)

EMG assesses peripheral nerve and nerve root function indirectly by recording muscle activity in the innervated muscle groups. Because of the continuous monitoring nature of spontaneous EMG signals, this modality is sometimes referred to as "free-run" EMG. SpEMG is sensitive to irritation of the nerve root from traction, manipulation, and stretching. Intraoperative SpEMG responses are often described as spike, burst, train, and "neurotonic" discharge patterns that as a rule of thumb are generally considered to reflect increasing severity or irritation of a nerve. Persistent EMG firing in train or neurotonic pattern is thought to denote a higher probability of nerve or nerve root injury while the presence of single spikes is less worrisome but may indicate close proximity to the nerve or nerve root [6]. Any of these signal patterns, however, may be indicative of potential nerve injury, particularly when temporally associated with surgical events such as nerve manipulation for access, decompression, or instrumentation insertion. Suction and the use of cold irrigation fluid may also result in activation.

It is important to remember that the absence of SpEMG firing does not necessarily reflect functional continuity of the monitored nerve. False negative (i.e., silent SpEMG) may occur after a nerve is transected, in a previously compromised nerve or in a patient with an underlying peripheral neuropathy.

As previously noted, these responses are blocked by paralytic agents; therefore, discussion of their planned use with the anesthesia team prior and during surgery is crucial.

Triggered Electromyography (TrEMG)

TrEMG has been demonstrated to be particularly useful for MISS [15–17]. Recording elicited or "triggered" responses from electrical stimulation of the nerve allows real-time assessment of nerve or nerve root integrity between the stimulus and distal muscle recording site(s). The amount of current required to depolarize a nerve or nerve root and cause the peripherally innervated muscle to contract is also often recorded. Studies suggest that direct, triggered stimulation of a healthy nerve root elicits a muscular response at approximately 2 mA. Measuring TrEMG thresholds to muscle activation during lumbar spine surgery has been used to help determine proximity of the stimulator to motor nerves.

The use of TrEMG is particularly useful in MISS including during the placement of percutaneous pedicle screws [17] or during the lateral, transpsoas approach to interbody fusion (XLIF technique) [16, 18, 19]. Although these are different surgical techniques and applications, both utilize the concept of obtaining a threshold response through varying the stimulating current which can be done programmatically using specialized software for controlling the stimulating current and monitoring the EMG responses. In the case of far lateral lumbar procedures that require careful dissection through the psoas muscle and past the lumbar plexus, TrEMG can provide rapid information concerning the relative proximity of motor nerve structures based on the required current needed for significant depolarization [16, 19]. For its use with percutaneous pedicle screw placement, a more detailed description is provided in the section subtitled, "IONM and MISS Pedicle Screw Placement," below.

Somatosensory-Evoked Potentials (SSEP)

SSEP has been a part of reconstructive spinal surgeries since the 1970s. First described by Nash et al. [20] in scoliosis correction procedures, its utility was confirmed by Dawson [21, 22] in the 1980s and the 1990s when it began to come into widespread use. This monitoring modality records potentials from the afferent fibers, primarily those from the dorsal column pathways. SSEPs do not give any direct information regarding the anterior spinothalamic or primary motor tracts (descending tracts) [22, 23].

Sensory impulses activated by peripheral nerve stimulation enter the cord via the dorsal root entry zone. The impulses ascend in the posterior spinal columns, eventually relaying in the thalamus with the final projection to the primary sensory area. Recordings are made from scalp electrodes confirming the end to end integrity of the pathway. Additional recordings from the cervical area and the peripheral nerves at Erb's point and the popliteal fossa are also frequently done both for redundancy and to segment the pathway when identifying the location of an insult.

Amplitude, the height of the wave deflection, and latency, the duration of time from stimulation until waveform occurrence, can all be measured individually from the upper and lower extremities.

Proposed alarm criteria are variable and preoperative injuries must be considered. However, a 50 % reduction in amplitude and 10 % decrease in latency are generally considered to be significant. This should be correlated with intraoperative events including correction maneuvers of the spine, hardware insertion, decompression, and hypotension [6]. Neural pathway compromise associated with patient positioning compression or stretch injuries can also be detected with changes in SSEP. Common factors that affect SSEP are halogenated anesthetic agents, nitrous oxide, hypothermia, and electrical interference. SSEPs can be moderately sensitive to inhalational agents which may especially blunt the cortical response amplitude and thus the overall sensitivity and specificity of their interpretation. The so-called "fade" or mild gradual decrease in the cortical amplitudes over the course of the procedure related to anesthesia is common.

Standardly recorded SSEPs do give information about the particular nerve stimulated, but do not give discrete segmental, dermatomal, or nerve root information. SSEP monitoring from the posterior tibial nerve, for instance, will only serve the L4 to S1 nerve roots and do not always show significant changes when a single root is involved. Dermatomal SSEP or DSEPs in which the stimulation site is a dermatomal patch and not a peripheral nerve do offer better dermatomal information [4]. Although more discrete to root injury, these responses tend to be not robust enough to be easily recorded in a noisy operating room environment making this modality more difficult to quantify and correlate with surgical outcomes [4].

Motor-Evoked Potentials (MEP)

Prior to availability of MEP, the only way to directly test motor tract integrity during surgery with an anesthetized patient was with an intraoperative Stagnara "wake up" test [21, 24]. Though the patients usually did not suffer any ill effects from this method, it was associated with a delay in diagnosis of neurologic deficit. MEPs were introduced in the 1980s and by the 1990s were being used routinely to monitor the corticospinal tracts.

While SSEPs capture data from ascending volleys, MEP or transcranial MEP (TcMEP) captures data from descending volleys (travelling in the reverse direction). Stimulation is extracranial, and recordings are from the distal muscles reflecting depolarization primarily of the corticospinal tracts. The majority of the associated motor fibers decussate at the medullary pyramids and travel as the lateral corticospinal tracts, while the minority of fibers remain uncrossed as the anterior corticospinal tracts. The blood supply to the anterior and lateral spinal cord comes predominantly from the anterior spinal artery, while the posterior spinal artery serves the posterior columns. As a result of this difference in blood supply, isolated ischemic injuries to the anterolateral cord may not be detected by SSEPs but are more likely detected by MEPs. MEPs are more sensitive to hypotension than are SSEPs. In addition, they are more acutely sensitive to inhaled anesthetic agents.

Standardized alarm criteria have not been universally adopted. At least four different methods are described in the literature: all or nothing waveform presence, amplitude change, stimulation threshold increase, and change in waveform morphology. The all or nothing criterion is the most commonly used [11] but may be used in conjunction with one or more of the others. All or nothing waveform monitoring is easy to follow and appears to provide time for the surgeon to modify his/her technique prior to permanent damage [25].

Multimodality Monitoring

Preserving neural function is the primary role of all neurophysiologic monitoring. False-negative SpEMG and SSEP recordings in which no alarm criteria are reached during intraoperative monitoring but postoperative deficits are present has been documented [26]. Utilizing more than one modality concurrently attempts to overcome that issue by broadening the structures being tested and recognizing the test with the highest sensitivity for the potential injury(s) taking place. It also provides some redundancy when individual modalities fail for technical reasons.

While multimodality monitoring is now widely used, it should be noted that SSEP monitoring alone has been shown to decrease the rate of neurologic complications in scoliosis surgery [22], and there is currently no class 1 data for combined modalities of monitoring that demonstrates superiority. At the same time there is no reported negative impact on outcomes with multimodality monitoring.

In the case of long tract spinal cord monitoring, MEP together with SSEP monitoring generally allows for better evaluation of patients with preoperative motor or sensory deficits than either MEP or SSEP alone.

Table 5.1 Summary of major spine studies reporting the sensitivity and specificity of various individual and multimodality monitoring techniques

			SSEPs		MEPs		EMG	
Authors and Year	Spinal area or condition	No. of procedures monitored	Sensitivity (%)	Specificity (%)	Sensitivity (%)	Specificity (%)	Sensitivity (%)	Specificity (%)
Nuwer et al. (1995) [22]	Scoliosis	51,263	92	98.9				
Kelleher et al. (2008) [30]	Cervical-thoracic spine	1,055	52	100	100	96	46	73
Gunnarson et al. (2004) [14]	Lumbar spine	213	28.6	98.7			100	23.7
Paradiso et al. (2006) [29]	Tethered cord	44	50	100			100	19
Multimodality monitoring: combined SSEPs, MEPs, EMG								
			Overall sensitivity (%)	Overall specificity (%)				
Sutter et al. (2007) [5]	All spine	1,017	89	99				
Quraishi et al. (2009) [31]	All spine	102	100	84.3				

From Gonzalez et al. [6]. Used with permission

Multimodality monitoring is tailored to the procedure, surgeon, and underlying pathology. For instance, SpEMG and SSEP are frequently used together for lumbar surgeries, particularly deformity surgeries. The high sensitivity of EMG is complemented by the higher specificity of SSEP making the combination of these modalities ideal for monitoring complex lumbosacral spine surgeries. Several large studies have confirmed the utility of IONM and particularly with multimodality monitoring [27–29]. Gonzalez et al. provided a summary of the sensitivity and specificity of several IONM modalities in their review paper replicated in Table 5.1 [5, 14, 22, 29–31].

IONM and MISS

For MISS to be worthwhile, it requires similar outcomes as open surgery with the same or fewer complications. In most MISS techniques the pathology and anatomy will not always be well visualized. IONM provides a useful adjunct to most if not all MISS procedures in compensating for the limited visibility and access to adjacent structures with the goal of reducing complications. The general approach is "see less—monitor more."

Spontaneous EMG has also been used to document adequacy of decompression [32], 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. When performing a MISS TLIF, SpEMG can identify possible nerve root irritation with retraction and/or interbody placement.

SSEP and/or MEP, although currently less widely used in MISS, nonetheless offers significant benefits and is likely to become more utilized as MISS applications become increasingly complicated and aggressive. Recognition of inadvertent cauda equina injury, to which SpEMG may not be as sensitive but SSEPs offer increased sensitivity, is one example. In addition, SSEPs should be used whenever the spinal cord itself is at risk and would be a requisite during, for instance, MISS scoliosis corrective procedures.

IONM and Percutaneous Pedicle Screw Placement

The most common and well-studied use of combined TrEMG and SpEMG in MISS is the placement of percutaneous pedicle screws [17, 33, 34]. A 2012 Medline search for MISS with IONM revealed 73 articles with the majority concerning pedicle screw placement.

The placement of percutaneous pedicle screws has become one of the primary procedures of interest to surgeons entering into the field of minimally invasive spine surgery. This technique is one of the first to be learned by surgeons new to MISS and a staple of all MISS techniques.

In the lumbar spine, TrEMG is the most commonly used method for assessing placement of screws using a mini-open or percutaneous technique. TrEMG during pedicle screw placement specifically tests the threshold current in mA required to depolarize the nerve in question. The pedicle bone surrounding the screw serves as an insulator and requires more current to trigger an EMG response when intact. A breach of the bone allows a smaller amount of

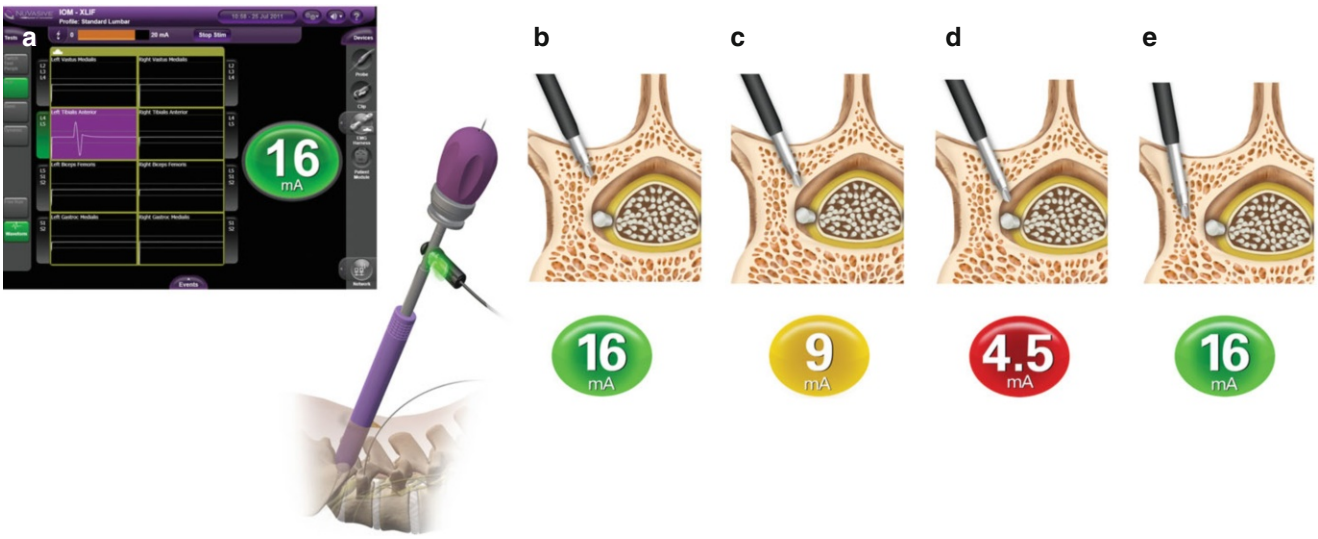

Fig. 5.2 Dynamic stimulation during percutaneous pedicle screw trajectory identification using an insulated pedicle access (Jamshidi) system. (**a**) Pedicle preparation with insulating tubes. Stimulation responses during pedicle cannulation: (**b**) *green* display with corresponding threshold current showing safe location of needle, (**c**) *yellow* display getting close to cortex, (**d**) *red* display showing close proximity to neurological pathways, and (**e**) *green* display showing safe values after redirect (Copyright NuVasive, Inc.; used with permission)

current to trigger a muscle response. The response is dependent upon an intact end-to-end nerve-neuromuscular junction muscle system. Processes which affect each of those elements may lead to factitiously high results. In addition, accurate measurements require that the entire current being delivered travels through the screw and is not leaked or bled off by contact with adjacent tissues. This typically requires adequate insulation of the stimulating instruments where ever they might come in contact with other than the intended target and a dry surgical field.

A TrEMG response of less than 7 mA in the lumbar spine indicates a likely breach [33–35]. Responses greater than 10 mA provide a reasonable probability that no breach has occurred. Glassman et al. reported that a threshold current of 15 mA or greater is indicative of a well-placed screw 98 % of the time [33] in the absence of neuromuscular blockade. These testing parameters are relatively standardized for steel or titanium screws, but false-negative responses have been reported when the screws are coated with hydroxyapatite. When possible, side to side and adjacent level thresholds should always be taken into account during interpretation.

Cortical violations in open procedures can reach up to 20 % without IONM even when using standard anatomical landmarks [36]. For MISS where visualization is less and the screws are typically placed percutaneously, extra care must be taken to avoid misplacement. The use of percutaneous pedicle screws (PPS) can be supplemented with fluoroscopy, computer-assisted navigation and neurophysiologic monitoring, or a combination of these [6, 37–41]. Each method has its limitations due to specific patient's requirements and learning curve(s), and each may not be available at all institutions. Although navigation and robotic techniques are becoming more widely accepted, they are not in regular use. A recent literature review revealed a range of accuracies with freehand techniques (69–94 %), with fluoroscopy (28–85 %), and with navigation (89–100 %) [42]. Youssef reported accurate pedicle screw placement simultaneously evaluating two types of IONM [43]. Ringel determined that when using a similar PPS insertion technique, only 3 % of the screws were rated as unacceptable and led to revisions [44].

The traditional pedicle screw IONM testing is a static test assessed after the screw has been placed. Technology has been developed to provide dynamic IONM information through TrEMG providing the surgeon real-time information during surgery while the trajectory for the pedicle screw is being created. This is accomplished by applying a nonlinear EMG threshold algorithm. The technology includes a ramping stimulating current at 5 Hz, with software algorithms to assess the discrete threshold current values required to elicit a myotome response (NVM5, NuVasive Inc, San Diego, CA). Care must be taken to avoid current leakage from stimulation of anything other than the target pedicle screw preparation instruments or the pedicle screw itself to avoid factitiously high threshold values [17, 37]. Testing is more sensitive for medial breaches since this orientation places the screw closer to the nerve. TrEMG gives no information for the rare misplaced screw that impinges the cord.

During percutaneous pedicle screw insertion testing of the nerve begins with the positioning of the Jamshidi needle used to facilitate K wire placement as shown in Fig. 5.2. Seventy two percent of Jamshidi needle trajectories will be altered due to this immediate feedback [2, 45]. Testing should continue with tapping and subsequent screw insertion especially if the initial thresholds are borderline. As the bone

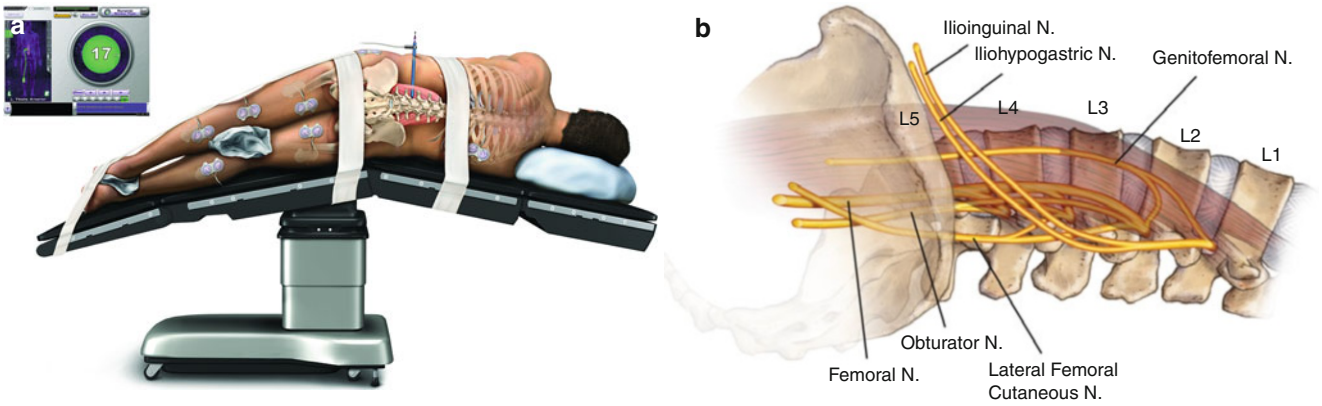

Fig. 5.3 (**a**) Patient position in lateral decubitus position for XLIF surgery. (**b**) Relative orientation of nerve anatomy of the lumbar spine [2] (Copyright NuVasive, Inc.; used with permission)

becomes more compressed with screw insertion and the current field changes an increasing value to depolarization indicates that a breach is unlikely, whereas a drop in the value from initial testing often indicates that a pedicle perforation may have occurred [17].

IONM and the Lateral Transpsoas Approach and XLIF

The lateral transpsoas approach was described in the late 1980s but was frought with excessively high complication rates [46]. A technique described by Pimenta combining the far lateral approach, with careful patient positioning and concurrent, IONM through TrEMG to safely traverse the psoas muscle has been described by Pimenta [47, 48] and reported by several other investigators [18, 49–51]. The extreme lateral interbody fusion (XLIF®) technique is distinguished from other lateral techniques through the use of integrated, discrete, and directional TrEMG. Prior descriptions using optical trocars and posterior retraction or resection of the psoas during the approach reported a complication rate of 30 % [46]. This is not unexpected when examined in the context of anatomical studies which identify the importance of careful psoas dissection to avoid injury to the nearby lumbar plexus and exiting nerve roots [2, 52, 53] illustrated in Fig. 5.3. It is especially true at the L4–5 disc space level due to the anterior direction of travel of the plexus. TrEMG may help in nerve avoidance by warning of nerve proximity and allowing redirection when appropriate especially when using probes which can provide directional information which provide a "navigational" experience past the lumbar plexus to reduce injury [16]. Preparation of the IONM monitoring system begins with careful placement of recording and stimulating electrodes. Intraoperative correction of monitoring problems is more difficult to trouble shoot and repair if the leads are not placed properly. Leads are typically placed on the tibialis anterior, bicep femoris, vastus medialis, and gastrocnemius muscles to cover responses from the L2 to S2 nerve roots [48]. Other muscle groups such as the cremaster may also be monitored [54].

TrEMG with the nonlinear EMG threshold algorithm technology applied to the lateral approach (XLIF®, NuVasive, Inc.) has the most reported experience [50, 55–57]. The directional capability of the commercial monitoring system was confirmed during a prospective, multicenter investigation of 100 patients [16]. In greater than 50 % of the procedures, the motor nerves were identified with directional and triggered EMG utilizing this system and alerted the surgeon to relative location and proximity. This study demonstrated effective identification of the superior and inferior plexus branches located within the psoas muscle that can be identified by altering the depth of the dilator and retractor [2]. This study represents the only prospective multicenter trial and its 2.8 % neural injury (all of which recovered at 3 months) serves as a standard outcome to maintain or improve. Complications, when using a combination of SpEMG and TrEMG for this technique have been historically reduced from greater than 30 % [46] to 1–3 % [50, 55].

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 greater than 10 mA are typically considered a safe distance from the nerve [2, 16] provided that there are no anesthetically induced neuromuscular blockades confirmed with the twitch test previously described. The importance of the directional information afforded by TrEMG is described in Fig. 5.4. With the directional stimulator present on the sequential dilators, the technology can identify the relative location and proximity of the plexus to the dilator. This is accomplished by rotating the dilation probe while continually applying a stimulating current during the psoas dissection. Additional intraoperative video demonstrating this concept has already been published [2].

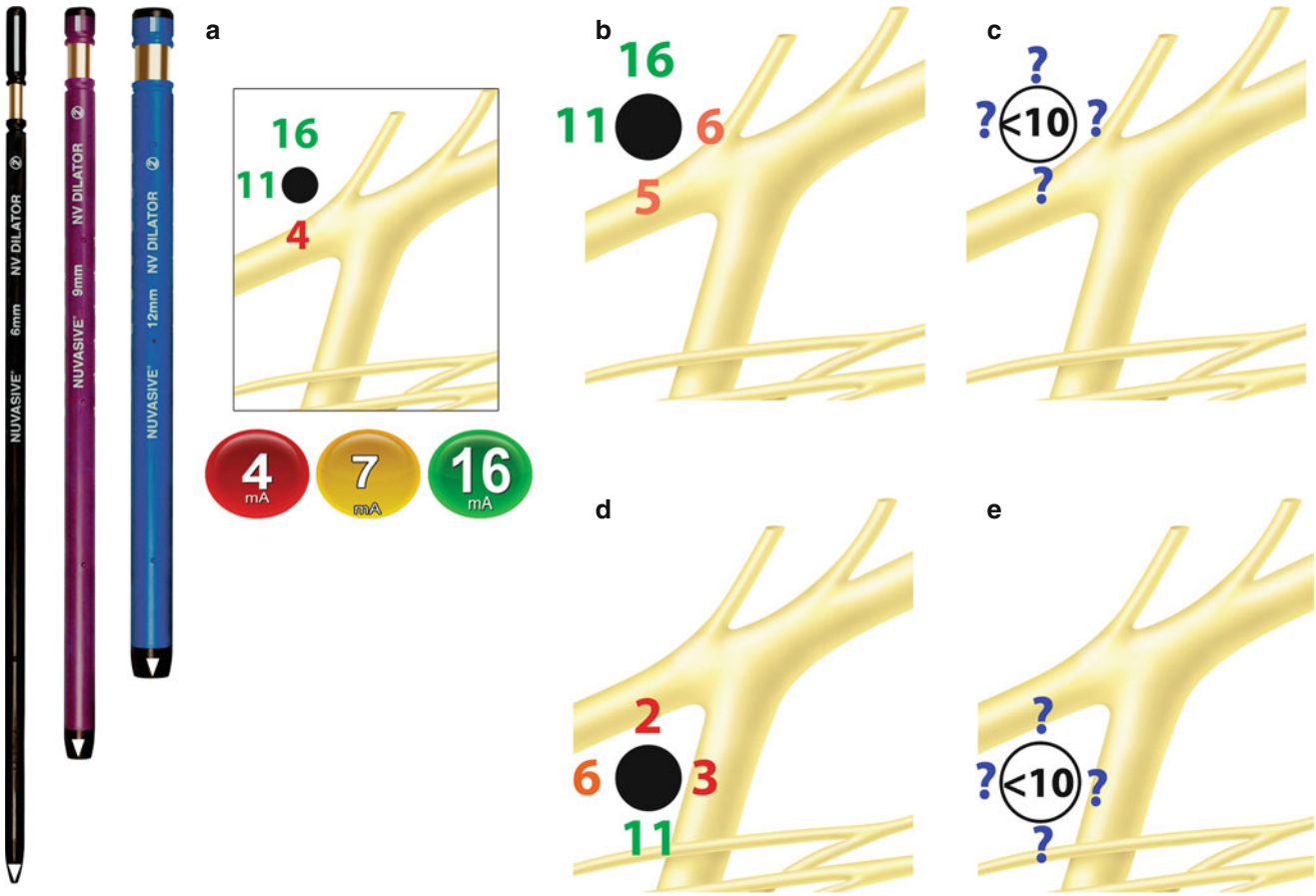

Fig. 5.4 The position of the insulated dilator relative to the motor nerves demonstrates the importance of discrete, directional feedback to the surgeon. (**a**) Insulated dilators with isolated electrode that provide directional stimulating current. (**b**) Favorable positioning of dilator with directional feedback (**c**) traditional neuromonitoring. (**d**, **e**) Unfavorable positioning between (**d**) NuVasive neuromonitoring (**e**) traditional neuromonitoring with no directionality

Once the passage through the psoas muscle is complete, SpEMG can be recorded throughout the procedure. This remains an option readily available to help insure nerve safety. However, it is important to remember that SpEMG has a very high sensitivity but a relatively low specificity. Changes in the TrEMG and SpEMG during the procedure should be considered in relation to operative events with appropriate steps taken to alleviate any problems. Real-time, directional, and discrete neuromonitoring is an integral part of the MISS lateral approach.

IONM in MISS Laminectomy and Transforaminal Lumbar Interbody Fusion (TLIF)

Neural injuries during MISS laminectomies and transforaminal lumbar interbody fusion (TLIF) procedures are often the result of compressive forces during decompression or retraction with interbody placement. EMG is well suited to identify these potentially damaging forces and provide the surgeon with a real-time feedback method to make specific surgical changes intraoperatively in order to avoid injury to the nerve structures [17, 58]. Prior to the routine use of EMG, the surgeon could be totally unaware of the potential of neural injury [6]. As noted above, EMG may not be as sensitive to cauda equina injuries and that the addition of SSEP monitoring may provide additional information and safety.

Compressed nerve roots are known to require a higher stimulation to depolarize. This knowledge has been used to infer the adequacy of the decompression with TrEMG by looking for a reduction in the threshold required for depolarization after laminectomy. In one study, 20 of the 22 patients showed a reduction of 50 % in the depolarization threshold [32]. Caution in interpretation of this technique is warranted, given that in our experience unchanged thresholds are certainly common after adequate decompression and it is unclear whether it is the decompression itself or just the disruption of local tissues or cellular gradients that lead to threshold changes in some cases.

A second observation involving SpEMG has also been described comparing pre-decompression recordings of the small number patients with neurotonic firing to post procedure recordings. The firing may cease following

decompression [6]. Unfortunately, this finding, more common in the cervical than lumbar spine, appears to be subject to high false-negative and false-positive rates and in any case is inapplicable to the vast majority of patients.

Following SpEMG while performing retraction and dissection for TLIF and interbody fusion can easily be accomplished with current techniques. The value lies in the EMG sensitivity to retraction of the nerve root and its immediate feedback. Intermittent firing during graft placement is the most common finding [17]. Continuous and persistent new train firing patterns after retraction raise the specter of increase risk of postop deficit.

IONM with MISS Thoracolumbar Corpectomy and Cervical Surgeries

IONM for standard approaches to the cord during cervical and thoracic surgeries are concerned with the risks of spinal cord and local nerve root injury. These risks remain with MISS and may be exacerbated due to limited or nonexistent direct visualization of the neural structures. Typical IONM application embraces the multimodality approach and ideally should include both SSEP and MEP monitoring to give a more comprehensive picture of cord function.

SpEMG should be geared to the surgical level(s). Muscles representing the specific spinal roots at risk from the level of the surgery should be monitored bilaterally. This helps to provide information about instrumentation placement that might be outside the expected and impinging on the opposite side of an approach. In addition, general practice when possible is to "bracket" the surgical site by monitoring nerve roots just above and below the expected area of risk. This provides information for easy comparison for detecting a lightening patient (coming out of anesthesia) or injury to a transiting nerve.

For cervical surgeries C5 muscles are generally added due to the incidence of C5 radiculopathy [59]. For thoracic surgeries the intercostal muscles are the only specific muscles innervated by the exiting root, and they may be monitored.

TrEMG is less useful for pedicle traverse and screw placement above T8 since the exiting root does not descend to the same degree as in the lower thoracic and lumbosacral regions and thus does not wrap the medial aspect of the pedicle. Standardized thresholds for reliable screw placement are therefore currently not available.

Surgeon-Driven, Attended, and Remotely Supervised Monitoring

Monitoring interpretation is generally provided in one of three ways. Commercial devices are available and have been optimized for a surgeon-driven approach. Alternatively interpretation may be provided by a neurophysiologist in the room or a neurophysiologist overseeing in "real time" a technologist in the room from a remote site [60, 61].

The methodology of real-time remote intraoperative monitoring oversight, described by Keim [60] in 1985 and later by Krieger and Sclabassi [61] in 2001, is now technologically readily available and offers access to a relatively scarce clinical resource. As the complexity of monitoring increases, some surgeons have taken advantage of the additional expertise that this model affords.

Summary

MISS allows minimization of some of the approach-related morbidity from tissue disruption associated with open surgery requiring large anatomical disruption for direct visualization. Adjunctive technologies such as fluoroscopy and IONM are useful in MISS to compensate for the reduction in direct visualization and to decrease inadvertent neural injuries. IONM specifically confers benefit by helping to identify, avoid, and recognize unintended injury to neural structures both in the surgical field and in the adjacent tissues. Multimodality IONM is important depending on the clinical circumstances for optimal sensitivity and specificity in detecting neural compromise. Coordination with the anesthetic team is likewise important to ensure that the anesthetic protocol does not limit the sensitivity and specificity of the monitoring.

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Image Guidance

6

Hussein Alahmadi and John E. O'Toole

Introduction

Intraoperative image guidance (IG) has become a growing part of spine surgery with many publications touting its advantages [1–10]. The role of IG has become especially clear in minimally invasive spine surgery (MISS) where anatomical landmarks are often unavailable because of the limited exposure. The term "image guidance" has been applied to a number of different imaging modalities used by spine surgeons over the years, including both two- and three-dimensional imaging systems and both preoperatively and intraoperatively acquired imaging studies. More commonly, however, IG refers to computer-based three-dimensional navigation used during surgery often for spinal instrumentation, such as pedicle screw insertion in the thoracolumbar spine.

Like any novel surgical technology, the use of IG adds its own cost and logistical complexities to the procedure. Many worry over possible increases in operative times, and issues like sterility maintenance and operating room setup can pose initial hurdles to spine surgeons adopting this new technology. An added concern is the risk of increased radiation exposure to the patient and, less commonly, the operating room staff. This chapter will explore the technical aspects of IG for spine surgery and review available data in demonstrating that with sufficient experience, IG can indeed play an efficient role while producing greater accuracy in the operating room.

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Improved Accuracy

Pedicle screw fixation is a standard technique employed in thoracolumbar spine fusion. Despite well-described anatomical landmarks for screw insertion [11], the learning curve remains steep [12]. Smaller thoracic pedicles and altered pedicle orientation in rotatory scoliosis cases can pose additional challenges. A medial or inferior breach of the pedicle wall can potentially result in spinal cord or nerve root injury, respectively. Historically, pedicle screw placement was done with a freehand technique where the surgeon relies solely on anatomical landmarks. Although spine surgeons are attentive to these landmarks regardless of adjuvant imaging modality, often, pedicle screw insertion is performed with the assistance of lateral and/or anterior-posterior fluoroscopy. Fluoroscopy provides only two-dimensional information at the particular moment of image acquisition unless the surgeon uses continuous fluoroscopy which adds significant radiation exposure to the procedure. More recently, the use of three-dimensional computer-based real-time navigation has been gaining popularity with literature demonstrating improved accuracy of screw placement [3–6, 13–15]. With this technology, an initial computed tomography (CT) scan is acquired to create the three-dimensional image needed for surgery. Older systems utilized preoperative CT scans and required intraoperative registration of patients' anatomy to the images.

This technique was not only cumbersome and time-consuming but also often lacked accuracy as the preoperative images were acquired with the patient in a supine position while surgery was most often performed in the prone position resulting in anatomic changes in the mobile spine. Newer systems allow for intraoperative CT acquisition with the patient in the surgical position and also utilizing a rigidly attached reference array to the bony anatomy that obviates the need for anatomic registration. Surgical tools with

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references attached are then verified to an optical tracking system, and the procedure is carried out under real-time tracking of the surgical instruments in space.

Although IG can be helpful in understanding complex anatomy in, for example, spinal tumor or reoperation cases, the major rationale for using IG is to decrease the incidence of suboptimal hardware placement. The reported range of pedicle screw misplacement using the freehand technique in the thoracolumbar spine varies in large series from 2 to 31 % [16–19]. These breach rates are typically reported from surgeons with extensive experience in freehand screw insertion during thoracolumbar fusions. For two-dimensional fluoroscopy-based technique, the rate of screw malposition ranges from 2 to 22 % [7, 20, 21]. Two well-conducted randomized controlled trials (RCTs) compared the rate of suboptimal screw placement between navigation and non-navigation techniques. Laine et al. [14] conducted an RCT of 100 patients to assess pedicle screw placement accuracy with and without computer-based navigation. There was no difference between the two groups with respect to pathology or operated spinal levels. Laine found the pedicle perforation rate to be 5 % in the navigation group and 13 % in the conventional group (statistically significant difference). There was no perforation more than 4 mm in the navigation group. In the other randomized trial, Rajasekaran et al. [15] compared the accuracy rate in deformity cases between the navigation technique and two-dimensional fluoroscopy. The cortical breach rate was 2 % in the navigation group compared to 23 % in the fluoroscopy group (statistically significant difference). In a single center experience, Silbermann et al. [6] compared, in a nonrandomized fashion, the rate of accurate lumbar and sacral pedicle screw placement between the freehand technique and computer-based navigation. The rates were 94 and 99 %, respectively. Only the operating room set up time was longer in the computer-based navigation group compared to the freehand technique group. In another comparative study, Merloz found the incidence of cortical breach in thoracolumbar pedicle screws to be 8 % in cases done with computer-based navigation and 42 % in cases with the freehand technique [22]. Gelalis et al. [3] performed a systematic review of 26 prospective studies that assessed the accuracy of different pedicle screw placement techniques and found the rate of accurate screw insertion to be 69–94 % in the freehand technique, 28–85 % in the fluoroscopy-assisted group, and 89–100 % in the CT-based navigation group. Screws that were inserted with the freehand technique were more likely to have medial breach of the pedicle wall. In a meta-analysis of 23 studies reporting the outcome of pedicle screw placement with and without computer-based navigation, Verma et al. [13] showed again a statistically significant improvement in pedicle screw placement accuracy with computer-assisted navigation. In two other meta-analyses of studies assessing pedicle screws placement accuracy [4, 5], the results again showed a lower incidence of suboptimal screw placement with computer-based navigation.

An important issue in pedicle screw placement is to minimize the violation of the superior facet, which can potentially minimize the rate of adjacent segment disease. Yson et al. [23] compared the rate of superior facet violation in IG minimally invasive technique to the open technique based on postoperative CT scan. The IG technique was associated with significantly lower rate of cranial facet violation.

The existing literature about the accuracy of pedicle screw placement with different techniques shows wide variation in the rate of suboptimal screws between different studies. This reflects, to some extent, the degree of heterogeneity between the patient populations in these cohorts. The studies include patients operated on at different levels/regions with many different pathologies. More importantly, it is difficult to account for individual differences between surgeons in the nonrandomized studies. The reported advantages of IG in screw insertion must be taken into the context of the experience and clinical setting of any individual surgeon interested in employing this technology. Also, the advantages of IG may be more noticeable in more complex cases where normal anatomy may be altered significantly. Nevertheless, the weight of the evidence has made it clear that IG significantly improves the anatomic accuracy of pedicle screw insertion in the thoracolumbar spine.

Most of the literature studying pedicle screw placement accuracy is based on postoperative CT scans evaluating the confinement of the screw within the pedicle. The clinical importance of these radiographic outcomes is less obvious. For example, a pedicle screw that is 1–2 mm outside the pedicle, especially if the breach is lateral, is unlikely to have any measurable clinical consequence. Few studies have tried to evaluate the impact of computer-based navigation on clinical outcomes, the most important of which would be neurological injury and need for reoperation for screw removal/repositioning. In the systematic review by Gelalis et al. [3], there was no difference in the rates of the clinically significant complications based on the technique. This can be explained by the fact that only a fraction of these suboptimally placed screws result in clinically noticeable difference and hence the existing studies might be underpowered to detect that clinical difference. In the review paper by Verma et al. [13], despite a significant improvement in pedicle screw accuracy with computer-based navigation, the improvement was just short of the statistical significance threshold when clinical outcomes were considered. Watkins et al. [24] compared the reoperation rate for inadequately positioned screws between the IG technique and the conventional one. In a cohort of 100 patients, IG reduced the rate of reoperation from 3 to 0 % with subsequent improved utilization of hospital resources. Further studies are needed to understand in what clinical contexts IG will exert its greatest effect in improving overall patient outcome.

Radiation Exposure

One of the main concerns of any intraoperative imaging during spine surgery is the radiation exposure to the patient and the operating room staff. The current recommendations by the International Commission on Radiological Protection include upper limits of radiation dose equivalent of 5 Rem/year of total body exposure and 50 Rem/year of extremity exposure [25]. Fluoroscopy and computer-based navigation techniques both share the added risk of radiation exposure with different exposure profiles. There is a relatively high upfront single exposure from the CT scan in the navigation technique compared to the cumulative exposure of multiple smaller doses with fluoroscopy. A major advantage of computer-based navigation is that the OR staff exposure to radiation can be reduced significantly. With IG, the OR team can stand outside the operating room while the CT scan is acquired. Minimal to no fluoroscopy may subsequently be needed during the procedure. This advantage is critical to surgeons who perform fluoroscopy-assisted procedures regularly where there is a potential for significant cumulative radiation exposure.

Bindal et al. [26] studied the radiation exposure of the surgeon in minimally invasive TLIF with two-dimensional fluoroscopy. The radiation dose was found to be 0.076 Rem to the surgeon's dominant hand and 0.027 Rem to the waist (under protective lead apron). The author concluded that around 194 procedures per year are needed to exceed the recommended upper limit for annual radiation exposure to the torso. Although most surgeons perform less than this number of TILF surgeries annually, fluoroscopy is used in many other procedures, and depending on individual details of each case, the annual radiation exposure to the spine surgeon can reach a concerning level. Rampersaud et al. [27] studied the radiation exposure to the surgeon specifically during pedicle screw placement under two-dimensional fluoroscopy. He found the average hand dose rate to be 0.0582 mRem/min. The dose rate to the surgeon's torso was 0.0533 mRem/min when the surgeon stood on the side of the radiation source and 0.0022 mRem/min when the surgeon stood on the side of the image intensifier. He concluded that maintaining good distance from the radiation source can significantly lower the radiation exposure to the surgeon. These two reports suggested that fluoroscopy can be associated with significant radiation exposure. Smith et al. [28] compared radiation exposure during pedicle screw fixation between two-dimensional fluoroscopy and a three-dimensional navigation system. In the navigation group, only one initial three-dimensional scan was obtained while the surgeon stood outside the operating room. The mean radiation exposure to the surgeon's torso was 4.33 mRem in the fluoroscopy group and 0.33 mRem for the navigation group (statistically significant difference).

The effect of IG on radiation exposure to patients is not as clear. The relatively fixed radiation dose of the CT scan in the navigation technique must be weighed against the more variable doses seen in fluoroscopy-based techniques. The latter can vary based on patient factors such as the operated levels or patient's body habitus. Also, surgeons vary significantly in the number of images they need to perform a particular procedure. There have been no studies to directly compare the radiation exposure to the patient in the navigation and fluoroscopy techniques in spine instrumentation. Izadpanah et al. [29] compared the radiation exposure to the patient during kyphoplasty between computer-based navigation and two-dimensional fluoroscopy. The study suggested that the computer-based technique was associated with less radiation exposure as measured by the dose area product which accounts for the dose and the irradiated area. Perisinakis et al. [30] studied the radiation exposure to the patent undergoing kyphoplasty under two-dimensional fluoroscopy and found that the average patient effective dose can be as high as 1.2 Rem. In our own experience, the senior author randomized patients with vertebral compression fractures to undergo kyphoplasty under either biplane fluoroscopy or CT-based IG navigation. Image guidance resulted in a statistically significant 50 % reduction in radiation exposure to the surgeon. However, there was an associated increase in patients' mean effective dose due to the initial cone-based CT scan, though well within acceptable limits (unpublished data). Further investigation is ongoing to better define the radiation exposures for both surgeons and patients in the use of CT-based IG.

Technique for Image-Guided Pedicle Screw Insertion

The IG technique is similar to standard pedicle screw instrumentation in most details. A few key principles and steps specific to IG are highlighted here. In our experience, the procedure is best performed on the OSI Jackson (Mizuho OSI, Union City, CA, USA) or other radiolucent operating table to ensure both proper patient positioning for fusion and access of the imaging device around the patient. After draping the surgical field, a reference frame for the optical tracking system is fixed to the patient. Options for fixing the reference array include a percutaneous pin inserted into the iliac crest via a 4 mm incision or a spinous process clamp applied to an exposed spinous process. Then, a three-dimensional scan of the patient is obtained with an intraoperative imaging device such as the O-Arm (Medtronic Navigation, Louisville, CO, USA) (see Fig. 6.1). The O-Arm does not necessarily have to be sterilely draped into the field but rather sterile sheets may be placed over the surgical field leaving only the reference array exposed for camera tracking. Following the scan, the O-Arm and surface sheets may be removed from the field. After acquisition, the images are automatically transferred to the computer-based system,

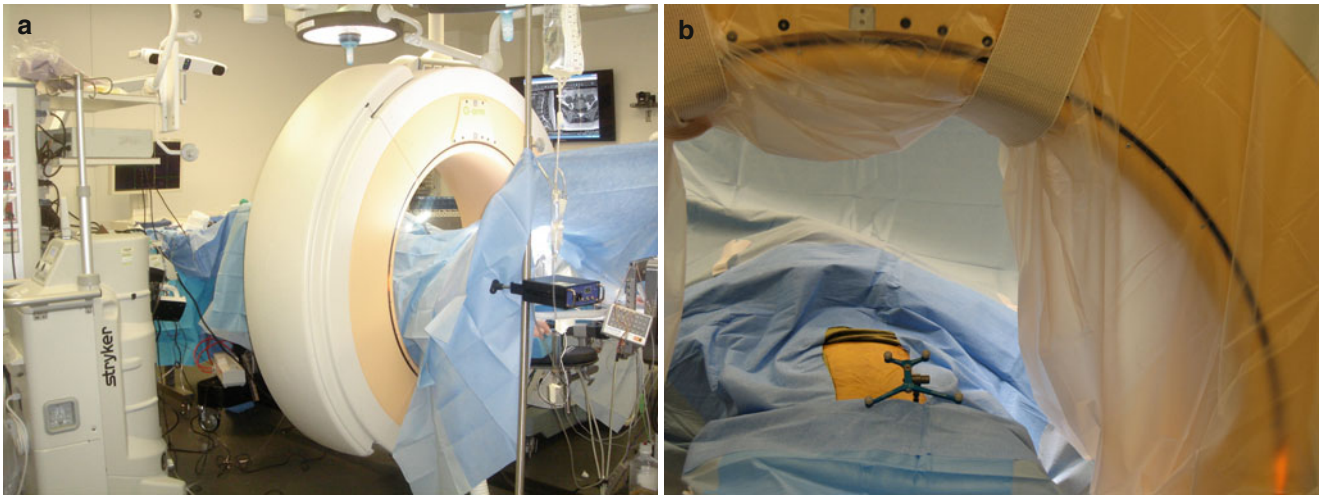

Fig. 6.1 Intraoperative photograph of (**a**) the O-Arm imaging device in place and prepared for image acquisition and (**b**) the percutaneous iliac pin with attached reference array in place

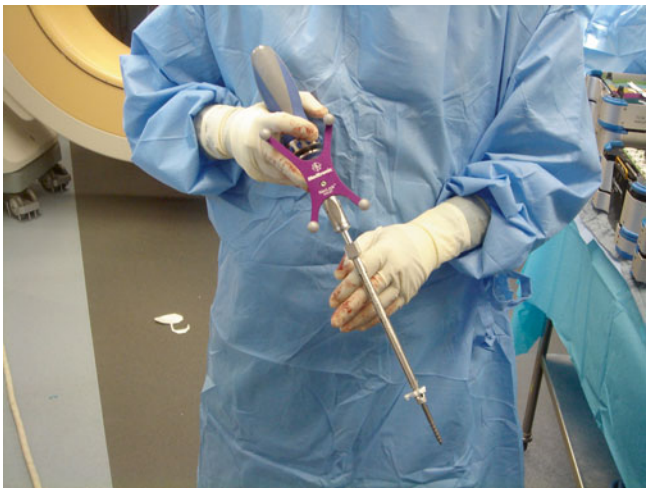

Fig. 6.2 Intraoperative photograph of navigated screwdriver with attached tracking array

such as the Stealth Navigation Station (Medtronic Navigation, Louisville, CO, USA). Trajectory planning, image modulation, and instrument selection can all be performed rapidly. A standard navigated probe can be used to plan out paramedian incisions to be used for screw insertion. The navigated surgical instruments are then registered to the optical tracking system so they can be tracked in real time (see Fig. 6.2). Typical instruments include awls, pedicle finders, taps, and screwdrivers. This allows for the complete sequence of screw insertion under navigation with no need for fluoroscopy (see Fig. 6.3). Percutaneous pedicle screws can be inserted in such a manner without using K-wires by following the same navigated path with each instrument up to and including screw insertion. Alternatively, the pedicle can be prepared through the tapping step and then K-wires inserted through a cannulated navigated instrument and clamped to the field for later screw insertion while the surgeon performs

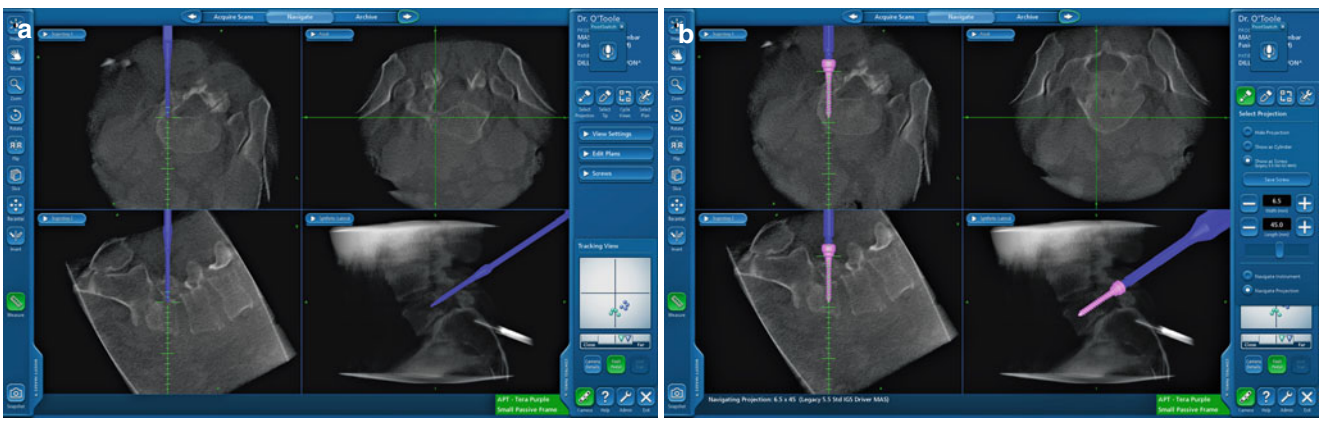

Fig. 6.3 Intraoperative screen shots of the Stealth Navigation computer system demonstrating the continuous three-dimensional views afforded during preparation of the pedicle with the tap (**a**) and final screw insertion (**b**)

decompression and/or fusion through a tubular retractor. Once the instrumentation is complete, the O-Arm can be returned to the field, if desired, and an intraoperative three-dimensional image can be obtained to check screw placement before the wounds are closed.

Summary

Image guidance can serve as a very important adjunct to the surgeon during MISS. There is robust data showing that IG decreases the incidence of suboptimal screw placement. The ability of IG to decrease the incidence of neurological complications or need for reoperations following thoracolumbar instrumentation remains unclear. IG offers particular advantages in cases of severe deformity or other altered anatomy as well as for the intraoperative training of residents and fellows. IG offers the further benefit of minimizing occupational exposures to ionizing radiation for the surgeon and OR staff. Future studies will help to modify imaging protocols in IG to also minimize patients' radiation exposure.

How widespread IG ultimately becomes in spine surgery will be based on balancing improvements in surgical accuracy (and resultant improvements in clinical outcomes) with concerns over cost, efficiency, and radiation exposures. Our personal experience has shown the technology to be both efficient and cost-effective by reducing screw revision rates and reducing occupational radiation exposures. Further research is needed to clarify the answers to these questions and better define the true role of IG in spine surgery.

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Robotic-Assisted Spine Surgery

7

Xiaobang Hu and Isador H. Lieberman

Introduction

Surgical robotics emerged during 1990s, and since then, progress has been made to optimize the use of robotic technology to the benefit of the patient. Surgical robots are in their simplest form, designed to enhance and complement the surgeon's freehand abilities during surgery. This can be in the form of passive positioning devices or even devices that mimic the surgeon's actions remotely. The potential advantages of robotic-assisted surgery are increased accuracy of implant placement and surgical procedures, improved clinical outcome, reduced operation time, reduced invasiveness of the procedure, and reduced radiation exposure to the patients, surgeons, and operating staff. The recently developed robotic systems span the spectrum of surgical disciplines and include the ROBODOC (Curexo Technology), which is used to bore the medullary cavity of bones for hip implants; the CASPAR system (OrthoMaquet GmbH) for hip replacement; the URS AESOP system for endoscopic camera support; and the Da Vinci (Intuitive Surgical) and Zeus (Computer Motion) systems for remotely manipulated minimally invasive procedures [1, 2].

There has been a growing interest in the spine surgery field to incorporate a robotic arm with image guidance in order to assist with surgical procedures. Traditional spinal surgery procedures, such as implanting screws and rods, osteotomizing bone, or decompressing the neural elements, can be lengthy and tedious. The surgeon may experience fatigue and hand tremor during these prolonged procedures [3]. In contrast, contemporary spinal surgery is characterized by finely manipulated less invasive trajectories to deeply seated critical bony structures that are usually accessed through less invasive percutaneous or limited corridors. With the significant advances in the image-guidance field, several robotic systems have been developed to address these challenges in spine surgeries, especially for the accurate placement of spinal instrumentation [4–6].

This chapter will discuss the development philosophy, clinical utility, and general results of a recently developed spinal surgery robotic system as well as the integration and application of such a robotic system during minimally invasive spine surgery.

The Robotic System

The recently developed system with which the authors have clinical experience is a bone-mounted hexapod miniature robot (Renaissance, Mazor Robotics Ltd). This robotic system consists of a cylindrical device composed of two endplates and six pistons which maneuver the endplates over six degrees of freedom (Fig. 7.1), as well as a workstation that runs an interface software which facilitates preoperative planning, intraoperative image acquisition and registration,

Fig. 7.1 The miniature robot

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Fig. 7.2 The robotic workstation

kinematic calculations, and real-time motion control of the robotic guidance device (Fig. 7.2).

Details of the system and related surgical techniques have been described previously [5, 7–9]. In general robotic-assisted spine surgery includes the following steps:

1. Preoperative planning (Fig. 7.3) using a CT with 1 mm slices. On this scan, the surgeon plans the placement of the implants in a virtual 3-D model of the spine. The surgeon then transfers this preoperative plan to the workstation to facilitate the plan.
2. Mounting the stabilization platform (Fig. 7.4) to the spine upon which the robotic device is attached.
3. Automatic image registration (Fig. 7.5) and referencing using two intraoperative X-rays obtained with a fluoroscope and a reference frame. This step serves to define the position of each vertebra in a 3-dimensional space with respect to the mounting platform.
4. Implant placement (Fig. 7.6) by dispatching the robot to the various trajectory positions according to the preoperative plan followed by drilling then implanting the appropriate pedicle screw, facet screw, or translaminar screw.

General Results of Robotic-Assisted Spine Surgery

Accuracy and Safety

Pedicle screw constructs are the foundation of spinal fixation and do afford multidimensional control and provide substantial rigidity to facilitate fusion. These advantages have led to the widespread use of pedicle screws in different spinal diseases, such as degenerative, traumatic, and developmental spinal conditions [10]. The accuracy and safety of pedicle screw placement depends largely on the patient's anatomic landmarks, the navigation system, and the surgeon's experience. Screw malposition may lead to serious vascular and neurologic complications especially when the patient's anatomy is altered [11]. Even in the hands of experienced surgeons, with conventional techniques the implant malposition rate ranges from 5.1 % up to 31 % as described by many authors in multiple review studies [12–15]. Fortunately in these studies, few of the malpositioned screws have led to substantial clinical consequences [12].

Devito et al. performed a retrospective, multicenter study to assess the accuracy of robotic-assisted pedicle screw placement. They reported that with 3,912 planned Screw/GuideWire (S/GW) insertions in 682 cases, 83.6 % (3,271 S/GW) were fully implanted under robotic guidance. The remaining cases were initiated under robotic guidance but were manually placed due to various reasons (such as registration issues, robot "reachability" limitation, device failure, and mechanical movement). For the 3,271 S/GW that were successfully placed by the robot, 98 % (3,204) were found to be clinically acceptable when assessed intraoperatively by fluoroscopic images. CT scans were available for 646 screws in 139 cases. The CT scans demonstrated that 98.3 % of the screws fell within the safe zone (89.3 % were completely within the pedicle and 9 % breached the pedicle by less than 2 mm). Neurologic deficits were observed in four cases, and no permanent nerve damage was reported after revision surgeries [7].

Kantelhardt et al. compared the accuracy of conventional and robotic-guided pedicle screw placement in 112 consecutive patients. They reported that the robotic group (55 patients) had significantly lower (1.1 %) screw deviations, and this rate did not differ significantly between percutaneous and open robotic-guided procedures. Meanwhile, intraoperative adverse events (1 major hemorrhage, 6 dural tears)

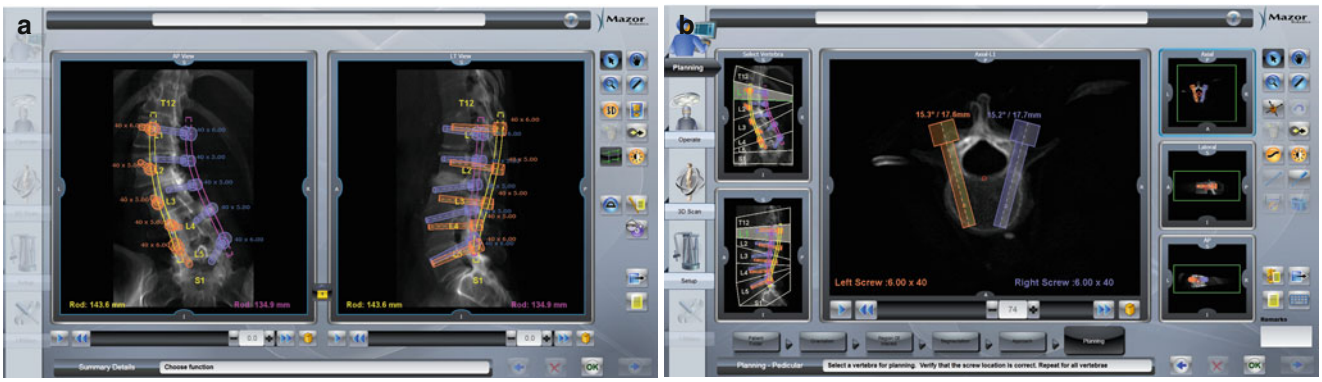

Fig. 7.3 (**a**) Anteroposterior and lateral demonstration of the preoperative planning. (**b**) Axial view showing the position of planned screws

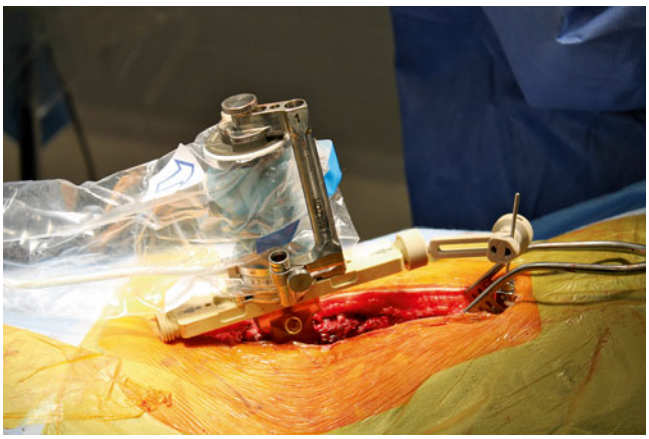

Fig. 7.4 Mounting the stabilization platform on patient

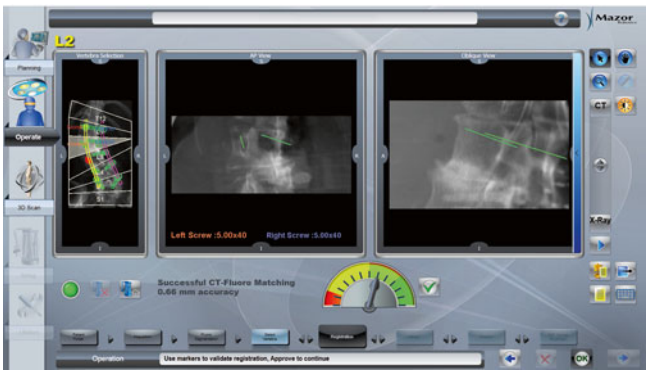

Fig. 7.5 Automatic image registration for the robotic system

were observed in robotic-guided cases (4.7 %), and the rate was 9.1 % in the conventional group. Postoperative cerebrospinal fluid fistulas were not observed in the robotic-guided group, but it was observed in 6.1 % of the conventionally operated patients. Postoperative infections occurred in 2.7 % of robotic-guided cases, and the rate was 10.7 % in the conventional group [16].

We recently evaluated the accuracy of robotic-assisted screw placement in a consecutive series of 102 patients starting with our first case experience. Robotic-guided screw placement was successfully used in 95 out of 102 patients. In those 95 patients, 949 screws (87.5 % of 1,085 planned screws) were successfully implanted. Of the 960 screws that were implanted using the robot, 949 (98.9 %) were successfully and accurately implanted and 11 (1.1 %) were malpositioned, despite the fact that the majority of patients had significant spinal deformities and/or previous spine surgeries. "Tool skiving" was thought to be the inciting issue with the misplaced screws. Intraoperative anteroposterior and oblique fluoroscopic imaging for registration is critical and was the limiting issue in four of the seven aborted cases [17].

These reports together with the initial cadaveric studies demonstrate the potential advantages of the robotic system to increase the instrument placement accuracy [5, 7–9, 16, 18–21].

Time

The amount of time taken to place an instrument using the robot system varies and it depends on multiple factors such as the surgeon's experience, his or her familiarity with the system, and accuracy of the registration process [22]. In a controlled, cadaveric implantation study, Lieberman et al. found that comparing to the conventional group, the robotic-assisted surgery group has shorter procedure time and shorter time per screw independent of surgeon experience with the system or setup time for the system. However, the authors did not include the time for setup of the frame or mounting of the robot in this study [23]. In a retrospective review of 112 clinical cases, Kantelhardt et al. found that the average time per screw was not significantly different between the robotic-guided group and the conventional group [16]. It is reported that single or multilevel registration can also affect the time taken to insert a pedicle screw [24]. Takahashi et al. showed that navigation systems allowing multilevel registration can significantly reduce pedicle screw insertion time and total operation time comparing with single-level registration [25]. To fully evalu-

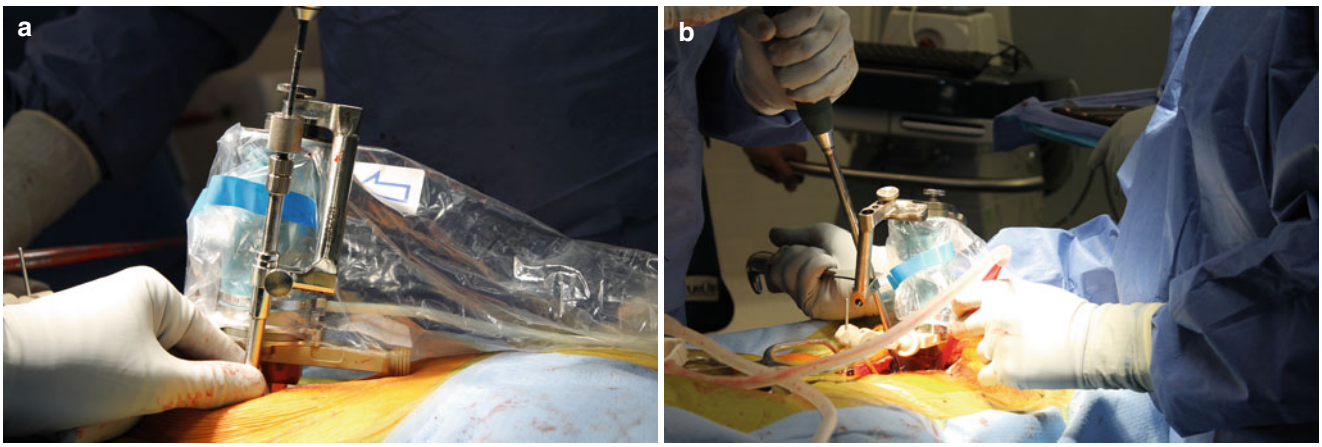

Fig. 7.6 (**a**) Drilling the pedicle screw path with robotic guidance. (**b**) Placing pedicle screw with robotic guidance

ate this issue, further studies are needed to assess the time-saving benefits of robotic-assisted spine surgeries.

Radiation Exposure

Spine surgeries require thorough knowledge of the anatomy, the orientation of vertebrae in 3-dimensional space, and their relationship to the underlying neurological structures. As such, many surgeons rely on intraoperative fluoroscopy or image guidance to achieve optimal screw/guide-wire position. It has been shown that conventional fluoroscopy-assisted pedicle screw placement results in significant radiation exposure to the surgeon and operating room staff [9, 21, 25–30]. Studies using a robotic system have shown a substantial decrease in the radiation exposure compared with conventional fluoroscope-assisted pedicle screw implantation surgeries [16, 23]. In addition when robotic devices are used for vertebral augmentations, there was significantly less radiation exposure than completely fluoroscopic vertebral augmentations [31, 32]. At the same time, because the robotic system requires thin-sliced, high-resolution CT scans, it has not yet been determined if the overall radiation exposure to the patient is more, less, or the same when comparing the preoperative CT scan to intraoperative fluoroscopic radiation exposure.

Spinal Deformity and Revision Surgeries

Pedicle screw implantation is especially challenging in patients with severe spinal deformities (such as scoliosis) and the patients who need revision surgeries by virtue of the altered anatomical landmarks. The published rates of pedicle screw malposition in spinal deformity range from 4.2 to 15.7 % [11, 33].

Devito et al. reported their experience for 80 patients with adolescent scoliosis, 14 male and 66 females, with an average age of 14.4, who underwent open posterior spinal instrumentation and fusion, with an average curvature of 66.5° (range 46–95). 1,163 screws were placed by the robotic system and 95.9 % of them were placed into their precise locations (99.9 % including otherwise acceptable placements). There were no device or implant-related complications and no screw revisions [18].

We recently analyzed a prospective series of over 100 deformity and revision surgeries, involving 1,085 screw implantations, using the robotic system. The cases were classified into four groups: patients who did not have a deformity or previous spine surgery (group 1); patients who had a deformity but no previous spine surgery (group 2); patients who had previous spine surgery but no deformity (group 3); and patients who had both spinal deformity and previous spine surgery (group 4). Overall, 949 screws were successfully implanted, 11 screws were malpositioned and repositioned manually, 110 screws were converted to manual placement due to technical issues related to the system, and 15 screws were not placed at the surgeon's discretion. These related technical issues included inability to obtain adequate intraoperative X-rays and either software or hardware malfunction. When we analyzed the rate of malpositioned screws, we noted no significant differences among all four groups (group 1, 3.92 %; group 2, 0.71 %; group 3, 2.94 %; group 4, 0.74 %). The overall screw malposition rate in this study was 1.01 % which appears to be an improvement over the historical figures [17, 34].

Minimal and Less Invasive Surgical Techniques

The robotic system has shown some advantages in minimal and less invasive spine surgeries, such as percutaneous screw placement. Pechlivanis et al. reported a prospective series of 31 patients receiving instrumented posterior lumbar interbody

fusion (PLIF) with percutaneous insertion of pedicle screws. In 29 cases, the integration of the robotic system was successful. 133 screws (levels range from L2 to S1) were inserted percutaneously under robotic guidance. Verified by post-op CT scans, they reported that 98.4 % of screws in the axial plane and 91.5 % of screws in the longitudinal plane were placed within 2 mm of the pre-op plan. They also found that the robotic system has a weak user dependency as the screws were placed by four different surgeons. No screw related complication occurred in their study [8]. In a large-scale cadaveric study, the author examined efficacy of the robotic system in percutaneous pedicle screw implantation. 234 pedicle screws were implanted in 12 cadavers (study group: 15 surgeons, 197 screws, 10 specimens; control group: two surgeons, 37 screws, two specimens). The results showed that the study group had significantly more accurate placements comparing to the control group (average deviation 1.1 ± 0.4 mm vs. 2.6 ± 0.7 mm; $p < 0.0001$) and fewer pedicle wall breaches of 4 mm (average 1.5 % vs. 5.4 %). In addition, the surgeons in the study group were able to complete the procedure more quickly [23].

In a retrospective multicenter study, Devito et al. reported that 49 % of the 635 robotic-assisted surgeries were done in a percutaneous approach which also highlights the contribution of the robotic system in surgical procedures without directly viewing the anatomic landmarks. They also discussed that the robotic platform allows the surgeon to locate the optimal entry point at the skin level, thus can reduce the required incision size [7].

Clinical Outcome and Cost-Effectiveness

To date, the only study comparing functional outcome of computer-navigated robotic-assisted screw placement to traditional open techniques reported that patients operated with robotic assistance required less opioids and had a shorter hospitalization and lower rate of adverse events in the perioperative period. The added benefit may be due to the fact that those patients in the robotic group had a higher proportion of percutaneous less invasive screw placements than the open group [16].

To date, there are no studies comparing the long-term functional outcome of spinal implantation with or without robotic assistance. Well-designed randomized control trials with appropriate follow-up will thus be needed to demonstrate, if computer-navigated robotic-assisted spine surgeries produce better clinical outcomes and are cost-effective compared to traditional spine surgery techniques.

As with all new technology, there will no doubt be additional cost associated with the use of robotic technology in the operating room. Once these technologies become validated, the laws of medical economics will prevail and the costs will stabilize. When considering the high cost of revision surgery for misplaced pedicle screws, utilization of robotics or navigation in difficult surgeries (such as patients with deformity) may prove to be cost-effective in those spine practices with a heavy volume of challenging cases [35].

Conclusion

Robotics has been incorporated in surgery in a growing number of medical disciplines, such as urology, gynecology, cardiology, and others. As importantly, it may change many aspects of the way we practice spinal surgery. Bone-mounted robotic guidance can facilitate accurate placement of pedicle screws, thereby reducing the risk of errantly placed screws and their associated morbidity. Some users have found that the system is also useful for non-pedicle screw procedures such as biopsies, vertebral augmentations (vertebroplasty and kyphoplasty), and tumor resections. The technology offers the benefits of precise preoperative planning for the most suitable entry points and the most appropriate trajectories and intraoperative execution of the plan. All of these parameters can be computed even in the presence of severe deformities and loss of anatomical landmarks. The use of surgical robots has been proven to be valuable in various open, less invasive, and percutaneous spinal procedures. These advantages may allow the surgeon to be more at ease about offering minimally invasive or percutaneous surgical options to patients and more comfortable about implementing pedicle-based fixation in general—while at the same time increasing the operating room personnel's sense of safety by reducing their radiation exposure. Meanwhile, more high-quality studies should be performed and more experience needs to be obtained before the full potential of the robotic system can be realized in the spine surgery field.

Surgery is a highly interactive process and the goal of computer-navigated robotic assistance is not to replace the surgeon with a robot, but to provide the surgeon with a new set of very versatile tools that can extend his or her ability to treat patients [36]. When considering robotic-assisted spine surgery, one must appreciate that the robotic system reported here is not actually doing the surgery. It is still the surgeon doing the surgery with the robot facilitating the preoperative plan. Likewise, one must recognize that the robot will not make a bad surgeon good. The robot is a tool that can help make a good surgeon more precise and efficient.

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Fusion Biologics

8

Praveen K. Yalamanchili and Scott D. Boden

Biology of Spinal Fusion

Spinal fusion in a lumbar intertransverse fusion model occurs through an integrated sequence of events that has been described histologically and molecularly [1–3]. Three distinct phases of spinal fusion healing—inflammatory, reparative, and remodeling—appear to occur in a stepwise fashion [4]. The inflammatory phase occurs over the first few weeks and consists of a hematoma and an influx of inflammatory cells. This initial response leads to the production of a fibrovascular stroma and results in neovascularization. Importantly, the cytokines released by the inflammatory cells are believed to have an important role in recruitment of osteochondroprogenitor cells. Additionally, intramembranous bone formation occurs over the transverse processes. The next phase, reparative, consists of differentiation of cells and endochondral ossification to facilitate union of bone forming at either transverse process. In the remodeling phase, the existing fusion mass is transformed to a mature mass oriented to lines of stress through resorption and enchondral bone formation. The sequence of spinal fusion has also been described at a molecular level, controlled by a variety of growth factors. These factors include platelet-derived growth factor (PDGF), tumor necrosis factor α[alpha] and β[beta] (TNF-α[alpha] and TNF-β[beta]), interleukins 1,6,10,12 (IL-1, IL-6, IL-10, IL-12), insulin-like growth factor 1 (IGF-1), and bone morphogenetic proteins (BMPs). Expression of several BMPs has been studied in relation to their temporal expression in bone healing [5]. Peak expression of BMP-6 occurred earliest, followed by BMP-2 and BMP-4. Within a posterolateral lumbar spinal fusion model, the described phases and molecular events occurred initially over the transverse processes followed by the intertransverse region in a delayed, but sequential, fashion [1]. A mixture of intramembranous and enchondral bone formation occurs throughout the process based on the evolving environment.

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Factors Affecting Fusion

Successful spinal arthrodesis requires the fundamental elements of blood supply to support healing, available osteoinductive factors and osteogenic cells to produce bone, an osteoconductive scaffold to guide bone formation, and a favorable mechanical environment [3]. An adequate blood supply provides oxygen, nutrients, control of pH, and a conduit for recruitment of cells. The abundant vascularity of certain regions of the spine, such as anterior cervical, is thought to be a major factor in comparatively increased fusion rates. Damage to the local blood supply, such as with radiation-induced inhibition of angiogenesis, can create significant challenges to bone healing and should be noted. Osteogenic cells can be found in local bone surfaces and in transplanted autograft bone. The surrounding soft tissue provides a source of osteoprogenitor cells as well, but to a lesser extent than bone sources [6]. Osteoinductive growth factors are expressed throughout the healing process and can also be implanted surgically at the site to promote bone formation. The surface area of decorticated host bone affects the available level of both osteogenic and osteoinductive factors. Decorticated host bone along with implanted graft also provides an osteoconductive region for bone growth. Therefore, adequate decortication is a vital element to successful spinal fusion [1]. Mechanical compression, such as occurring in interbody graft, tends to promote fusion, whereas tensile loads, such as in posterolateral lumbar fusions, provide a more challenging environment. Internal fixation helps offset some of the tensile load and increases fusion rates. The rate of spinal fusion is also affected by a variety of local and host factors. Local factors such as excessive trauma, tumor, and

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scarring from multiple fusion attempts are detrimental. Host factors that are known to be inhibitory to bone healing include nicotine, malnutrition, corticosteroid, or nonsteroidal antiinflammatory drug usage [3].

Graft Properties

Bone graft material promotes bone healing through osteogenecity, osteoconductivity, osteoinductivity, or a combination thereof [2]. A graft's osteogenic potential is determined by its cellular content, specifically the number of osteogenic precursor cells capable of differentiating into bone-forming cells. Osteoconduction is a physical attribute of a graft that permits it to act as a scaffold allowing vascular and cellular invasion and proliferation. A purely osteoconductive graft ideally resorbs over time and is replaced with new bone formation in a process referred to as creeping substitution. Osteoinduction is a molecular level process whereby specific growth factors stimulate the recruitment of undetermined mesenchymal cells and facilitate their differentiation into chondrogenic and osteogenic cells. Additional important properties of bone graft include biocompatibility and mechanical stability. An ideal bone graft provides all of these elements, is available in sufficient quantity, and causes minimal morbidity to the patient.

Alternatives to bone graft can be divided into graft extenders, graft enhancers, and graft substitutes [7]. Graft extenders allow the use of less autogenous bone graft or the same amount of graft to be stretched over a larger area with a similar fusion rate. Graft enhancers increase the rate of spinal fusion when combined with the standard or decreased amount of bone graft. Graft substitutes are used in place of bone graft to provide equivalent or superior fusion rates.

Autograft

Fresh autogenous bone graft is bone transplanted from one part of an individual to another anatomic site. Autograft provides the aforementioned necessary elements of bone graft material and therefore has long been referred to as the gold standard in relation to spinal fusion. However, the osteoinductivity of autograft may not be as substantial as once thought, as autograft is mineralized and the BMPs are not completely exposed. Advantages include complete osteointegration and no risk of donor-associated or immune-mediated reaction. However, it is not necessarily an ideal bone graft. Some major disadvantages exist, including limitations in graft availability and quantity. Patients who are undergoing multisegmental fusion or revisions in which graft has already been harvested may not have sufficient graft to accommodate their needs. In addition donor site morbidity has been reported to be as high as 40 %, with some patients complaining of donor site pain months after the procedure [8, 9].

Posterior iliac crest is the most commonly used site for harvesting bone graft, with the anterior iliac crest, rib, and fibula providing other options. Graft can be harvested as cancellous, cortical, corticocancellous, vascularized, and bone marrow alone. Cancellous grafts contain a greater amount of osteoconductive, osteoinductive, and osteogenic elements, but possess little structural stability [2]. In addition, cancellous bone has a trabecular structure that allows more rapid graft angiogenesis and influx of osteoblastic cells. New bone is formed initially on existing trabeculae, but eventually the grafted tissue is resorbed and replaced [10]. As the spine is stressed, the fusion mass is remodeled into a mature fusion, typically over a course of 6 months in humans. Cortical bone has lower biologic potential than cancellous bone due to a limitation of viable cells and lower surface area per unit volume, affecting the osteogenecity and osteoconductivity, respectively. Cortical bone is incorporated by invasion of the graft's preexisting haversian canals by host blood vessels and cells [2]. The major advantage of cortical graft is its ability to provide mechanical support to resist compressive loads, which provides utility as anterior interbody graft. However, the strength of cortical graft is not constant from implantation. Osteoclastic resorption is coupled with new bone formation, leading to an initial weakening of the graft of up to one-third prior to consolidation [11]. Corticocancellous grafts are a hybrid exhibiting some structural stability with elements of the porous structure of cancellous bone. Local bone graft tends to be morselized cortical or corticocancellous bone graft. Vascularized bone grafts transplant bone along with vessels to provide a viable graft but are associated with significant donor site morbidity that limits their use to situations where the recipient bed is especially compromised.

The utility of bone marrow aspirate (BMA) in spinal fusion is dependent on the concentration and viability of osteogenic precursor cells. There are multiple animal studies demonstrating effectiveness of bone marrow alone as graft material; however, this data in humans is more limited [12–14]. This is in part due to the large variability in available stem cells in bone marrow depending on the location and method of harvest as well as host factors such as age. Marrow is thought to contain stem cells on the order of 1 in 50,000 in young individuals compared to 1 per two million in the elderly [15]. Muschler et al. showed a mean of 2,400 osteoblastic progenitors in a 2 mL aspirate of bone marrow from the iliac crest [16]. When performed, aspiration should be limited to 2 mL for each aspiration site due to the rapidly declining number of stem cells caused by dilution with peripheral blood. In addition, there is a suggestion that the vertebral body may be a more suitable site for bone marrow aspirate than iliac crest [17]. Centrifugation and

concentration techniques can potentially increase the concentration of the target cells manyfold [18]. A commercially available collagen ceramic composite was developed specifically for use with bone marrow aspirate. There is limited clinical data with this product, but one recent clinical study showed a slower fusion rate but equal clinical outcome with the use of local autograft and the carrier/BMA compared to local autograft with cancellous allograft in posterolateral lumbar fusion [19]. In addition, a study by Minamide et al. in an animal posterolateral spinal fusion model showed that a high number of bone marrow cells (1×10^8 cells/mL) are needed to achieve fusion as a stand-alone bone graft alternative [20]. Such a number may not be obtainable even in marrow concentrate. Despite recent advances, the role of bone marrow in spinal fusion has yet to be defined.

Traditional rates of fusion using iliac crest autograft have varied substantially, depending on location of fusion, outcome criteria, patient characteristics, internal fixation, number of levels, and underlying pathology [21]. Anterior cervical fusion rates with iliac crest and plate fixation can exceed 97 %. Posterior cervical fusion rates are 93–100 %. Posterolateral lumbar fusion with autograft tends to be associated with the highest pseudoarthrosis rates, ranging from 5 to 44 %. Studies investigating autograft alone in the setting of minimally invasive techniques are limited. Recently, Kasliwal et al. evaluated 40 patients who underwent minimally invasive transforaminal lumbar interbody fusion (MITLIF) with pedicle screw fixation and a cage filled with local bone shavings [22]. The authors used computed tomography (CT) to evaluate fusion and Oswestry Disability Index (ODI) and visual analog scores (VAS) for clinical assessment. Fusion was demonstrated in 67.5 % of patients, but clinical outcome was graded as good to excellent in 92 % of patients, independent of fusion status.

Allograft

Allograft is tissue transplanted from one individual to another within the same species. There are multiple advantages of allograft bone over harvested autogenous bone graft. Allograft bone is available in vastly greater quantities than autograft. It is available in various formulations and can be obtained from any bone, leading to greater options in shape and size. Allograft also eliminates the morbidity associated with harvest of autogenous bone graft. Disadvantages include limitations in their effectiveness and the potential for disease transmission and immunogenicity associated with transplanted tissue.

Most bone banks adhere to guidelines set forth by the American Association of Tissue Banks with respect to procurement, processing, and sterilization of donated bone grafts, although there may be variations between banks [23]. The properties of allograft can be highly dependent on these techniques. The graft is available in fresh, frozen, and freeze-dried varieties [24]. Fresh allograft does not utilize any preservation techniques, retaining its structural property and cellular content. The donor cells and cell fragments can elicit an intense immunogenic rejection response. In addition, fresh allograft has a greater potential for disease transmission, limiting the use of fresh allograft in spinal fusion. Frozen allograft is cooled and stored at −70 °C, reducing immunogenicity and providing a shelf life of 5 years. Studies have shown that deep frozen bone retains its mechanical properties and can be used immediately when thawed [25]. Freeze drying is a similar process but involves reducing the water content to less than 5 %. This process causes the greatest reduction in immunogenicity but also leads to destruction of BMP, unlike the other described techniques, and a decrease in graft mechanical strength. Studies have shown that freeze-dried allograft has 55–90 % of the bending strength of fresh bone [26]. Freeze-dried bone also requires rehydration prior to usage. Sterilization techniques include gamma irradiation, gas, or ethylene oxidation. Heating and autoclaving is avoided due to destruction of matrix proteins. Gamma irradiation less than 3 MRAD does not appear to affect strength. Disease transmission is thought to be rare. An estimate of receiving a bone graft from an HIV-infected donor is less than one in 1.1 million [27].

Allograft incorporation occurs in a sequence of events analogous to autograft integration, culminating in the eventual complete replacement of donated tissue [23]. In addition, significant differences in the histology of incorporation occur based on whether the graft is cancellous or cortical. Cancellous graft shows a more rapid integration, whereas cortical bone remains a mixture of necrotic and viable bone over a prolonged period of time. Structural allograft may take many years to incorporate, and 50–90 % of the graft may still be composed of necrotic tissue at 5 years after transplant. In addition, there is an initial weakening of the graft due to osteoclastic activity preceding appositional bone deposition. Therefore, structural allograft is more dependent on internal fixation for clinical function.

There are multiple studies investigating the use of allograft in spinal fusion in traditional procedures. Results in posterior spinal fusions have been mixed. An et al. studied patients undergoing a lumbar instrumented posterolateral fusion with autogenous iliac crest bone graft on one side and allograft on the other [28]. The autograft fusion rates were 80 % compared to 40 % for frozen allograft, 0 % for freeze-dried allograft, and 50 % for autogenous plus freeze-dried allograft. This study, combined with others, advocates against the use of allograft alone in posterior spinal fusion in adults. Typically, the greatest success with the use of allograft is found in adolescent idiopathic scoliosis [29] and interbody fusions utilizing structural allograft. Arnold et al. showed a

98 % fusion rate at minimum 12-month follow-up of 89 patients undergoing posterior lumbar interbody fusion with machined allograft spacer and posterior pedicle fixation [30]. In addition, structural allograft has been found to be very useful in the anterior lumbar and cervical spine [23, 31].

Demineralized Bone Matrix

The bone-forming capability of demineralized bone matrix (DBM) has been demonstrated for many decades since Marshall Urist initially described it [32]. It is an attractive bone graft alternative as it is cost-effective and readily available from human tissue banks. DBM is a form of allograft bone created by the acid decalcification of cortical bone. The decalcification process removes the mineral component of bone, leaving behind the organic matrix, consisting of 93 % type I collagen, 5 % noncollagenous proteins, and 2 % residual mineralized matrix. This processing destroys the antigenic materials in bone, making DBM less immunogenic. In addition the disease transmission rate of DBM is lower, and the probability that DBM might contain HIV has been calculated to be one in 2.8 billion [33]. However, the decalcification also prevents DBM from providing any structural or mechanical support. The remaining collagen component provides an osteoconductive surface, whereas the proteins, the most significant of which are the BMPs, impart osteoinductive properties [2]. Bone formation with DBM in a submuscular or subcutaneous environment differs from true enchondral bone formation in certain key ways [7]. DBM induces chondrogenesis and the formation of cartilage. However, bone formation occurs after cartilage is resorbed, as opposed to the concurrent formation of bone with calcified cartilage resorption that occurs in classic enchondral bone formation.

DBM is available in a variety of commercial preparations, and its effectiveness has been correlated to formulation. After extraction, DBM exists as a particulate powder. In order to increase handling and delivery, this powder is coupled with a carrier and turned into a gel, putty, paste, or sheet. Various carriers have been used, including glycerol, poloxamer, gelatin, calcium sulfate, lecithin, hyaluronic acid, collagen, and cellulose. The mixture of DBM to carrier often significantly favors the carrier, approximately 85–15 %. Studies have shown variability between different commercially available DBM products [34]. In addition, Bae et al. have shown significant differences in BMP levels in separate lots of the same DBM product [35]. These differences also predicted the performance of the respective product in a rat in vivo fusion model.

Studies in validated animal lumbar spinal fusion models have shown mixed results with the use of DBM alone but have mostly been supportive of its use as a bone graft enhancer or extender [36, 37]. Human clinical trials are more limited. Initial studies suggested that DBM with local graft could lead to similar fusion rates in a posterolateral lumbar fusion model when compared with iliac crest autograft [38, 39]. Prospective clinical data is limited, but Kang et al. performed a randomized clinical trial comparing a commercial DBM matrix with local bone to iliac crest bone graft in a single-level posterior instrumented fusion. The authors found comparable fusion rates and clinical outcomes at 2 years between the groups [40]. Not all trials have been positive [41], however, and due diligence should be used when choosing a DBM.

Ceramics

A ceramic is a solid, inorganic compound bound by ionic bonds. In spinal fusion, this material is used as an osteoconductive and biodegradable bone graft alternative. Ceramics serve as a scaffold for bone formation, and the porosity and pore size of these products can be manipulated during manufacturing to affect potential bone ingrowth. After implantation, ceramics are remodeled in a different fashion than normal bone. They are resorbed by a foreign-body giant cell reaction rather than by osteoclasts [42]. The rate of resorption is determined by the chemical composition, porosity, and surface area. Ideally, this rate would mirror the rate of formation of new bone, but it can vary significantly. A ceramic that is resorbed quickly, such as calcium sulfate, which is reabsorbed in a few weeks, has limited use in spinal fusion [43]. Conversely, a non-resorbable graft may hinder fusion mass remodeling, leave permanent stress risers, and obscure the evaluation of fusion mass on films. Calcium phosphate-based ceramics, such as hydroxyapatite (HA) and tricalcium phosphate (TCP), are the most commonly used in spinal surgery. TCP is absorbed over several months whereas HA can take years for complete resorption. Bone formation occurs into the implanted ceramic at the bone-ceramic interface without a cartilaginous intermediary. This requires the direct apposition of ceramic to bone, a healthy host environment, and interface stability [44, 45].

Ceramics have multiple potential advantages [46]. They avoid donor site morbidity and are nontoxic, nonimmunogenic, and easy to sterilize. They have little risk of disease transmission. Ceramics are available in virtually unlimited quantities and can be cut and molded to a variety of shapes, leading to utility in a variety of indications. However, ceramics are brittle and have little tensile strength or shear resistance, requiring initial shielding. In addition, oftentimes HA and TCP are used in conjunction with other graft materials as bone graft extenders rather than stand-alone bone graft. Composite grafts are currently commercially available, consisting of a mixture of a ceramic with collagen or other bone graft alternative and can serve as a carrier for BMA.

Despite studies with early success [47, 48], preclinical data on the use of ceramics has been mixed. Miller et al. examined a New Zealand white rabbit model undergoing non-instrumented posterolateral lumbar fusion using 100 % autograft, 50 % autograft, or 50 % autograft with either of two commercially available ceramic or collagen composite bone graft extenders. They found no difference in fusion between the 50 % autograft group and the 50 % autograft group with either composite graft [49]. Another study in a similar rabbit model found that the use of a HA/TCP/collagen composite with BMA and a decreased quantity of harvested autograft was equivalent to an increased quantity of autograft alone [50]. In a sheep lumbar intertransverse fusion model, silicated calcium phosphate graft was found to be biomechanically, radiographically, and histologically equivalent to autograft, with both groups achieving 100 % fusion at 6 months [51].

Recent clinical studies are heterogeneous but have been more promising. Ceramics have been used in the cervical spine with some success. Tanaka et al. utilized porous interconnected hydroxyapatite ceramic spacers combined with BMA in patients undergoing open-door laminoplasties for cervical myelopathy [52]. They found comparable bone bonding to autogenous spacers on postoperative CT scans with good clinical results. In the lumbar spine, results are more varied. A retrospective study of 42 patients undergoing 1- or 2-level lumbar instrumented posterolateral fusions for degenerative disorders utilizing silicate calcium phosphate-based ceramic showed a 76.5 % fusion rate at 2 years with statistically significant back and leg pain scores [53]. Park et al. performed a retrospective review of 32 patients who underwent posterolateral lumbar fusion using a TCP product and found an 83.3 % fusion rate on CT at 12 months after surgery [54]. Yamada et al. advocate a hybrid technique using porous TCP, percutaneous harvested bone graft, and BMA [55]. In a prospective, comparative study they compared this technique vs. local bone graft alone and found a significant difference at 6 months after surgery, with similar rates at 2 years. However, their control was local bone graft, not ICBG, placed on the contralateral side of the same patient. In a similar case–control study, the ICBG was used on one intertransverse space and coralline hydroxyapatite with either ICBG or local bone was used on the contralateral space [56]. In this study, local bone mixed with ceramic failed to yield a satisfactory fusion rate. However, as will be discussed in upcoming sections, ceramic mixed with human growth factors has shown positive results in multiple studies. Given the heterogeneity of the compounds used and results, it is difficult to formulate a blanket recommendation on the use of ceramics in spinal fusion at this time. Although ceramics appear reasonable for use as bone graft extenders or enhancers, caution should be exercised before using them as a stand-alone bone graft substitute.

Growth Factors

Numerous growth factors are involved in osteoinduction during bone formation. They are involved throughout the process of cellular proliferation, differentiation, and bone matrix formation. The BMPs belong to the TGF-B superfamily and play a vital role in this process [2]. BMPs attach to specific receptors on the surface of osteoprogenitor cells, activating intracellular secondary messenger systems. Within the cell, small signal molecules termed SMADs modulate the cell response. With a lower concentration of BMPs, mesenchymal stem cells enter the chondrocyte pathway towards enchondral bone formation. With higher concentrations, BMPs can induce direct bone formation, as occurs in intramembranous bone formation [36]. They are divided into three subclasses based on amino acid sequences. Early BMP extracts required a large amount of bone to obtain small quantities of protein, which often times had a heterogeneous mix of growth factors. With advances in technology, the genetic code of the BMPs were first sequenced and cloned in 1988. The BMPs are now available as recombinant proteins and multiple BMPs have been studied in the setting of spinal fusion [57]. Of these, rhBMP-2 and rhBMP-7 are utilized in human applications. The FDA approved rhBMP-2 in 2002 for spinal fusion procedures in skeletally mature patients with degenerative disc disease at one level from L4 to S1 in conjunction with an FDA-approved interbody fusion device via an anterior approach. In 2004, rhBMP-7 received FDA approval as a substitute for autogenous bone when attempting revision posterolateral lumbar fusion in compromised patients. In addition, rhBMPs have been studied and used in multiple off-label applications. One study estimated that at least 85 % of principal procedures utilizing BMP were off-label [58].

The delivery system of rhBMP is important to its effectiveness, as rhBMP is a water-soluble protein that will diffuse away from the implantation site if not confined to region of interest. The diffusion can lead both to an attenuation of the osteoinductive capacity of BMP and an increase in side effects. Before implantation, the rhBMPs are attached to an appropriate carrier to restrict them to the graft site and control the rate of release. The ideal carrier is still under investigation, but various carriers have been studied, including ceramics, collagen, autograft, DBM, and polylactic acid polymers. In a recent study using New Zealand White rabbits undergoing posterolateral fusion, Lee at al investigated the use of an rhBMP-2 long-term delivery system utilizing heparin-conjugated PLGA nanospheres [59]. The authors found an increased spinal fusion rate and Young's modulus of the fusion mass in the long-term delivery group compared to short term. Currently, rhBMP-2 and rhBMP-7 are available for human use with a purified Type I bovine absorbable collagen sponge.

Multiple animal studies have demonstrated the bone-forming capability of rhBMPs. Both rhBMP-2 and rhBMP-7

have been used as bone substitutes for autograft using various carrier matrices in anterior and posterolateral spinal fusion models in rats, rabbits, dogs, sheep, and nonhuman primates with success [60–64]. A recent animal study of interest was performed by Taghavi et al., evaluating the use of a BMP binding peptide that binds rhBMP-2 in a rodent posterolateral fusion model. The authors suggested that its use might result in prolonged exposure of BMP to the fusion site, require smaller amounts of rhBMP-2, and reduce side effects [65].

In humans, anterior lumbar fusion is the original indication for rhBMP-2. A prospective randomized pilot trial compared anterior interbody fusion with the use of a tapered cylindrical threaded case with either ICBG or rhBMP-2/collagen sponge for single-level lumbar degenerative disc disease. All 11 patients who received rhBMP-2 showed radiographic fusion, compared to two of three patients in the ICBG group. Clinical outcomes were similar [66]. This was confirmed in another prospective randomized study comparing rhBMP-2 and ICBG in anterior lumbar interbody fusion [67]. The authors found that 18/22 patients (82 %) who received rhBMP-2 had bone formation outside of the cage, compared to 10/20 patients (50 %) who received ICBG. Mummaneni et al. have studied the use of rhBMP-2 for TLIFs, within and anterior to a cage, and found it to be a safe alternative to ICBG alone, with a rapid creation of interbody fusion [68]. In addition, rhBMP-2 has also been used successfully with an interbody femoral ring allograft, protected by pedicle screws [69].

Posterolateral lumbar spinal fusion is another area where rhBMPs have been shown to be effective. Boden et al. performed a prospective randomized clinical pilot study for a single-level posterolateral lumbar fusion using an experimental carrier [57]. Patients were randomized to groups with pedicle screw instrumentation with autograft or rhBMP-2 or rhBMP-2 alone. On each side, 20 mg of rhBMP-2 was delivered on a hydroxyapatite/TCP carrier. The radiographic fusion rate was 100 % for the rhBMP-2 group with or without instrumentation and 40 % in the autograft/instrumentation group. In addition, the rhBMP-2 groups had faster improvements in Oswestry scores. Dimar et al. performed a prospective, randomized study comparing ICBG to rhBMP-2/compression resistant matrix for single-level lumbar degenerative disease. There were 45 patients in the iliac crest group and 53 in the rhBMP-2 group. There was no significant difference in outcome measures, but the fusion rate was lower in the ICBG group (73 %) vs. the rhBMP-2 group (88 %) with a p-value of 0.051. Singh et al. performed a prospective CT analysis of posterolateral lumbar spine fusion comparing ICBG vs. ICBG with rhBMP-2/ACS. The authors found a 97 % fusion rate in the rhBMP-2 group compared to 77 % in the ICBG group at 2 years, without any evidence of soft tissue ossification, dural ossification, or laminar bone regrowth [70]. Hamilton et al. investigated the use of rhBMP-2 in disabled to bedridden elderly patients who underwent multilevel total lumbar laminectomy and uninstrumented fusion [71]. The authors found that, of 47 patients available for follow-up, 80 % appeared fused and more than 85 % had improved pan and function scores. They suggested that rhBMP-2 might be a useful alternative in an elderly population. There appears to be significant support to the use of rhBMP-2 in posterior spinal fusion, and some authors have suggested a Grade of Recommendation of 1A for its use in this indication [31].

rhBMP-7 has shown some clinical success in posterolateral lumbar fusions. In a prospective, randomized controlled pilot study comparing rhBMP-7 to ICBG in the treatment of symptomatic lumbar stenosis with degenerative spondylolisthesis, Vaccaro et al. found a 55 % fusion rate in the rhBMP-7 group vs. 40 % in the autograft group [72]. A 20 % improvement in Oswestry score was identified in 85 % of the rhBMP-7 group vs. 64 % of the ICBG group. Although the fusion rate is lower than seen in studies for rhBMP-2, this can potentially be explained by the authors performing an uninstrumented fusion. In a follow-up study, Vaccaro et al. performed a similar study in 335 patients who were randomized in 2:1 fashion to receive either rhBMP-7 or autograft. The authors found that rhBMP-7 was statistically equivalent to autograft with respect to their primary end point, which was modified overall success [73]. Kanayama et al. performed a prospective randomized controlled study evaluating rhBMP-7 in instrumented posterolateral lumbar fusion. When compared with local autograft with HA-TCP granules, the rhBMP-7 group showed similar radiographic fusion rates. All of the radiographically fused patients underwent surgical exploration and histologic assessment. Of the presumed fused patients, all had evidence of new bone formation but only 4 of 7 rhBMP-7 patients and 7 of 9 HA-TCP/autograft patients had solid fusion. Given the available data, it appears that rhBMP-7 promotes bone formation, but further investigation is required to define its role in spinal fusion surgery.

The use of rhBMPs in the cervical spine is more controversial. Baskin et al. performed a prospective, randomized controlled cervical fusion study using fibular allograft ring and an anterior cervical plate with either ICBG or rhBMP-2/collagen sponge [74]. At 2 years the rhBMP-2 group had a 100 % fusion rate and mean improvement in neck disability and arm pain scores superior to ICBG. A prospective nonrandomized study compared allograft bone and rhBMP-2 to ICBG in primary anterior cervical discectomy and fusion (ACDF) [75]. The dosage of rhBMP-2 used was 0.9 mg per level. The authors showed similar results in terms of patient outcomes and fusion rates but higher dysphagia in the BMP group. In the posterior cervical spine, a retrospective review of 204 consecutive patients undergoing posterior cervical

fusion showed that patients who received BMP had a higher rate of fusion and lower rate of instrument failure without a difference in perioperative complications [76]. However, these patients also had a higher rate of recurrent/persistent neck pain.

The safety profile of rhBMPs in the lumbar spine has been investigated extensively. In a retrospective review of 55,862 cases of spinal fusion, there was no significant difference between fusions with and without BMP with regard to overall perioperative complications (8.4 % vs. 8.5 %; $P=0.5$) in the thoracolumbar and posterior cervical spine [77]. In a study of rhBMP-7 in the lumbar spine, there was no evidence of local or systemic toxicity of ectopic bone formation [73]. In addition, animal studies have shown a lack of systemic toxicity, which is thought to be the result of rapid systemic clearance (half-life 10–15 min) of BMPs [78]. In addition, a prospective cohort study investigating blood serum antibodies of patients treated with rhBMP-2 showed low and transient formation of anti-BMP-2 antibodies which did not have any clinical sequelae [79]. Vertebral body osteolysis appears may occur with the use of BMP, but does not appear to affect the rate of fusion or final outcome [80]. There is also some limited data suggesting that minimally invasive posterior interbody fusion with rhBMP-2 may be associated with radiculopathy or heterotopic bone formation [81, 82]. However, the overall clinical significance of these findings has yet to be determined, and there has been no link between the use of rhBMP-2 in posterolateral lumbar fusion and radiculitis. In addition, Glassman et al. suggest that rhBMP-2/ACS can be used safely in posterolateral lumbar fusion in the presence of a repairable dural tear [83]. At this time, no definitive link between rhBMP-2 and cancer has been proven. A retrospective cohort study using Medicare claims data in 93,654 elderly patients who underwent lumbar fusion study did not reveal any association between exposure to BMP and an increase pancreatic cancer [84]. There is also suggestion that BMP may be inhibitory to cancer. A rat study showed that local administration of rhBMP-2 in a metastatic breast cancer model actually decreased local tumor growth and delayed the onset of paresis [85]. A recent article suggested that the rate of complications associated with rhBMP-2 might be higher than originally thought [86]. The association between rhBMP-2 and retrograde ejaculation (RE) has come under scrutiny. Some authors contend that the rate of RE is higher after anterior lumbar interbody fusion (ALIF) with rhBMP-2 compared to controls [87]. Lindley et al. found similar RE rates between patients treated with artificial disc replacement and patients treated with anterior lumbar interbody fusion and rhBMP-2 [88]. However, this is still under investigation.

The use and safety profile of rhBMPs in the anterior cervical spine is a topic of much debate. In a retrospective multicenter review of spinal fusion cases, anterior cervical fusions with BMP were associated with more overall complications (5.8 % vs. 2.4 %; $P<0.001$) and more wound infections (2.1 % vs. 0.4 %; $P<0.001$) than fusions without BMP [77]. In addition, there are reports of retropharyngeal swelling, hematoma formation, and airway obstruction [89]. These concerns led to an FDA warning regarding the use of rhBMP in the cervical spine. Some authors attribute these complications to the use of high dose (up to 2.1 mg/level) of rhBMP-2 and placement of sponges outside of a contained spacer [90]. Dickerman et al. suggested that rhBMP-2 could be safely used in anterior cervical fusions, if the dose was limited to 1.05 mg and placed into the center of an interbody spacer [91].

At this time the clinical use of BMPs appears to have a favorable safety and efficacy profile for many spine applications, but there is still investigation to better define the parameters for their use. Critical decision making regarding the surgical site, technique, patient selection, and knowledge of potential side effects is necessary prior to usage of rhBMPs.

Other Biologics

Platelet concentrate is sometimes used in spinal fusion. Platelet degranulation and release of growth factors is a normal part of fracture healing. An autologous growth factor concentrate (AGF) can be created by ultraconcentration of platelets. The clinical results have been mixed. Jenis et al. performed a prospective clinical study comparing anterior-posterior lumbar interbody fusion with wither ICBG or allograft with AGF and suggested equivalence [92]. Sys et al. utilized platelet-rich plasma (PRP) in a prospective randomized controlled trial in posterior lumbar interbody fusion [93]. The authors found no statistically significant difference in outcomes between patients who received autograft alone and autograft with PRP. Hee et al. suggest that despite not increasing overall fusion rates, AGF in TLIF procedures may promote a faster rate of fusion [94]. PRP preparations can be highly variable between manufacturers, and the exact role for AGF in spinal fusion is still under investigation.

Mesenchymal stem cells (MSCs) are self-renewing and pluripotent cells that have been identified in a variety of tissues. Isolation of these cells is possible through density gradient centrifugation and cell culturing techniques. Bone marrow-derived MSCs are a readily available source and can be expanded greatly in number from a small marrow aspirate. Preclinical studies have shown promise. Huang et al. showed that MSCs differentiated into osteoblasts and produced a satisfactory fusion mass in a rabbit posterolateral spinal fusion model [95]. A recent investigation showed that vertebral body bone marrow stem cells are comparable to MSCs obtained from the iliac crest [96]. In a clinical study,

Gan et al. used bone marrow-derived MSCs combined with porous TCP for posterior spinal fusion with a 95.1 % spinal fusion rate in 41 patients [97]. The use of MSCs in spinal fusion shows promise, but clinical studies are limited and MSCs are not widely used in spinal fusion surgery.

Gene therapy consists of transferring a specific DNA sequence to target cells that subsequently express the protein of interest. An exhaustive review of this topic is beyond the scope of this chapter and the authors refer the reader to various journal articles on the subject [98]. However, there are multiple animal studies that have utilized gene therapy to express osteoinductive factors and exhibited a successful spinal fusion [99–101]. The concern for clinical application of these agents is safety. Although this is an area of significant potential benefit and increasing interest, it has not yet reached the arena of clinical use.

Spinal fusion is a multifaceted process that has only been partially elucidated. Although tremendous strides have been made in the past decades regarding the biology and sequence of events in spinal fusion, there are still many areas that require further investigation. Increased understanding has facilitated the creation of various alternatives to the traditional gold standard of autograft that aid in successful spinal fusion. These bone graft alternatives vary widely in their attributes, and it is imperative for the operating surgeon to have a familiarity with the biology of healing, the efficacy of the agents, and their potential side effects, to make an informed decision regarding their use.

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Lasers

9

Christopher A. Yeung and Anthony T. Yeung

Introduction

The topic of lasers in spine surgery is highly controversial. When one performs an Internet search on spine surgery, there are numerous websites emphasizing the use of laser technology as a high-tech treatment option for spinal disorders. Almost every physician and institution have a website and there is intense competition for patients. Thus, "laser treatment" is presented as a high-tech, sophisticated, and less invasive treatment option for patients who are researching surgical options.

Unlike other surgical subspecialties that commonly utilize lasers such as ophthalmology, plastic surgery, urology, vascular surgery, otolaryngology, and gynecology, the use of lasers in spine surgery is not ubiquitous. In fact the majority of spine surgeons do not utilize lasers in their practice and this leads to skepticism, criticism, and equating the use of lasers in spine surgery to a gimmick. This criticism is understandable when one encounters claims of superior outcomes from laser surgery and inferences that the laser is some sort of miracle cure for back pain. In reality the use of the laser is typically a small part of the overall operation and is not the defining factor on whether or not the patient achieves a successful outcome. The laser is simply one of many tools a spine surgeon can utilize to shrink and remove tissue.

In traditional open spine surgeries, there is no significant advantage to utilize lasers since there are already effective and more efficient tools to remove both soft tissue and bone when decompressing nerves and ablating. However, with the development of minimally invasive spine surgical techniques with tubular retractors utilizing both the microscope and endoscope, there is limited exposure. Thus, the typical tools to decompress nerves such as pituitaries, Kerrison rongeurs, and drills are relatively bulky and can significantly obscure the surgical view. In cases of endoscopic spine surgery, these traditional tools will not fit down the working cannulas that accommodate the tools. In these instances small-diameter laser fibers can be used without obstructing the surgeon's view and are effective at shrinking, vaporizing, and removing tissue. In some cases this is the only tool that is feasible and thus lasers facilitate the least invasive of the procedures that are considered minimally invasive spine surgeries.

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Basic Physics of Lasers

Laser stands for light amplification by stimulated emission of radiation and was invented in 1958 by Charles H. Townes and Arthur L. Schawlow [1]. They were attempting to create a device for studying molecular structure. They extended research from microwaves to the infrared region of the spectrum and utilized a series of mirrors to focus these shorter wavelengths. In 1960, a patent was granted for the laser. Townes won a Nobel Prize in Physics in 1964 and Schawlow in 1981.

Light can be amplified and focused into a very intense beam. The light can be of different wavelengths and is classified as ultraviolet (UV) (150–400 nm), visible (390–700 nm), or infrared (greater than 700 nm) as part of the electromagnetic spectrum.

Atoms at their resting or ground state can be excited to a higher energy level when they absorb electrical, optical, or thermal energy. When the atom returns to its ground state, it releases energy as a photon. This occurs naturally and spontaneously. If the atom is hit with another photon while on its descent from the excited state to the ground state, two photons of the same frequency are released. This occurs in phase (coherence) with and in the same direction as the bombarding photon. This process is called stimulated emission and when these photons then stimulate enough atoms to create a population inversion where there are more atoms in the excited stage than the ground state, a powerful coherent beam of energy is produced—emitted radiation.

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Lasers consist of three components: (1) an active medium or lasing medium, (2) an optical cavity or resonator, and (3) an energizing source or pump. The energy source activates the atoms of the active medium within the resonator. The active medium can be a gas, solid, or liquid. Different media produce light at different wavelengths or energies. The resonator contains the active media and is fitted with two parallel mirrors facing each other. The back mirror is 100 % reflective while the output mirror is only partially reflective. The stimulated photons are reflected within the resonator and hit atoms in the excited state, producing more photons. The energy builds and is amplified by the reflected photons. This energy is released through the output mirror in the form of an intense beam of monochromatic (same wavelength), collimated (parallel, nondiverging), and coherent (same direction) light. This beam of light can be focused with precision to a minute focal point (higher power density). This focused energy can cut or vaporize tissue. The beam can also be diffused and spread over a larger surface area to lessen the depth of penetration and produce more tissue coagulation (lower power density).

Laser Interaction with Tissue

The power or energy of the laser is measured in watts (W), a measurement from the International System of Units (SI). This measures the rate of energy conversion. One watt is equal to 1 joule (J) of energy per second. Efficient and effective lasers can produce tissue changes at relatively low watts which limits excessive heat and thermal injury to the surrounding tissue.

Different laser wavelengths interact with tissue differently. The main differences are how they interact with water and pigments. Higher wavelength far and mid-infrared lasers are absorbed well by water and thus can effectively ablate tissues with high water content at low energy levels (W), thus limiting heat diffusion into tissues. Near-infrared lasers are poorly absorbed by water which requires more energy into these tissues and higher heat that can cause thermal damage. Visible and UV lasers are poorly absorbed by water but are readily absorbed by pigment. Thus, they are effective in treating pigmented tissue. Naturally occurring chromophores are melanin in skin and hemoglobin in blood.

History of Lasers in Spine Surgery

In Germany Ascher was one of the first to utilize the CO_2 laser for removal of small spinal cord tumors and meningiomas [2]. He built on his experience with hemostasis and vaporization in the resection of tumors of the brain and spine and applied this to disc surgery in 1985 and performed the first laser discectomy with the Nd:YAG laser [3]. A 400-nm laser fiber was placed through an 18-guage needle into the disc space and fired in short bursts to vaporize disc tissue to decrease the intradiscal pressure. The vaporized tissue was allowed to escape through the spinal needle.

In 1987 Choy reported on the use of Nd:YAG laser for percutaneous laser disc decompression (PLDD) to indirectly decompress the disc space furthering Ascher's technique after conducting 2 years of in vitro basic science research [4]. These in vitro experiments showed that the intradiscal pressure increased 312 kilopascals (1 kPa = 7.5 mmHg) with every 1.0 mL increase in volume after injecting discs with saline. This pressure increased linearly with small increases in volume. This led him to conclude that removal or vaporization of a small amount of nucleus pulposus could significantly decrease the intradiscal pressure in contained disc herniations. Subsequent in vitro experiments showed the intradiscal pressure was decreased an average of 51 % after applying 1,000 J of energy from the Nd:YAG laser fiber. This created laser tracts measuring 10 × 3 mm in diameter [5]. This has formed the biomechanical basis for indirect disc decompression procedures. Clinically Choy reported that 71–75 % of patients treated for radicular symptoms due to nonextruded disc protrusions received good to excellent results based on MacNab criteria [4]. Hellinger, Casper, and others have reported similar success rates with this technique [6, 7].

In 1993 Mayer and Brock reported on the use of spinal endoscopy in combination with laser discectomy which allowed direct visualization of the amount of tissue vaporized. This was a prospective randomized study comparing the laser-assisted posterolateral endoscopic lumbar discectomy (PELD) to traditional posterior discectomy in 40 patients (20 in each group). They found an 80 % success rate in the PELD group compared to 65 % success rate in the posterior discectomy [8]. This was not statistically significantly different.

In 1990 Davis reported 85 % success rate for 40 patients utilizing posterolateral endoscopic laser discectomy with the potassium-titanyl-phosphate (KTP) 532-nm laser [9].

In 1993 Anthony Yeung reported on the potential of using indigo carmine injected into nucleus pulposus as a chromophore to enhance the effectiveness of the KTP/532 laser in posterolateral endoscopic discectomy [10]. In a retrospective study in 2000, he reported a clinical success rate of 70 % using MacNab criteria on 100 patients treated with posterolateral endoscopic discectomy assisted with the KTP/532 laser [11]. Most patients were treated for symptomatic disc protrusions and extrusions with predominant leg pain, but there was a small subset with predominant back pain complaints.

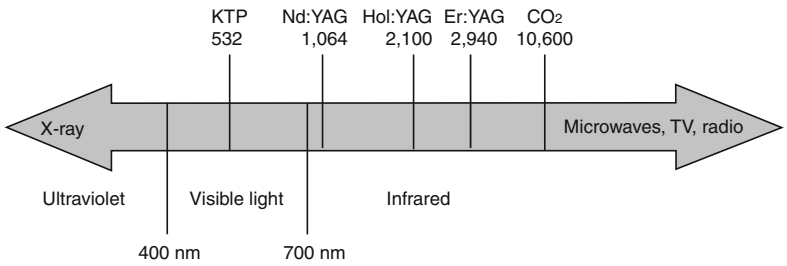

Fig. 9.1 Wavelengths of the common lasers in the electromagnetic spectrum. The holmium: yttrium-aluminum-garnet (*Hol*:*YAG*), neodymium: yttrium-aluminum-garnet (*Nd*:*YAG*), erbium: yttrium-aluminum-garnet (*Er*:*YAG*), potassium-titanyl-phosphate (*KTP*) lasers, and carbon dioxide (CO_2) lasers in nanometers (*nm*)

Knight expanded the use of lasers in spine to include bone removal to help alleviate neuroforaminal stenosis. Knight and Goswami reported on the use of the side-firing Hol:YAG in foraminal decompressions for isthmic spondylolisthesis. In 79 % of patients a good or excellent outcome was obtained with an average follow-up of 34 months based on at least a 50 % reduction in ODI and VAS back, buttock, and leg pain [12]. Of the initial group, only two went on to have spinal fusion. He also reported laser foraminoplasty results on 250 consecutive patients with chronic low back pain (CLBP) and sciatica in 2001 [13]. Inclusion criteria for this prospective study included patients with MRI-proven multilevel disc disease with a combination of back, buttock, or leg pain present for over 1 year resistant to nonoperative treatment. Knight cautioned against an overreliance on purely mechanical concepts of back pain production and felt that neural mediated back pain also arose from irritated and inflamed tissue in the epidural, foraminal, and extraforaminal area. He felt that dynamic repetitive mechanical impingement from foraminal osteophytes and disc protrusions could cause this irritated tissue and that removal of this tissue and decompression of the foramen alleviated the back pain as well as the radicular pain. Pain reproduction with spinal probing of structures near the neuroforamen while the patient was sedated, but in an aware and responsive state, helped determine the source of pain and what structures needed to be addressed. Good to excellent results defined as a 50 % decrease in Oswestry Disability Index and VAS were seen in 60 % of patients, and clinically significant improvement was seen in 73 %, defined as greater than 20 % improvement in the ODI and VAS. No further surgery was required in 95 % of the patients at 30-month follow-up.

Anthony Yeung began using the Hol:YAG side-firing laser to perform dorsal endoscopic facet rhizotomy as an alternative to percutaneous radiofrequency ablation (RFA) in 2006 [14]. The Hol:YAG laser was shown to be effective at thermal ablation of the facet capsule and tissue lateral to the facet joint, including the medial branch of the dorsal ramus. This can even be effective in patients who had excellent pain relief after medial branch blocks, but failed to achieve pain relief after percutaneous RFA. Direct visualization allows for direct confirmation of tissue ablation and thus a more thorough treatment.

Types of Lasers

There are many types of lasers available for use in spine surgery. To be effective and safe, the laser must ablate, vaporize, and coagulate in a precise manner with limited thermal energy into the adjacent tissue. For minimally invasive endoscopic spine surgery, the laser must also be amenable to delivery through fiber-optic cables to work well through the endoscope. The holmium: yttrium-aluminum-garnet (Hol:YAG), neodymium: yttrium-aluminum-garnet (Nd:YAG), erbium: yttrium-aluminum-garnet (Er:YAG), and potassium-titanyl-phosphate (KTP) lasers all can be delivered through fiber-optic cables (Fig. 9.1). The CO_2 laser has excellent tissue properties, but cannot effectively be delivered through fiber and thus has limited use in MIS spine surgery. The Hol:YAG laser is the most widely used laser in spine surgery.

CO_2

The far infrared CO_2 laser has a wavelength of 10.6 μm and is highly absorbed by water. It has good tissue ablation with minimal heat diffusion into the tissues. Despite the good effectiveness and safety of this laser, it is not effectively delivered through fiber-optic cables and is thus impractical to use in endoscopic spine surgery.

HOL:YAG

The Hol:YAG laser is a mid-infrared laser with a wavelength of 2.1 μm. It is well absorbed by water, but not as well as the CO_2 laser. It has the ability to cut, coagulate, shrink, and vaporize tissue, especially tissue with high water content like nucleus pulposus, joint cartilage, and ligaments. This is because it is well absorbed by water. This allows greater tissue ablation after the application of the same amount of energy compared to other lasers. This also helps prevent thermal injury, necrosis, and charring of the tissues compared to other lasers. The depth of tissue penetration is only about 0.4 mm so very precise targeting of the tissue can be accomplished while minimizing damage to adjacent sensitive tissue like a nerve root. It is a pulsed laser which

minimizes heat absorption in adjacent tissues. The pulse width and frequency can both be adjusted. It can be delivered through both straight- and side-firing fiber-optic cables which makes it effective for endoscopic surgery. Because of these characteristics, the Hol:YAG is used routinely by otolaryngologists and urologists and is also the most widely used laser type in spine surgery.

ND:YAG

The Nd:YAG laser is a mid-infrared laser with a wavelength of 1.06 μm. It can be delivered by fiber-optic cables like the Hol:YAG laser. However, the depth of tissue penetration is 3–5 mm and produces more heat in adjacent tissues. This is due to the fact that it has less water absorption and thus transfers more energy to the surrounding tissue. Experimentally it produces more thermal necrosis and charring.

ER:YAG

This laser is also a mid-infrared laser with a wavelength of 2.94 μm. It has a very high specificity for water and produces a minimal thermal damage zone of 40 μm. It is very good at tissue cutting and coagulating and is mostly used in dermatology and ophthalmology.

KTP

The KTP laser uses a Nd:YAG laser beam directed through crystals of potassium, titanyl, and phosphate to produce a laser beam in the green visible light spectrum with a 532-mm wavelength. It is most effective in pigmented tissues and thus use of indigo carmine to stain the white nucleus pulposus has been utilized clinically. Since the laser produces a beam in the visible light spectrum, it was often difficult to see the tissue effect during use due to the scattering of the light unless a filter was used.

Current Uses in Spine Surgery

Percutaneous Posterolateral Laser Discectomy: Indirect Decompression

One of the earliest common uses for the laser was in fluoroscopically guided, posterolateral percutaneous laser disc decompression. This technique relies on the theory that removing a small amount of central nucleus pulposus in a contained disc herniation will decrease the intradiscal pressure and decrease the associated pain and inflammation [5, 15]. This is a blind, fluoroscopically guided technique and similar to other technologies such as automated percutaneous lumbar discectomy (APLD, Nucleotome/Clarus) and Coblation (ArthroCare). APLD uses a powered shaver or nucleotome to remove disc and Coblation utilizes a probe delivering plasma energy to perform the discectomy. A recent review article of PLDD concluded that there is level ll evidence about the subject similar to APLD and pointed out the paucity of randomized clinical trials [16].

The published advantages of PLDD include simple minimally invasive technique, small caliber instruments, documented reduction of intradiscal pressure, low complication rate, and no spinal instability. There are however many disadvantages which include inability to reach subligamentous fragments, no documentation of the area of vaporization, and inability to control the thermal energy spread to the endplates and nerve roots. Most surgeons prefer to utilize lasers under endoscopic visualization to monitor the thermal effects on the tissue, which helps prevent complications.

Laser-Assisted Spinal Endoscopy (LASE)

The laser-assisted spinal endoscopy system has essentially supplanted the previously described percutaneous fluoroscopically guided procedure for indirect disc decompression. LASE integrates a straight-firing Hol:YAG laser, endoscope, illumination, and irrigation in a steerable 3-mm cable. This is also commonly used for a procedure called percutaneous endoscopic laser-assisted annuloplasty (PELA). This tries to accomplish annular denervation similar to what intradiscal electrothermal annuloplasty (IDET) tries to accomplish. While the small endoscope does provide visualization, the quality of the images is far inferior to the optics in the standard rigid lens endoscopes. These procedures are mostly done by interventional pain management physicians. There is limited data to support its use. Lee reported on 30 patients treated for discogenic low back pain with short-term follow-up of 9.7 months. The modified Korean ODI decreased from 79 to 22, the VAS decreased from 8 to 2.4, and the modified MacNab showed a good outcome in 90 %. Longer-term studies are needed [17].

Selective Endoscopic Discectomy with Direct Visualization

The Hol:YAG side-firing laser is one of the most useful tools in posterolateral selective endoscopic discectomy (SED). The small-diameter fiber tip fits down the working channel of the rigid rod-lens endoscope and allows precise tissue removal under direct visualization (Fig. 9.2). Endoscopic visualization is of very high quality, similar to typical knee and shoulder arthroscopy. The side-firing nature of the laser tip can reach tissue that is not amenable to resection with any other tool. Visualized posterolateral SED has proven to be successful in treating all types of disc herniations, effectively relieving sciatica [18–28].

The Hol:YAG side-firing laser is used to vaporize and remove tissue in addition to other tools. Posterior annular

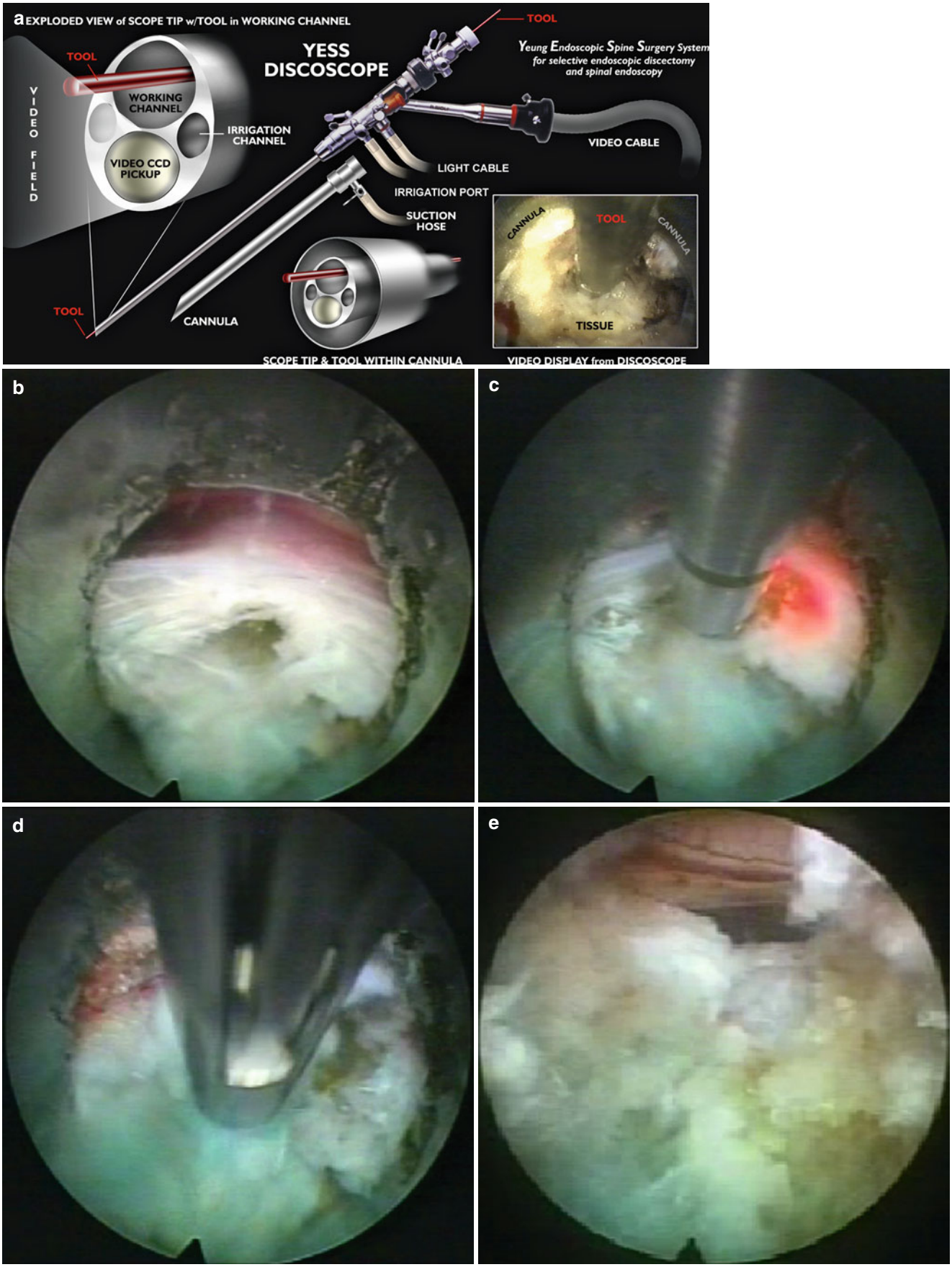

Fig. 9.2 Illustration of the (**a**) endoscope with the laser fiber (tool) in the working channel and (**b**) intraoperative images of the intact posterior annular fibers, (**c**) laser targeting the posterior annular fibers to free up the extruded herniated disc fragment, (**d**) extracting the herniation with pituitary rongeurs, (**e**) visualization of the decompressed traversing nerve root

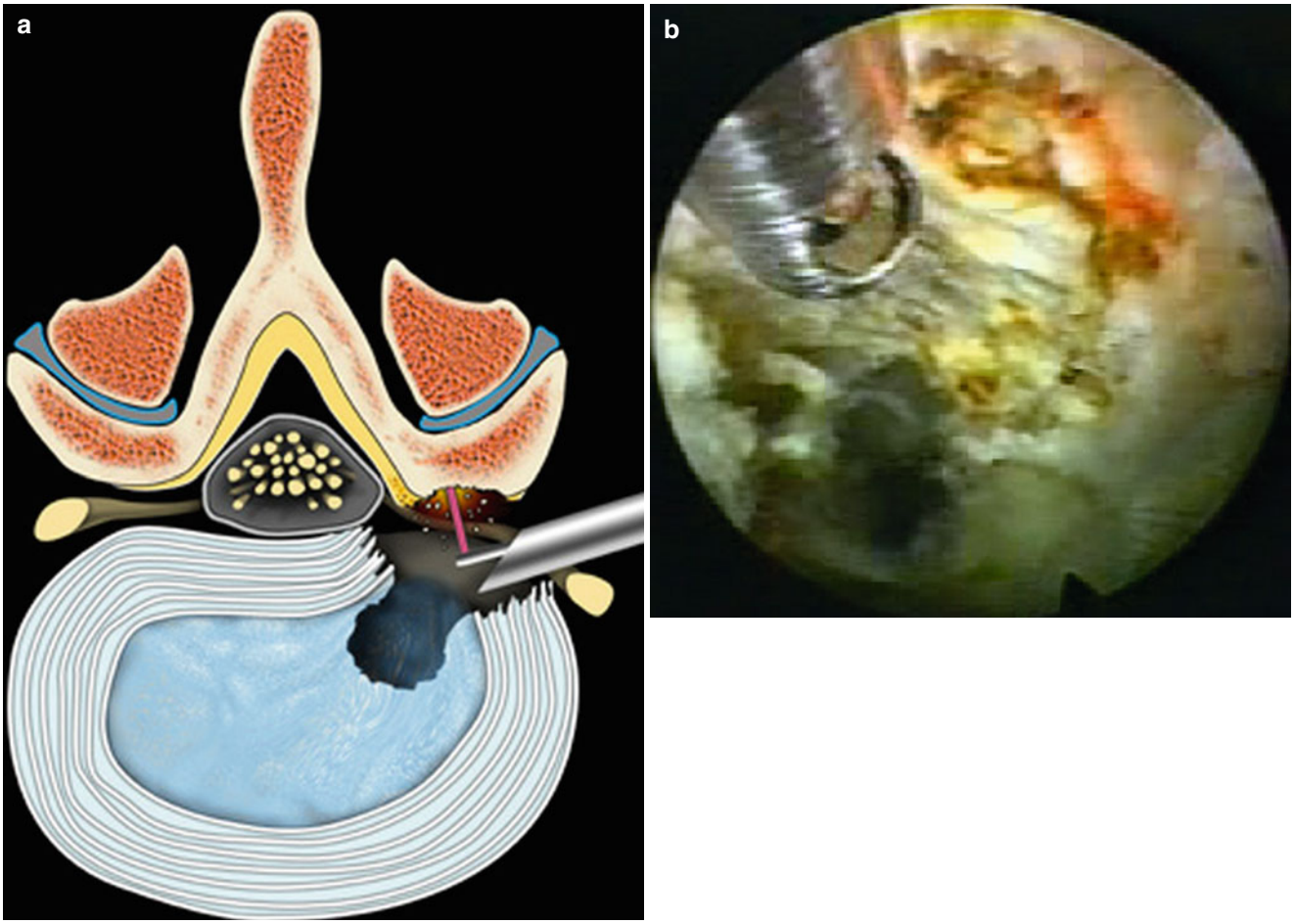

Fig. 9.3 Illustration of the (**a**) position of the endoscope and laser under the superior articular facet. (**b**) Intraoperative endoscopic view of the side-firing Hol:YAG laser removing bone from the ventral aspect of the superior articular facet

fibers can tether the extruded herniation in the epidural space and prevent extraction of the full extruded fragment. The laser is especially useful to release these posterior annular fibers to facilitate complete removal of the fragment with the pituitary rongeur. The laser is also effective at removing bone, specifically the undersurface of the superior articular facet (SAP) that can cause foraminal stenosis. This will allow a shallower trajectory approach to the disc and allow more access to the posterior aspect of the disc where the offending disc herniation may be located. This is used in conjunction with endoscopic burrs. This technique is especially useful at L5–S1 where the pelvic brim limits how far lateral one can start the surgical approach.

Foraminoplasty: Decompression of Foraminal Stenosis

The Hol:YAG side-firing laser has been used along with endoscopic high-speed burrs to remove boney neuroforaminal stenosis and alleviate radiculopathy. The laser is powerful enough to ablate bone and safe enough to operate near the exiting nerve root. Typically the undersurface of the SAP is removed starting at the base of the caudal pedicle and working cephalad towards the tip of the SAP until the exiting nerve root is totally decompressed (Figs. 9.3 and 9.4). Knight has reported 60 % good to excellent results and 73 % with clinically significant improvement with laser foraminoplasty on 250 consecutive patients with chronic low back pain (CLBP) and sciatica as mentioned earlier [13]. No further surgery was required in 95 % of the patients at 30-month follow-up. He also reported successful treatment of neuroforaminal stenosis in 24 patients with isthmic spondylolisthesis with 79 % good/excellent outcomes at 34 months post-op [12]. Chiu, Yeung, and Schubert have also described retrospective results of lumbar foraminoplasty in conjunction with posterolateral selective endoscopic discectomy [14, 29, 30].

Facet Nerve Ablation

Radiofrequency ablation (RFA) of the facet capsule nociceptors and sensory branches of the dorsal ramus is widely

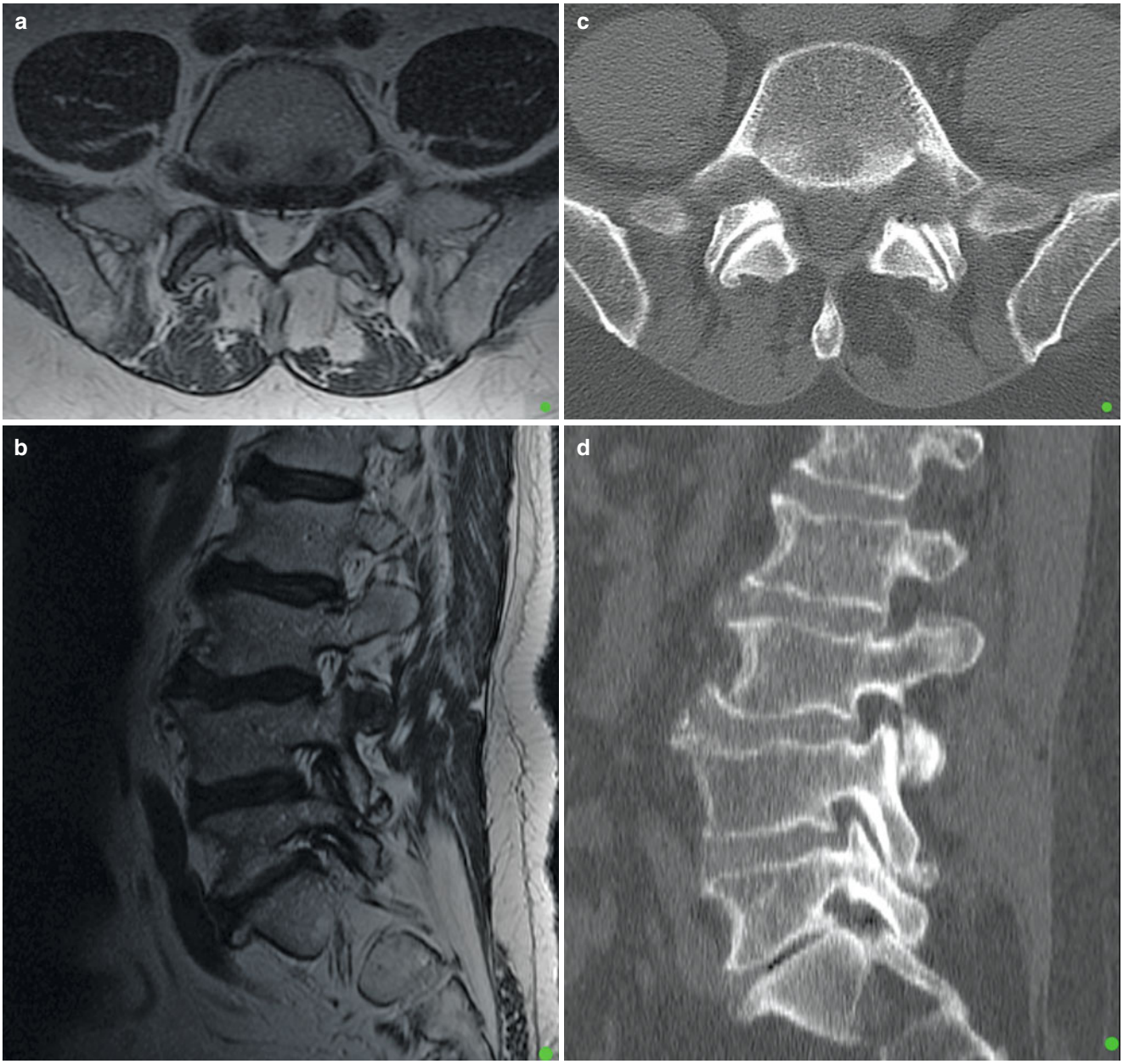

Fig. 9.4 (**a**, **b**) Preoperative MRI showing symptomatic left foraminal stenosis. (**c**, **d**) Postoperative CT scan showing the area of foraminal decompression after removal of the undersurface of the superior articular facet (foraminoplasty)

performed for chronic axial facet-mediated pain mostly by interventional pain management physicians (Fig. 9.5). An alternative is to utilize laser energy to perform the thermal lesioning. This can be done under fluoroscopic guidance similarly to RFA or under direct endoscopic visualization (Fig. 9.6). Visualized confirmation of nerve and tissue ablation certainly has theoretical advantages to ensure appropriate destruction of the painful nociceptors. Dorsal endoscopic rhizotomy provides this visualized feedback as the surgeon can ablate the soft tissue off the lateral facet joint and dorsal transverse process. Radiofrequency probes are tools that are also utilized through the endoscope, but the laser is observed to be more efficient and aggressive at ablating the tissue. The authors' preliminary unpublished experience shows this new technique to provide good relief of facet-mediated pain and may last longer than traditional percutaneous RFA. Often the medial branch of the dorsal ramus is not visualized since it can be buried in an osseous tunnel or within the facet capsule. The intermediate and lateral branch can be seen more consistently. Appropriate candidates for this procedure are identified after medial branch blocks are shown to provide pain reduction, thus identifying the facet joints as pain generators.

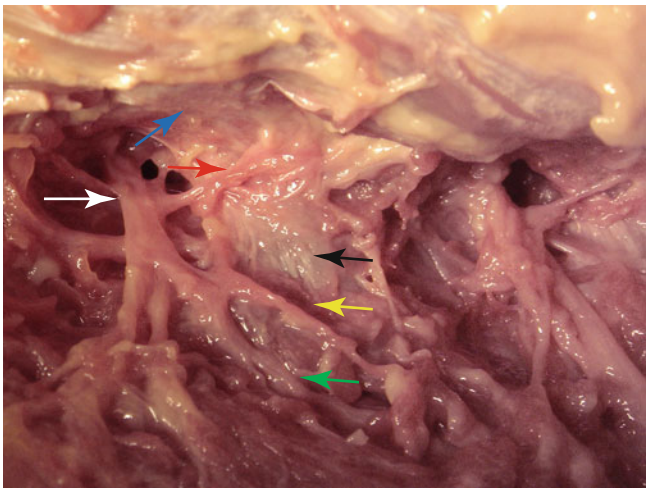

Fig. 9.5 Fresh cadaver dissection of the dorsal ramus and its branches in relation to the transverse process (*black arrow*). The dorsal ramus (*white arrow*) starts ventral to the intertransverse ligament. The medial branch (*red arrow*) innervates the facet capsule (*blue arrow*) and is often in a periosteal tunnel. The intermediate (*yellow arrow*) and lateral (*green arrow*) branches can be found traversing the transverse process more laterally. These different branches are a convenient way to describe the multiple branches of the dorsal ramus, but in reality, there is a complex and variable pattern of branches

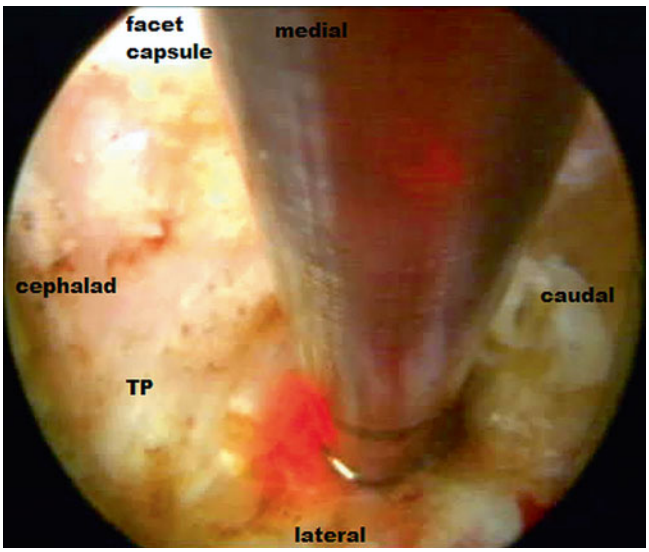

Fig. 9.6 Endoscopic visualization of the medial branch of the dorsal ramus. The soft tissue is ablated along the lateral facet capsule at the base of the transverse process and stripped off the dorsal aspect of the transverse process from the cephalad to caudal extent of the bone. The laser can even ablate the medial branch when it is within a fibrous or periosteal tunnel

Revision Spine Surgery

In cases of failed back surgery, patients' continued radicular symptoms are often attributed to epidural fibrosis and scar tissue around the nerve roots. Since lasers can precisely target tissue and vaporize it, some use a laser to remove this scar tissue around the nerve roots and dura. There is no good data to comment on the efficacy of this procedure and beneficial effects would be difficult to prove given the heterogeneous category of failed back surgery syndromes and the likelihood of many different factors contributing to a patient's persistent pain.

Advantages of Lasers for MIS

Lasers are the smallest effective cutting "knife" and can be delivered through a very small opening. This makes it very useful for MIS surgery. Lasers are also very precise and can be used in tight spaces, adjacent to sensitive structures such as nerve roots. The ability to have side-firing probes and steerable straight-firing probes allows the laser to treat all the hard-to-reach areas in the endoscopic or microscopic field of view. Dissection with lasers also simultaneously can coagulate and achieve hemostasis.

While there are many studies involving the use of lasers in spine surgery, in today's era of evidence-based medicine, there is a paucity of well-designed randomized studies. Most of the studies are level ll or lll based on the United States Preventive Services Task Force (USPSTF) criteria. The first uses of lasers in spine surgery for percutaneous laser disc decompression were dependent on the effects of the laser for the efficacy of the procedure. More recently lasers are used more as an accessory tool in visualized minimally invasive procedures to help decompress nerves and remove tissue, but are not the only tool utilized to accomplish this. There are basic science studies that show the effects of the various lasers on different tissues to form the basis for their clinical use; however, it will be difficult in the future to have clinical studies that support or refute the specific value the laser adds to these minimally invasive procedures when it is just one of many tools.

Complications/Hazards of Lasers

Neurologic injury can occur if the laser is focused on the nerve roots. Excessive use adjacent to the nerve root or dorsal root ganglion can also cause thermal injury. The severity of injury can vary from transient dysesthesia to a full motor and sensory deficit [31]. Sometimes the dysesthesia can be severe and result in a type of reflex sympathetic dystrophy or causalgia. This presents as burning pain, skin hypersensitivity, and sometimes swelling or warmth.

Aseptic discitis can occur as an inflammatory response to any thermal trauma associated with tissue vaporization [32]. This condition is typically transient but, if severe, can lead to progressive degeneration. Aseptic discitis will present with

new axial back pain and possibly a fever. Laboratory studies can show mildly elevated WBC, ESR, and CRP. MRI can show increased degeneration with disc space collapse, modic changes, and inflammation. Bone scan will be positive, but leukocyte scan and cultures will be negative. Histological examination will show signs of acute inflammation but no signs of pyogenic inflammation. This condition needs to be differentiated from infectious discitis.

Osteonecrosis of the endplates can also occur if the laser energy is fired directly at the endplates [33]. This is characterized by increased axial back pain that is nonresponsive to anti-inflammatory medication. MRI will show an arcuate area of increased T2 signal and decreased T1 signal in the subchondral marrow at the site of injury. Steroids are helpful at reducing symptoms of this.

To avoid these complications it is important to avoid using the laser continuously for prolonged periods of time. Continuous use can cause excessive heat to build up in adjacent tissue and cause thermal damage. Intermittent lasering with pauses of even a few seconds can help reduce these complications. Also careful direction of the laser and use under direct visualization is recommended.

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Part III

Surgical Techniques: Minimally Invasive Posterior Decompression

Posterior Cervical Decompression

10

Neil M. Badlani and Frank M. Phillips

Introduction

Posterior cervical decompression is an effective technique for treatment of cervical radiculopathy from various sources of central and foraminal stenosis such as herniated nucleus pulposus, osteophytes, and other degenerative changes [1–3]. Posterior cervical laminotomy and foraminotomy in particular have shown proven results of 92–97 % success in relieving radicular pain [4]. When dealing with cervical pathology, surgical treatment options include both anterior and posterior procedures. Posterior cervical decompressive procedures avoid the approach-related complications of anterior procedures such as esophageal injury, vascular injury, recurrent laryngeal nerve paralysis, and postoperative dysphagia [5–7]. Furthermore, posterior decompressive procedures preserve motion and decrease the long-term sequelae of anterior fusions such as adjacent segment degeneration [8–11].

Open posterior cervical approaches involve sometimes extensive stripping of paraspinal musculature which can result in significant postoperative pain or muscle spasm [12, 13]. Minimally invasive posterior surgical techniques have therefore been developed. Minimally invasive foraminotomy has been shown to achieve equivalent decompression compared to open techniques in cadaveric models [14, 15]. Clinical results have shown equivalent efficacy with a reduction in blood loss, length of stay, and postoperative pain compared to open surgery [12, 16, 17]. The procedure has also been shown to require less surgical time than an anterior cervical discectomy and fusion [18]. This chapter will review the technique of posterior cervical decompression using a minimally invasive tubular retractor system.

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Indications for Procedure

The primary indication for minimally invasive posterior cervical foraminotomy or laminotomy is monoradiculopathy from foraminal compression of a cervical nerve root caused by either bony stenosis or soft disc herniation. This can be for either single or multilevel disease. Other indications include continued symptoms after failed anterior decompression or when an anterior approach is contraindicated such as an active anterior infection, tracheostomy, prior irradiation, or previous radical neck surgery. The ideal surgical candidate has primarily radicular symptoms with minimal neck pain or motor weakness and a positive Spurling's maneuver.

Minimally invasive posterior surgical decompressive techniques can also be expanded to treat patients with bilateral radiculopathy or even symptoms from mild central stenosis. This can be done by either a bilateral approach for performing bilateral foraminotomies or a unilateral approach with extension of the decompression centrally for stenosis. This is an effective treatment for patients with central spondylotic stenosis from ligamentum flavum or facet hypertrophy, without instability, and is most suitable in single-level disease.

Contraindications

Contraindications for minimally invasive posterior surgical decompression include patients with pure axial neck pain without radiculopathy. Patients with both radicular complaints and significant neck pain should be cautioned that their neck pain may not improve after decompression. Cervical instability is a contraindication, as well as any significant kyphotic deformity, as posterior decompression alone may be ineffective in this situation. Preoperative imaging should be carefully checked for an aberrant vertebral artery which may also preclude posterior decompression. Finally, patients with significant myelopathy and a primarily central pathology to their stenosis should be approached very

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carefully with this technique. If the central stenosis is caused primarily by ventral compression, an anterior approach may be more effective.

Technique

Equipment

The procedure requires a tubular retractor system, Mayfield cervical tongs and attachment to a regular operating room table, operating microscope or surgical loupes, high-speed drill or burr, minimally invasive bayoneted surgical instruments for use with the tubular retraction system, and intraoperative fluoroscopy.

Positioning

After induction of general anesthesia and placement of appropriate neurologic monitoring devices, the patient is placed in the Mayfield cervical tongs and carefully transitioned to the prone position. With the Mayfield tongs, the cervical spine is fixed in a neutral or slightly flexed position. The table used must be radiolucent in the area of the cervical spine. The surgical area is shaved. A standard sterile prep and drape of the posterior neck is utilized.

The authors prefer to clamp the attachment arm for the tubular retractor on the side opposite the surgical approach and this should be done during initial setup. The C-arm should also be brought in from the side opposite the surgeon while the microscope should be used from the primary surgeon's side (Fig. 10.1).

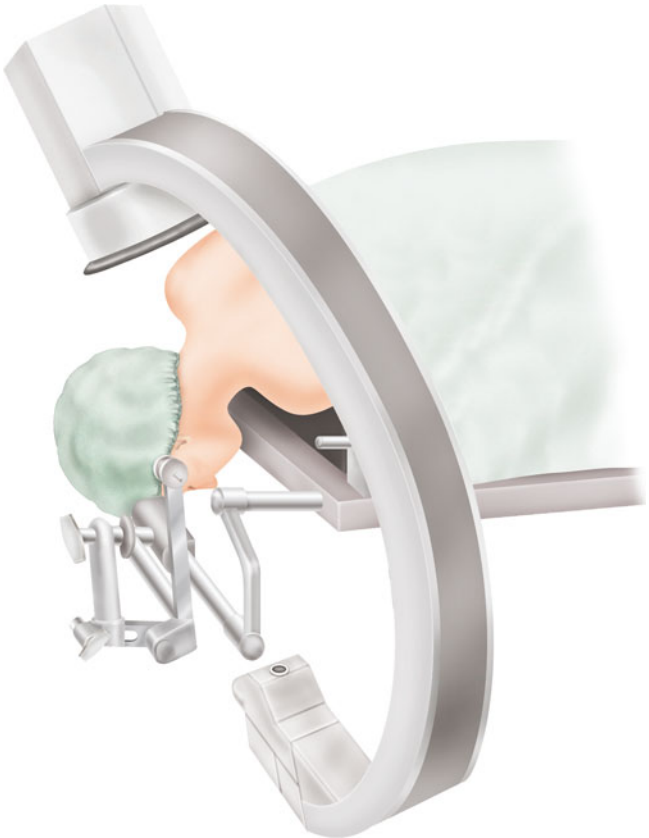

Fig. 10.1 The patient is placed in a Mayfield pin holder with frame extended as far as possible to allow adequate AP fluoroscopic visualization. The fluoroscope is rotated so the line of view is perpendicular to the spinal laminar line (Image provided by Medtronic, Inc. The METRx® System incorporates technology developed by Gary K. Michelson, MD)

Docking and Exposure

Docking the tube in the most ideal position for minimally invasive posterior cervical decompression is a critically important step for a successful surgical outcome. This can be done in a variety of ways with the goal being docking the retractor at the lamina-facet junction, in line with the disc space at the level in question (Fig. 10.2).

Docking on the AP fluoroscopic image has the advantage of direct visualization of the lamina-facet junction making positioning of the tube accurate. Most tubular retractor systems have an initial K-wire that can be passed sharply though the skin and fascia and docked onto the desired position. These should be used with great caution particularly in the cervical spine, because of the risk of inadvertent misplacement. A safer alternative, preferred by the authors, is to localize the incision with a spinal needle which should also be introduced with caution approximately 1.5 cm lateral to the midline at the level in question and aimed toward the

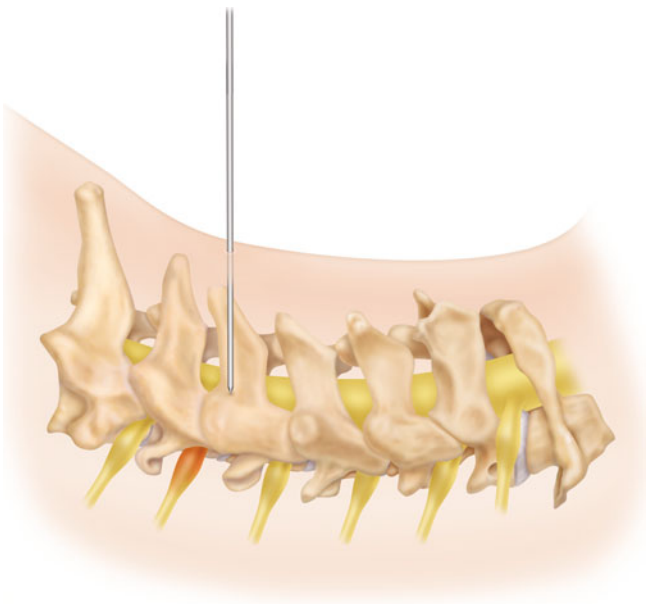

Fig. 10.2 The initial dilator is advanced through the deep cervical fascia and safely docked well lateral on the lateral mass in line with the disc space (Image provided by Medtronic, Inc. The METRx® System incorporates technology developed by Gary K. Michelson, MD)

facet joint to avoid inadvertent injury to the neural elements. Fluoroscopy is then used to confirm the level for the surgical incision and the trajectory of the spinal needle. On the AP image, the level can often be determined most clearly by counting cephalad from the first thoracic rib. This can be particularly helpful in the lower cervical spine in larger patients where this is difficult to see on a lateral image.

After localization, local anesthetic with epinephrine can be injected to minimize bleeding. The incision is made equal in length to the diameter of the tubular retractor, usually 18 mm, and carried sharply down through the fascia as well, maintaining the same incision length. In cases of an ipsilateral decompression, the incision is typically positioned about 1.5 cm lateral to the midline. If a central decompression is to be performed as well, the incision is made slightly more lateral to the midline to allow angulation of the tubular retractor to the contralateral side. A more lateral incision may also be necessary in larger patients.

Blunt finger dissection of the muscles can be performed followed by direct palpation of the facet joint and docking site. Sequential tubular dilators are then used to create the working surgical corridor. . The smallest dilator can be used to carefully palpate the underlying anatomy including the facet joint and caudal and cephalad extent of the lamina. Sequential dilation in the cervical spine should be done with great care using a twisting motion in a controlled fashion with each dilator to avoid inadvertent neural injury. After dilation, a tubular retractor of appropriate length is placed and the dilators removed. The length of tubular retractor selected should be adequate to reach from the skin edge to the lamina and the authors typically use an 18 mm diameter tubular retractor for a foraminotomy (Fig. 10.3).

Once the tubular retractor is docked, secure the tube by attaching it to the table-mounted holder. C-arm fluoroscopy is then used to confirm ideal position. An AP image can be taken directly down the path of the tube to confirm that it has been docked at the junction of the lamina and medial aspect of the facet. The C-arm can then be transitioned to a lateral position and an image can be taken to confirm that the retractor is directly in line with the disc space in question, docked at the inferomedial edge of the cephalad lateral mass of interest. Subtle adjustments should be made at this point prior to the commencement of the procedure to ensure optimal access to the pathology.

Docking can also be done exclusively on the lateral image as well. The incision is made by feel about 1.5 cm lateral to midline in line with the disc space of interest as seen on the lateral image. Dilators are passed as described above and docked at the inferomedial edge of the cephalad lateral mass of interest in line with the disc space (Fig. 10.4). This technique allows for perhaps more precise alignment with the disc space from initial dilation, but requires more use of tactile feedback to confirm that docking is done at the correct position in the AP plane at the laminofacet junction.

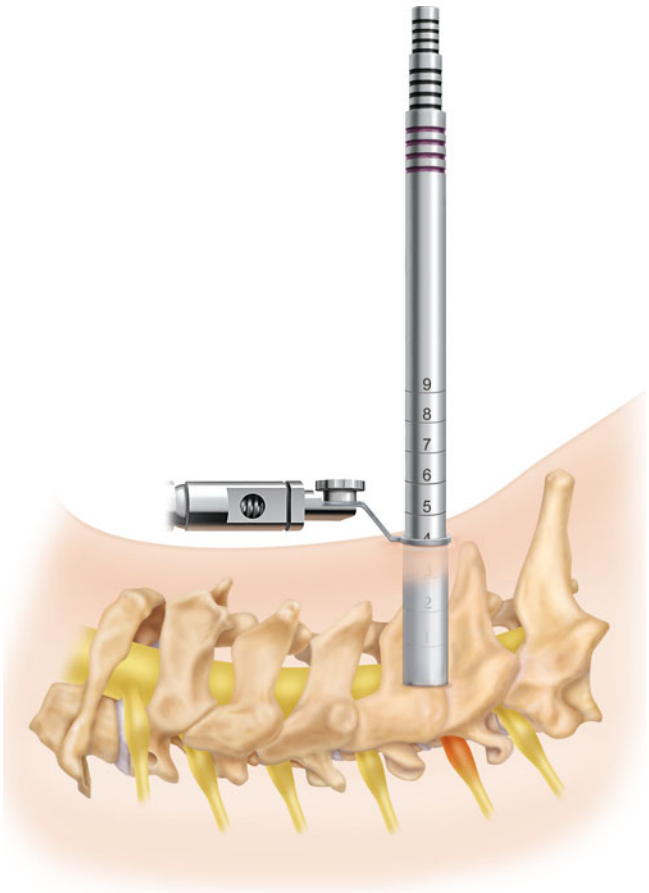

Fig. 10.3 Posterior cervical soft tissue is slightly more dense and requires more care to be taken as dilators are rotated incrementally down to the lateral mass until the desired tubular retractor is in place (Image provided by Medtronic, Inc. The METRx® System incorporates technology developed by Gary K. Michelson, MD)

An operative microscope is introduced for working through the tubular retractor if the surgeon chooses. Palpation of the boney architecture can be performed with a blunt suction tip starting laterally and proceeding carefully medially. Soft tissue should be cleared away completely with monopolar cautery and pituitary rongeur for visualization of the bony structures (Fig. 10.5). Definition of familiar anatomic landmarks is vital including the inferior laminar edge, ligamentum flavum, and the medial portion of the facet joint.

Ipsilateral Decompression

Identify the inferior edge of the cephalad vertebra, the superior edge of the caudal vertebra, and where they come together in a "V" at the medial edge of the facet joint (Fig. 10.6). A small up-angled curette is used to define these edges and the canal and then detach the ligamentum flavum from the undersurface of the inferior edge of the cephalad lamina. A partial laminotomy with a #1 or #2 Kerrison rongeur is helpful to better define the lateral edge of the

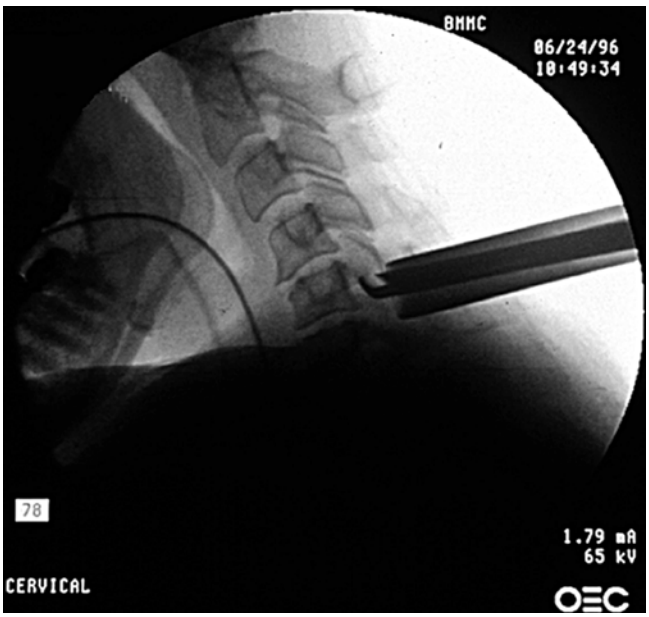

Fig. 10.4 Lateral X-ray of tubular retractor docked in appropriate position in line with the disc space of interest (Image provided by Medtronic, Inc. The METRx® System incorporates technology developed by Gary K. Michelson, MD)

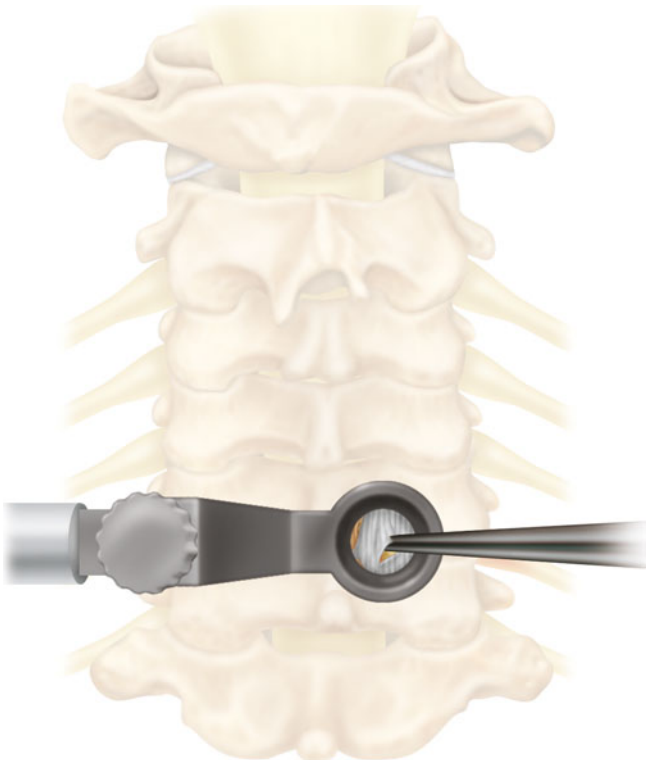

Fig. 10.5 The soft tissue over the lamina and intralaminar space is removed with an extended Bovie on low power and pituitary rongeurs (Image provided by Medtronic, Inc. The METRx® System incorporates technology developed by Gary K. Michelson, MD)

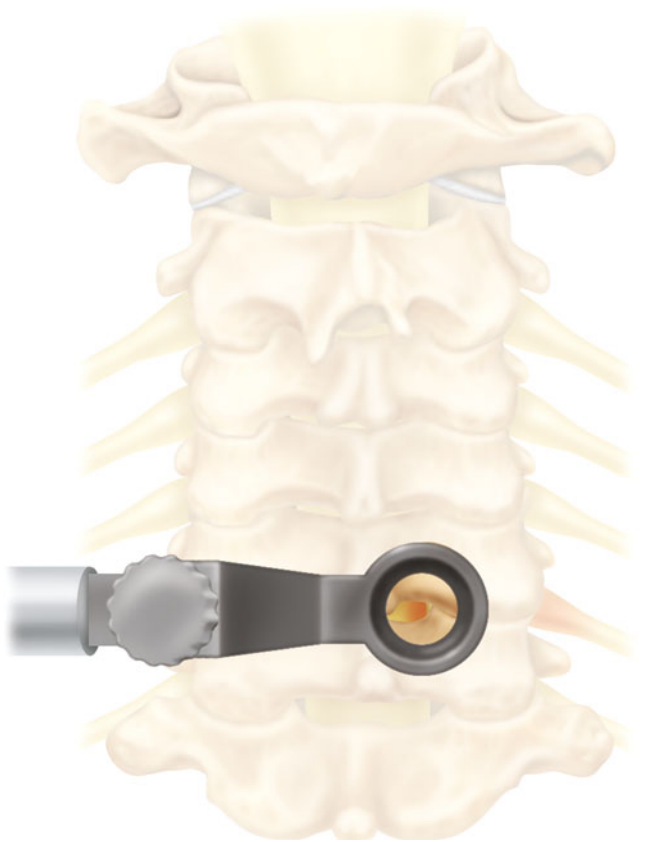

Fig. 10.6 The junction of the two lamina with the medial facet is visualized through the tube (Image provided by Medtronic, Inc. The METRx® System incorporates technology developed by Gary K. Michelson, MD)

spinal canal (Fig. 10.7). Removal of ligamentum flavum in this area can reveal the lateral edge of dura and proximal portion of the nerve root.

The foraminotomy is begun with a 2 mm high-speed burr. Remove bone first from the inferior articular process of the cephalad vertebra proceeding systematically from medial to lateral, superficial to deep. Preserve at least half of the facet joint for stability [19]. Then resect bone from the superior articular process of the caudal vertebra again proceeding systematically from medial to lateral, superficial to deep. The quality of the bone should be noted from bleeding cancellous bone in the middle of the articular process to cortical bone which does not bleed as the foramen is approached. The final wafers of bone which make up the borders of the foramen can be removed with a small footplate Kerrison rongeur or an up-angled curette which is likely safer in conditions of tight foraminal stenosis.

After the bony resection is complete, a nerve hook can be passed into the foramen to confirm adequate room for the nerve root. This can also be used to palpate the superior and inferior pedicles bordering the foramen.

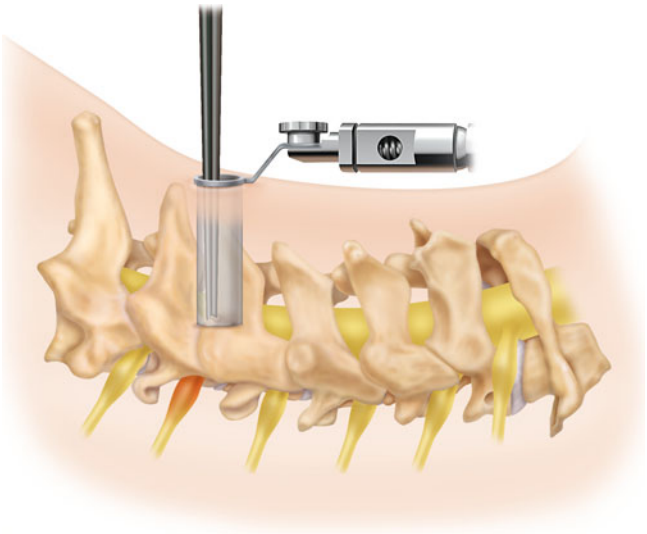

Fig. 10.7 The initial laminar bites are taken in the caudal lamina in a caudal then lateral and then cranial direction as the cranial laminar edge is addressed last (Image provided by Medtronic, Inc. The METRx® System incorporates technology developed by Gary K. Michelson, MD)

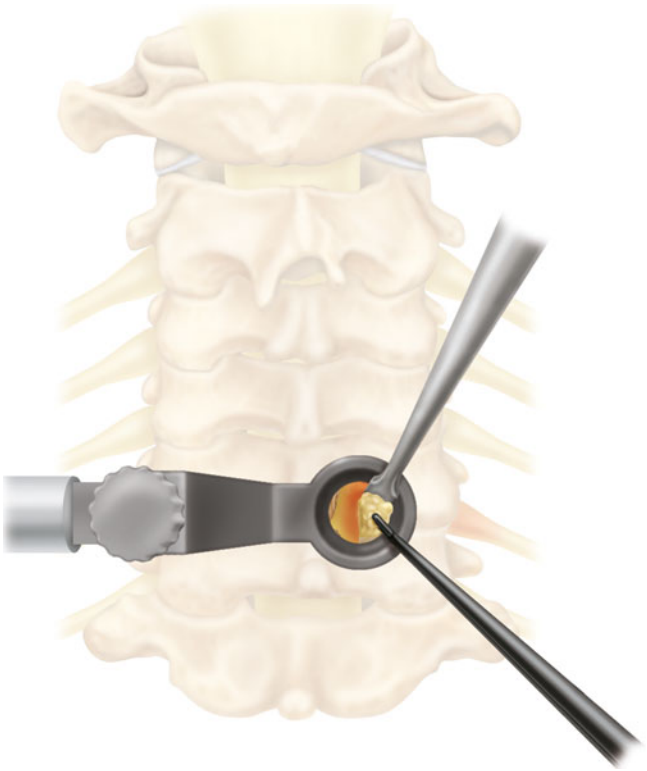

Fig. 10.8 The cervical penfield and hook can be used to gently retract the root in the axilla. The disc will frequently be seen in this location. The bayonetted knife may be used to incise the ligament as needed. The disc material is removed with pituitary rongeurs (Image provided by Medtronic, Inc. The METRx® System incorporates technology developed by Gary K. Michelson, MD)

If a disc herniation is present, this is usually located in the axilla of the nerve root and the root itself is displaced superiorly and laterally. Additional gentle retraction of the nerve root can be done with a blunt suction tip for better visualization of the disc herniation. The nerve hook should be passed ventrally and inferiorly to tease the disc fragment out (Fig. 10.8). Most herniated disc material can be removed or alternatively a down-angled curette can be used to tamp the material ventrally back into the disc space. The epidural venous plexus in this area frequently bleeds and must be controlled with hemostatic agents and bipolar electrocautery when necessary.

After excision of the disc fragments, a nerve hook is again passed to ensure decompression of the foramen. Hemostasis is ensured and the tubular retractor is withdrawn.

Central, Bilateral, or Multilevel Decompression

For multiple levels with unilateral pathology, the incision can be made between the levels of interest. Docking and decompression at each level would then proceed as described above.

For bilateral symptoms, primarily from bilateral foraminal stenosis, there are two options for treatment using minimally invasive techniques. Two separate incisions can be made, each approximately 1.5 cm lateral to midline, and two separate approaches and foraminal decompressions can be performed as described above. This technique of bilateral dilations and laminotomies to remove dorsal compression has been shown to be effective in a series of ten patients with minimal blood loss, excellent outcomes, and no complications or instances of postoperative instability or reoperation at 15-month follow-up [20].

An alternative is a single-incision approach, made directly in the midline, followed by two separate lateral fascial incisions and approaches as described above. This may require a slightly longer midline skin incision and some retraction of the skin with elevation of small subcutaneous flaps to reach the ideal position for the fascial incisions and decompression.

When both sides of the spinal canal require decompression, central laminectomy and bilateral decompression can be achieved from a unilateral approach. The initial incision should be made on the more symptomatic side, particularly of the foraminal pathology. The incision and docking is performed as described above. The procedure begins with an ipsilateral laminotomy with removal of only bone and preservation of the ligamentum. The tube is then "wanded" to approximately a 45° angle off the midline in order to visualize the remainder of the ipsilateral lamina and the base of the spinous process. It may be necessary to tilt the operating table away from the approach side for better visualization of midline and the contralateral side.

A plane should be created with a fine curette between the ligamentum and the undersurface of the spinous process and lamina. The high-speed drill/burr is then used to burr away the lamina, undercutting the spinous process toward the contralateral facet. Generous removal of the undersurface of the spinous process facilitates a safe portal for continued drilling toward the contralateral side, minimizing any downward pressure on the dura and spinal cord. Once the contralateral facet is reached, the ligamentum should be released for the most part. The remaining attachments can be dissected away with a curette and the ligamentum can then be safely removed with Kerrison rongeurs revealing direct visualization of the dural structures and adequacy of decompression. Any remaining compressive elements from the contralateral facet or superior edge of caudal lamina can be removed with Kerrison rongeurs or fine curved curettes.

After the contralateral decompression has been completed, the tubular retractor can be wanded back to the ipsilateral side. Then decompression of the ipsilateral side including foraminotomy can be performed as described above. Adequate hemostasis is achieved, followed by removal of the tubular retractor and closure of the incision. This approach to laminectomy preserves most of the supporting ligamentous structures likely leading to less postoperative kyphosis.

These techniques of minimally invasive posterior cervical decompression can be expanded even further. There have been reports of minimally invasive cervical laminoplasty in cadaveric models [21]. There has also been further advancement recently to include multilevel decompressions and instrumented cervical fusions with a minimally invasive approach [22].

Wound Closure and Postoperative Care

The cervical fascia can be closed using interrupted sutures. However, if it is not possible to reach the fascia in an obese patient, the deep subcutaneous tissues are reapproximated followed by skin closure. Use of a skin sealant along the incision allows the patient to shower in the early postoperative period. A surgical dressing can be used according to surgeon preference.

Most patients can be discharged from the hospital on the day of surgery as this has routinely been reported as an outpatient procedure [23]. No cervical collar is necessary but a soft collar can be utilized to lessen the patient's muscle spasm. Early mobilization is encouraged following an MIS decompression. Most patients have been shown to return to sedentary work in 1 week [24]. Patients are encouraged to walk as much as they can tolerate and only strenuous activity is restricted for about 4–6 weeks. Low-potency oral narcotics or over-the-counter medication such as ibuprofen or acetaminophen are generally adequate for pain control in the postoperative period. Postoperative muscle spasms can be painful after use of the tubular retractors and scheduled cyclobenzaprine can be very helpful to alleviate this.

Pearls and Pitfalls

- Always check the preoperative imaging for an aberrant vertebral artery, as well as understand the anatomic location of the compressive pathology.
- The operative microscope provides optimal visualization of the operative field during the surgical procedure and is encouraged for this type of surgery.
- Before incision and docking, clamp the attachment arm for the tubular retractor to the table and place it in a position near its eventual location.
- Use extreme caution if utilizing a K-wire during docking as inadvertent passage into the dura is a risk. Dock on solid bone of the lamina and lateral mass. Although there are initial risks with docking, compared to an open procedure in which midline structures and the interlaminar space is approached, docking directly on the lateral mass during an MIS procedure avoids the spinal canal during exposure.
- Incise the fascia the length of final tubular retractor before dilation. Proceed with controlled dilation using a twisting motion and avoid the axial force used in the lumbar spine during docking.
- Minimize "wanding" if possible because this can lead to muscle creep making visualization more difficult. Therefore, take the necessary time initially to dock in the best position using fluoroscopy.
- Avoid excessive nerve root retraction. If necessary, drill slightly into the superomedial quadrant of caudal pedicle to allow greater access to anterior pathology without excessive superior root retraction.
- Beware of the anterior motor branch rami of the cervical nerve root which can look like a fragment of herniated disc.
- Preserve 50 % of the facet joint to avoid instability.

Complications and Management

The risks and complications of minimally invasive tubular retractor-based surgery are similar to those of open spine surgery. The risks therefore include bleeding, infection, durotomy, nerve or spinal cord injury, iatrogenic instability, and medical complications. Overall a 2–9 % complication rate has been reported with durotomy and infection being the most common [12].

A learning curve is unavoidable when first utilizing minimally invasive decompression surgery. During this phase, extra time for the procedures, careful technique, and a graduated approach to case difficulty are prudent. Convert to a traditional open approach if necessary. Most

importantly do not leave the operating room until satisfied with the decompression.

Blood loss is usually negligible during this procedure. Avoid dissecting lateral to the facet joint which will cause unnecessary bleeding. The epidural venous plexus can be a source of bleeding and this is best controlled preemptively with hemostatic agents and bipolar electrocautery.

Infection is quite uncommon following tubular-based decompression surgery. In the event of a surgical site infection, traditional techniques of debridement and antibiotic therapy should be pursued.

Dural tears remain a challenge with minimally invasive decompression surgery. Dural tears can be minimized with careful technique but can never be eliminated completely. With minimally invasive surgery, the paucity of wound "dead space" significantly decreases the occurrence of persistent CSF leakage or of a dural-cutaneous fistula in comparison to traditional open surgery. Small, stable dural tears may be successfully managed by placing a small pledgette of a hemostatic agent at the site followed by use of a dural sealant (e.g., fibrin glue). The patient should be positioned with the head of the bed at approximately 45° overnight. Larger tears may require 2–3 days lumbar drainage. Some larger tears may necessitate suture repair.

Neurologic injury is also quite rare and must be minimized through careful technique. In patients with any concerns of significant central cervical stenosis or myelopathy, fiber-optic intubation should be used to minimize neck manipulation. Other neurologic injury is avoided with cautious maneuvers during docking and decompression. Possible causes of neurologic injury arise from excessive cervical root manipulation within a tight foramen or direct dural compression during dilation.

Conclusion

Minimally invasive posterior cervical decompression is a useful approach for patients with symptomatic radiculopathy from foraminal stenosis caused by either bony compression or soft disc herniation without instability or fixed kyphosis. The technique can be expanded to allow for multilevel or central decompression for some patients with cervical stenosis. While a learning curve for minimally invasive decompression should be anticipated, tubular retractor approaches to spinal decompression are able to achieve equivalent clinical results with reduced morbidity when compared to traditional open surgery [12, 16, 17].

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Thoracic Decompression

11

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Surgical Indications and Contraindications

Pathology of the ventral thoracic spine comprises a wide spectrum of diseases including disc herniation, vertebral body pathologic fracture, discitis/osteomyelitis, primary or metastatic spinal tumor, spinal epidural abscess, and trauma. Traditional posterior decompression has limitations on its ability to expose ventral pathology, but surgeons have had greater success with an open posterolateral, lateral, or anterior surgical techniques. Anterior surgical approaches increase the risk of injury to the pleura and underlying lung, mediastinum, and heart. Consequently, the ability to perform a posterolateral or lateral approach to treat midline thoracic pathology is an important tool in the armamentarium of a spine surgeon. Minimally invasive spine surgery (MISS) posterolateral techniques can be successfully applied to treat midline thoracic pathology and will be illustrated in the following two cases: thoracic discectomy and lateral extracavitary corpectomy with spinal reconstruction.

Symptomatic thoracic disc herniations are uncommon spine pathology. The thoracic spine is relatively immobile and the stress forces distributed among its connections to the thoracic cage (ribs, costal facets and ligaments, sternum) decrease the likelihood of disc herniation compared to the cervical or lumbar spine [1]. The rate of surgical treatment for thoracic disc herniations is estimated between 0.5 and 4 % of all disc surgeries; greater than 75 % of thoracic disc herniations are located below T8 [2–7]. A retrospective review performed by Brown et al. [8, 9] and Awaad et al. [9] showed that 27 % of patients with thoracic disc herniations eventually require surgical intervention for myelopathy. Clinical studies have shown that laminectomies have limited success rates for thoracic disc herniation compared to posterolateral, lateral, or transthoracic approaches (57 % vs. 80 %) [2, 3, 5, 6, 10–19]. In addition, some patients suffered worse neurologic outcomes from thoracic posterior laminectomies [2, 8, 15]. Classically, ventral midline thoracic disc herniations (especially calcified discs) are treated with an anterior thoracotomy approach for optimal visualization and safe decompression. However, the potential complications and morbidity are high from this traditional approach [10, 12, 17]. Recent literature has shown MISS techniques for thoracic disc herniations achieve equivalent decompression with excellent patient outcomes [11, 13, 18]. Khoo et al. [14] compared 13 patients with thoracic disc herniations treated by MISS extracavitary approach for thoracic discectomy with interbody fusion to 11 patients treated with the classic transthoracic approach. Their early results showed the MISS group had superior VAS scores, decreased use of narcotics, and a lower incidence of complications. A similar MISS approach to thoracic disc herniations will be discussed in this chapter.

Thoracic vertebral body pathology often presents as axial back pain that is worse with upright posture. Etiologies may include pathologic fracture from osteoporosis, infection, metabolic disease, cancer, or trauma. If the posterior vertebral body cortex is involved with retropulsion of fragments into the spinal canal, compression of the spinal cord can occur, leading to myelopathy. Similarly, dorsal extension of tumor or an epidural abscess can also cause thoracic spinal cord compression without overt vertebral body fracture. Thoracic vertebral body disease can also be approached in a similar fashion to a thoracic disc herniation. Proposed surgical approaches include transpedicular/transfacet, modified costotransversectomy, lateral extracavitary, transthoracic, and thoracoscopic. Similar to open approaches for thoracic disc herniation, however, the limitation in these surgical approaches is imposed by the amount of soft tissue dissection required for appropriate access to the thoracic spine

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pathology. As discussed above, this results in increased postoperative morbidity [19–21].

Surgical indications for thoracic disc herniations and vertebral body pathology are symptomatic patients demonstrating intolerable radiculopathy, myelopathy, or myeloradiculopathy. Surgery is also indicated for diagnosis of pathology, debridement of infections (disc osteomyelitis), cancer resection (primary or metastatic), and stabilization of actual or impending spinal instability (trauma, pathologic fractures). This chapter will focus on minimally invasive spine surgery (MISS) techniques for thoracic decompression. The paramedian MicroEndoscopic Discectomy (MED) for thoracic disc herniation and the MISS lateral extracavitary corpectomy for thoracic vertebral body disease will be discussed.

Preoperative Considerations

Patients with a thoracic disc herniation usually present in the fourth decade of life with mid-low back pain, radiculopathy, or myelopathy [2, 8, 9]. At the time of diagnosis, greater than 70 % of patients demonstrate clinical signs of myelopathy or thoracic radiculopathy [7–9, 16]. Thoracic myelopathic patients typically describe a chronic and progressive *stepwise decline* in their lower extremity coordination and gait ataxia over a period of months to years. Classic descriptions of lower extremity dysfunction include "loss of balance" or "inability to locate their feet" while walking which leads to increased falls. Other complaints may include low back pain, burning paresthesias in extremities, or bladder and bowel changes. On physical exam, patients may exhibit signs of extremity weakness, gait imbalance, positive Romberg sign, hyperreflexia in the lower extremities, clonus, or Babinski's sign.

In contrast, patients with thoracic radiculopathy usually complain of radiating pain in a dermatomal distribution specific to the compressed nerve root(s). The pain may radiate from the midline around the chest or abdomen and be described as a burning pain with associated paresthesias. These symptoms of "chest pain" or "abdominal pain" may be initially misdiagnosed as cardiac or GI in origin. On physical exam, there may be decreased sensation to light touch, pinprick, and temperature in a dermatomal distribution from the compressed nerve root. With chronic compression, there may be evidence of muscular atrophy or diminished to absent reflexes in the abdominal muscles.

A thoracic disc herniation may be seen on CT but is more clearly delineated on a CT myelogram or MRI. CT would be helpful to define the bony detail and determine if the disc is ossified or if there is compression from osteophytes. The MRI can clearly define if the disc is midline or paracentral, migration of the disc, severity of foraminal stenosis with nerve root compression (radiculopathy), and the severity of spinal cord compression (myelopathy) or the presence of spinal cord edema.

Similar to thoracic disc herniations, vertebral body pathology can also present with spinal cord compression and myelopathy. Prominent symptoms include mid-low back pain that worsens with axial loading or radiculopathy from nerve root compression. Further history, physical exam, and diagnostic workup should elucidate etiologies for vertebral body disease: infectious (fever, spine tenderness to palpation, recent infection, IV drug use, immunosuppression), cancer (personal/family history of cancer, bone pain that is worse at night), metabolic (history of GI or renal disease, abnormal endocrine syndromes, osteoporosis), and trauma (fall, assault, car accident).

Imaging of thoracic vertebral body disease should include CT, MRI with and without contrast, and standing long-cassette X-rays. The CT is essential to define the bony anatomy, evaluate for infectious or cancer involvement and for preoperative surgical planning, and detect any fractures and bone quality. The MRI can better define infectious or cancer etiologies, involvement of the nerve roots or spinal cord, or paraspinal extension of vertebral body lesions. Standing long-cassette X-rays are useful to detect any regional or global sagittal or coronal deformities resulting from the thoracic vertebral body disease that may need additional reconstruction. Comparing the supine CT or MRI to the standing long-cassette X-rays can sometimes demonstrate spinal instability (increased kyphosis or subluxation).

Due to the inherent rigidity of the thoracic spine granted by the rib cage, spondylotic changes are significantly less common than in the cervical and lumbar spine. The most common pathologies in the thoracic spine requiring corpectomy are tumors, trauma, and infection. When performing corpectomy, obtaining adequate exposure is critical due to the relative intolerance of the thoracic spinal cord to manipulation and mobilization. Treating the complex pathologies listed above can require significant reconstruction and prolonged recovery due to the anterior transthoracic approach and the need to mobilize ribs and other adjacent critical structures including the lungs, pleura, aorta, and mediastinal contents.

The lateral extracavitary approach was first described by Capener [22] in 1954 and modified by Larson [23–25]. It has since been modified and popularized by numerous spine surgeons [26–30]. It provides a posterolateral approach to the vertebral body and spinal canal without entering the pleural cavity. The approach is predominantly utilized in clinical scenarios where significant canal compromise is present, requiring generous exposure for decompression. Vertebral body collapse in scenarios such as osteomyelitis, traumatic burst fracture, and pathologic fracture due to metastatic tumor is a common clinical indication. While a corpectomy can typically be performed via a transpedicular approach, the trajectory can limit visualization of the posterior vertebral wall necessary for adequate decompression. Alternatively, transthoracic and retropleural approaches provide an excellent corridor for decompression, but patient comorbidities and surgeon preference limit their applicability.

Historically, patient comorbidities and the significant muscle dissection and blood loss required for the lateral extracavitary approach have been the limiting factors in application. Aggressive preoperative patient risk mitigation is essential prior to surgery. Evaluation and optimization of cardiovascular, pulmonary, and hematologic risk factors, including coagulopathy is of the utmost importance. Partnership with an experienced preoperative medical team and anesthesia team is generally encouraged. Appropriate transfusion parameters and careful antibiotic selection are also important.

Prior to any surgical intervention, extensive discussion with the patient and family should be held to ensure appropriate expectations of surgical outcomes. Patients with radiculopathy should have completed a trial of physical therapy, pain management, steroids, or epidural injections prior to conceding a failure of medical management. Decompression of the nerve root typically results in immediate relief of pain symptoms, but weakness and paresthesias may take longer to improve, and recovery can be incomplete. Similarly, patients with myelopathy should be counseled that the surgery is intended to prevent further neurologic decline and while some patients may experience some improvement, the surgery is not designed to return patients to their previously healthy baseline. All potential risks of the surgery including intraoperative complications from surgery or anesthesia and postoperative complications (UTI, wound infection, venous thrombosis) should be clearly discussed with the patient prior to surgery.

In this chapter, we will discuss the available MISS approaches for thoracic decompression: the MISS posterolateral approach for a paracentral thoracic disc herniation and the MISS lateral extracavitary approach for a midline thoracic disc herniation and thoracic vertebral body disease (corpectomy).

Surgical Technique

Operative Setup

The anesthesia and positioning setup is similar for both the MISS posterolateral and MISS lateral extracavitary approaches unless otherwise stated. General endotracheal anesthesia is performed in a routine manner except in cases requiring fiber-optic intubation. Neuromonitoring with motor evoked potentials (MEP), somatosensory evoked potentials (SSEP), and free-run electromyography (EMG) is implemented. An arterial line may be added for cases with spinal cord compression to ensure adequate cord perfusion by maintenance of elevated mean arterial pressure. A Foley urinary catheter is placed if there is concern for an extended length of surgery. Sequential compression devices are used in conjunction with knee-high compression stockings to minimize the risk of deep-venous thrombus formation. Perioperative antibiotics with skin flora (gram-positive) coverage are given prior to incision. Muscle relaxants are usually unnecessary after anesthesia induction as MISS approaches require minimal muscle dissection or retraction.

The head is secured with either the Mayfield head holder or a ProneView protective helmet system (Dupaco, Inc.) and the patient is positioned prone on an open Jackson table. The surgical site is cleaned with alcohol solution and the midline is approximated by palpation of the spinous processes between two fingers and outlined by a marking pen. The surgical site is then sterilely hand-scrubbed with a Betadine solution, painted with alcohol, and reprepped with DuraPrep. The patient is draped in the usual sterile fashion and the fluoro machine is brought into the field to localize the level of pathology (Fig. 11.1). Prior to any surgical incision, the

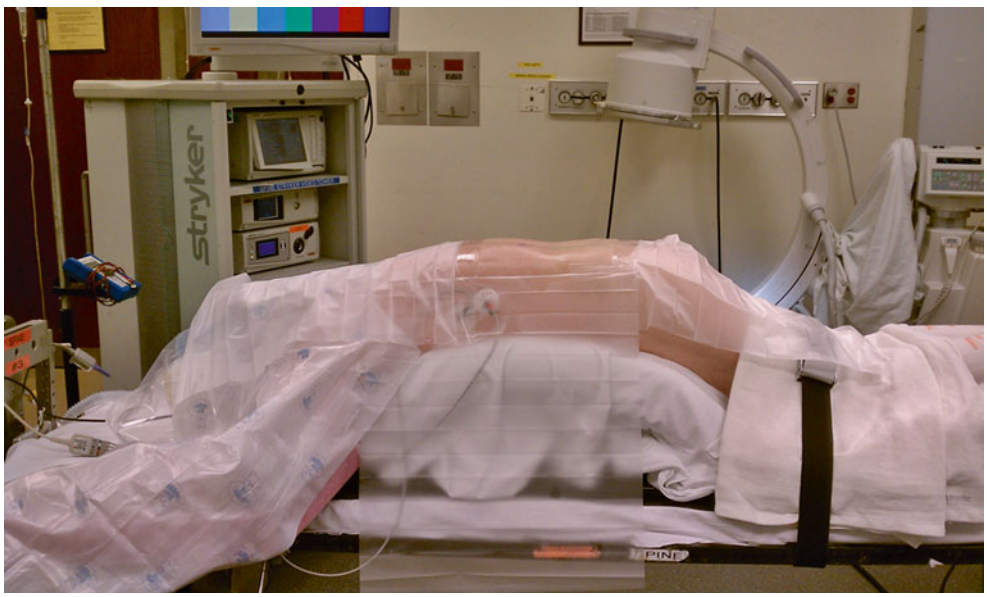

Fig. 11.1 Patient positioned prone on a Wilson frame with fluoroscopy available for localization

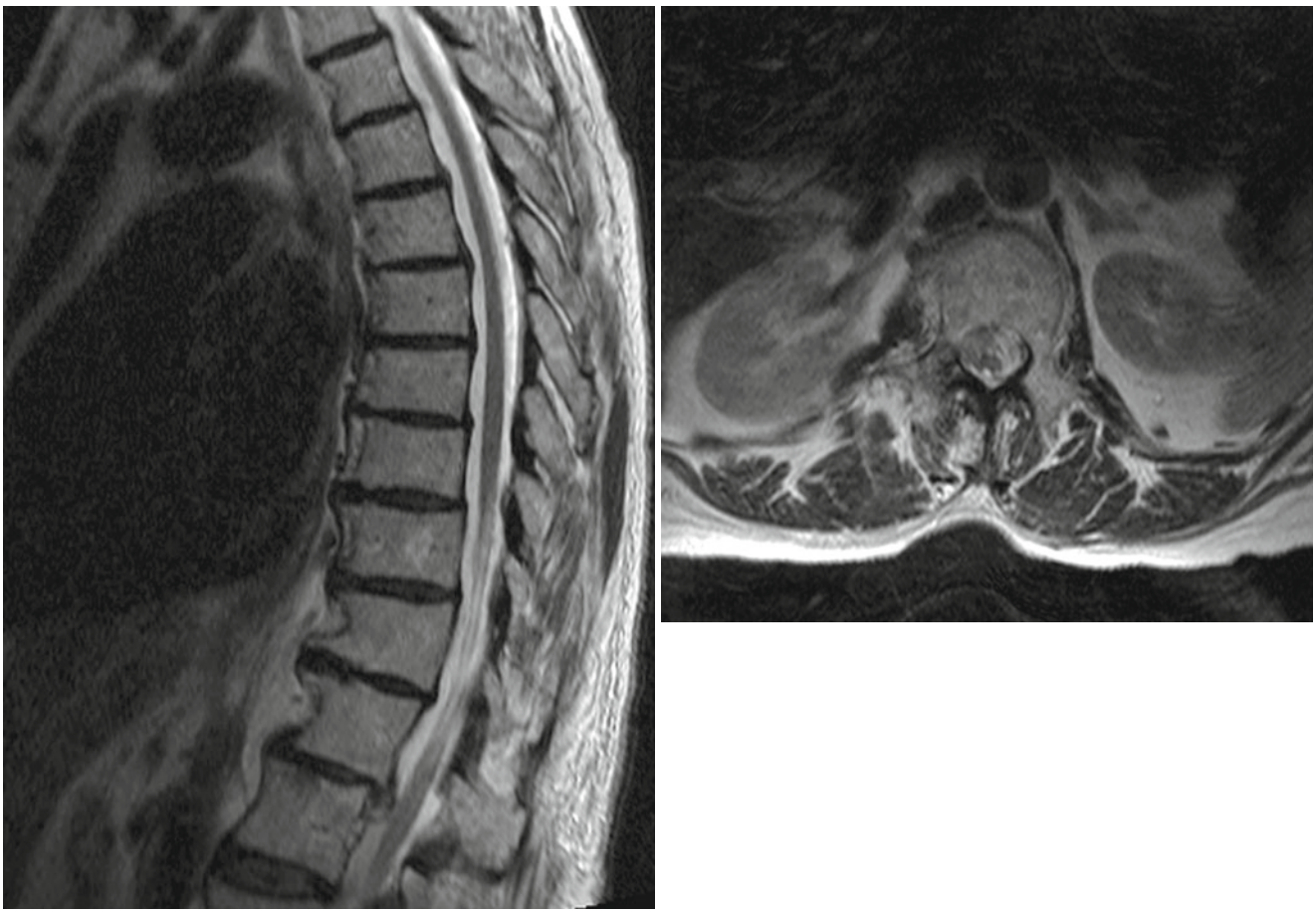

Fig. 11.2 MRI of thoracic spine—(*left*) T2 sagittal demonstrating mid-thoracic disc herniation. (*Right*) T2 axial demonstrating right paracentral thoracic disc herniation with spinal cord compression

preoperative radiographs should be reviewed to confirm the number of ribs in anterior-posterior projection and the number of lumbar vertebrae and to corroborate the pathologic level on MRI with these radiographs.

Miss Microendoscopic Discectomy (MED) for a Paracentral Thoracic Disc Herniation

The preoperative MRI of the thoracic spine should be reviewed to confirm the surgical level (Fig. 11.2). An ipsilateral paramedian line is drawn approximately 1.5 cm from the midline. Fluoroscopy is positioned for lateral X-rays and the surgical level is approximated with a small dilator tube placed over the paramedian line. The correct vertebral level should be confirmed by counting vertebral bodies from the sacrum with lateral X-rays and confirmed by counting ribs from the anterior-posterior X-rays. The point of entry is marked prior to injecting the skin and underlying fascia with local anesthesia. A 2 cm incision (oriented rostral-caudal) is made with a scalpel followed by monopolar electrocautery through the fascia of the paraspinal muscles. Blunt dissection with the surgeon's finger will develop a safe plane and is used to guide a K-wire or initial tubular dilator down to the laminofacet junction. An X-ray confirms the surgical level and placement of sequential muscle-splitting tube dilators is then performed. The final tubular retractor (~18 mm) is secured in place with the table-mounted flexible retractor arm and the final position is confirmed by lateral X-rays. At this point, the microscope, loupes, or the endoscope (preference of the senior author) is used to facilitate soft tissue dissection over the laminofacet junction.

Prior to using the endoscope, it should be optimally focused, contrast/brightness adjusted, orientation confirmed with a stationary object, white balanced, and "defogger" applied. The tip of the endoscope should be placed as close as possible to the surgical field (approximately 1 cm away) to improve visualization. Long-handle monopolar electrocautery and suction are used in all minimally invasive tubular systems. Caution should be used with the endoscope as monopolar electrocautery activity adjacent to the endoscope tip may create an "electrical arc" and burn the endoscope

lens. Under improved visualization, monopolar electrocautery is used to dissect the soft tissue away from the laminofacet junction, working from the rim of the dilation tube toward the center in a 360° fashion, staying on bone at all times to prevent inadvertent "plunging" into the spinal canal. A pituitary is used to remove cauterized soft tissue and an up-angle curette is used to create a plane between the laminofacet and the underlying ligamentum flavum. A hemilaminotomy is performed using a combination of pituitary and Kerrison rongeurs, followed by resection of the ligamentum flavum until the disc space is visualized.

After the initial exposure and hemilaminotomy, the medial one-third to one-half of the facet is dissected free and a pneumatic burr is used to thin out the facet joint. Removal of one-third to one-half of the medial facet at a single level is rarely associated with future spinal instability. To improve access to the disc space, a high-speed burr is used to Resect 2–3 mm of the superomedial portion of the caudal pedicle, which improves visualization and mobility for decompression. If using loupes or a microscope, rotation of the operating table away from the surgeon in an oblique fashion can also assist in visualization without retraction of the thoracic spinal cord. The dura and nerve roots can be protected behind a strategically placed 1 cm × 1 cm cotton pledget. An annulotomy knife or 15-blade scalpel on a long handle is used to incise the disc for a discectomy procedure. A micropituitary is used to retrieve the disc fragments. A right-angle nerve hook and right-angle spatula is used to dissect any free floating disc fragments that are subsequently removed with the pituitary. A small micropituitary is used to carefully extract the herniated disc fragment, taking care to avoid traction injury to the nerve root or the thecal sac. Any disc fragments should be removed if easily accessible but "should not be chased" behind the thecal sac. If the thoracic disc herniation is in the midline, a posterolateral approach may not adequately address the pathology. This can be treated through a MISS lateral extracavitary approach which can treat both midline thoracic disc herniations as well as thoracic vertebral body disease. This technique is described below.

Miss Microendoscopic Lateral Extracavitary Corpectomy for Thoracic Vertebral Body Disease

The patient is positioned, prepped, and draped in similar fashion as described above for a MISS thoracic microdiscectomy. Fluoroscopy is used to localize the pathologic level and marked. Percutaneous pedicle screws are placed two levels cephalad and caudad to the corpectomy level using the "bull's eye" technique. On anterior-posterior X-rays, Jamshidi needles are aligned directly in parallel with the ipsilateral pedicles in a "bull's eye" technique (Fig. 11.3). A 3 cm paramedian

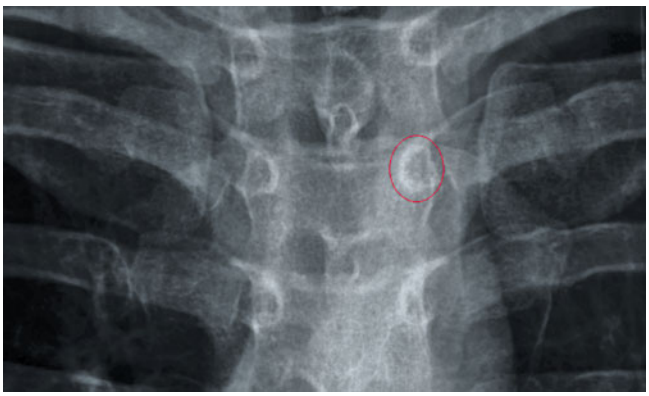

Fig. 11.3 Anterior-posterior X-ray of the thoracic spine demonstrating the "bull's eye" target for placement of percutaneous pedicle screws, Pedicle is outlined by the highlighted *circle*

incision is made bilaterally and the Jamshidi needle is docked onto the junction of the ipsilateral lateral margin of the superior facet and mid-transverse process. A K-wire is drilled 2 cm into place and the Jamshidi needle is removed. The fluoroscope is placed into lateral position and after advancing the K-wire into the vertebral body, sequential muscle-splitting tubular dilators are placed through which the pedicle screw tract is tapped. It is important to ensure that "tapping" of the screw tract is in parallel with the K-wire. If the trajectory is not parallel to the K-wire, the pedicle screw may be misplaced or the K-wire may fracture. The pedicle screws are then placed with fluoroscopic guidance into the posterior vertebral body. At this point, the K-wire is removed and the pedicle screw is placed towards the anterior vertebral body wall. Percutaneous rods are used to complete the instrumentation part of the surgery. This is the typical sequence for placement of percutaneous pedicle screws and attention is now turned toward the MISS lateral extracavitary corpectomy. A preoperative CT scan of the thoracic spine demonstrating a mid-thoracic sagittal-coronal split fracture of the vertebral body is provided as reference (Fig. 11.4).

The ipsilateral paramedian incision used for the percutaneous screw placement is incorporated for the lateral extracavitary approach. The initial dilator is guided on to the lateral facet of the surgical level by the surgeon's finger and confirmed by X-rays. Sequential muscle-splitting tube dilators are placed, followed by an expandable tubular retractor and connected to the table-mounted flexible arm. The soft tissue is removed by electrocautery, and exposure of the ipsilateral laminofacet, transverse process, costovertebral joint, and proximal rib head is completed. The laminectomy and facetectomy are performed as previously described in the chapter with a combination of a high-speed burr and Kerrison rongeurs. An osteotome may be used to initially resect the transverse process and laminofacet junction to provide additional autograft for fusion material. Subsequently, a pediculectomy is performed with the high-speed burr by the

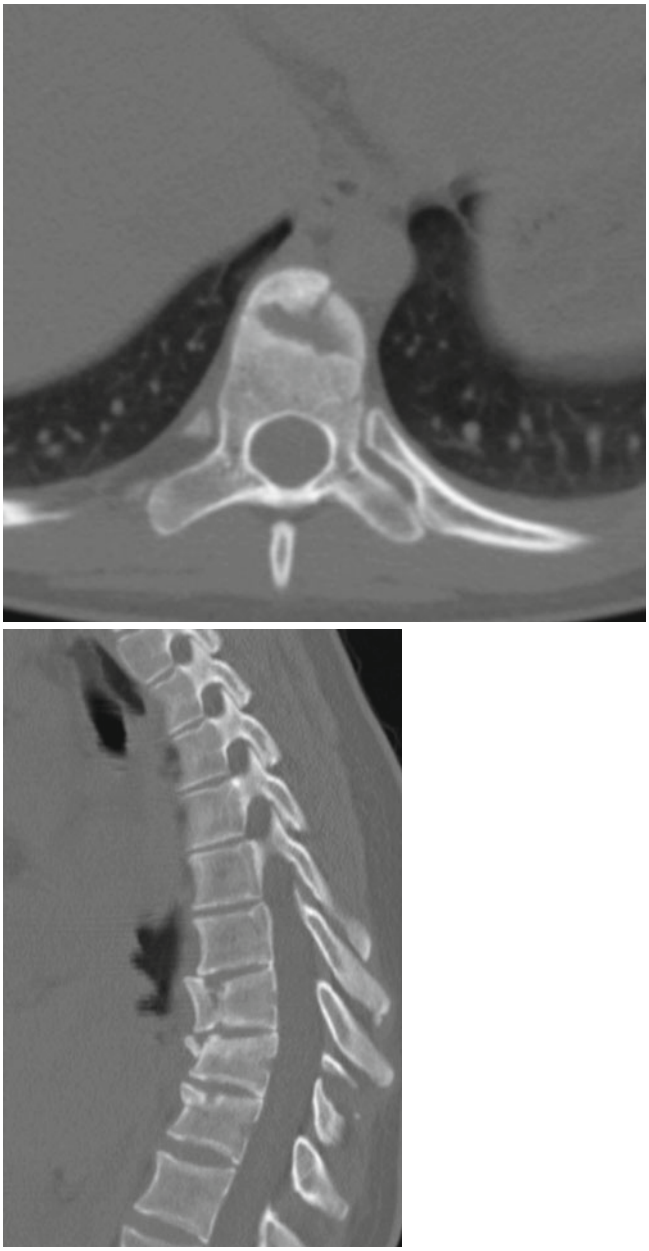

Fig. 11.4 Preoperative CT thoracic spine—axial (*top*) and sagittal (*bottom*) slice demonstrating sagittal and coronal split fractures of the thoracic vertebral body

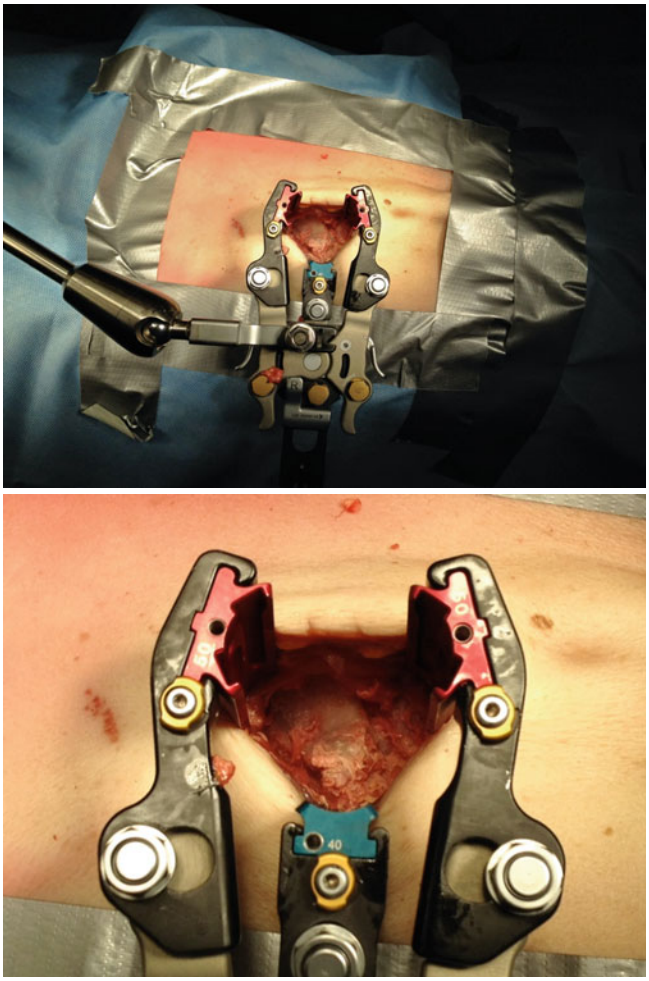

Fig. 11.5 (*Top*) Expandable retractor with rib resection and bony elements removed exposing the pathologic vertebral body for corpectomy. (*Bottom*) Zoomed in exposure from an MIS lateral extracavitary approach for a thoracic corpectomy

"inside-out" method. A Penfield #1 can be used to perform circumferential blunt dissection of the soft tissue away from the pedicle. Careful dissection at the caudal aspect of the pedicle is important to avoid injuring the exiting nerve root. The residual cortex of the pedicle is resected with Kerrison and pituitary rongeurs. Removal of the rib at the surgical level is important to improve the angle of the surgical approach and limit retraction of the thoracic spinal cord. A subperiosteal dissection of the rib at the pathologic level is completed. Blunt dissection of the ventral and inferior aspect of the rib is preferable with a Penfield #1 or rib dissector to avoid injury to the underlying pleura and neurovascular bundle. Subsequently, the rib is resected distally with a Leksell rongeur and saved for autograft. To improve the surgical exposure of the pathologic vertebral body, the ipsilateral thoracic nerve root and associated vasculature may be ligated. This is accomplished with multiple hemostatic clips or 4-0 silk ties followed by sharp division of the neurovascular bundle between the ligated ends (Fig. 11.5). Discectomies are performed cephalad and caudad to the vertebral body to define the "surgical borders" followed by preparation of the adjacent endplates. The discectomies are performed in standard fashion with an annulotomy knife, pituitary rongeurs, and angled curettes. The adjacent endplates of the "surgical borders" should be completely free of disc or cartilaginous material to optimize bony fusion. The corpectomy begins with a high-speed burr to drill out the center of the vertebral body with the "inside-out" method until a thin cortical shell remains at the ventral, dorsal, and contralateral edges. A combination of

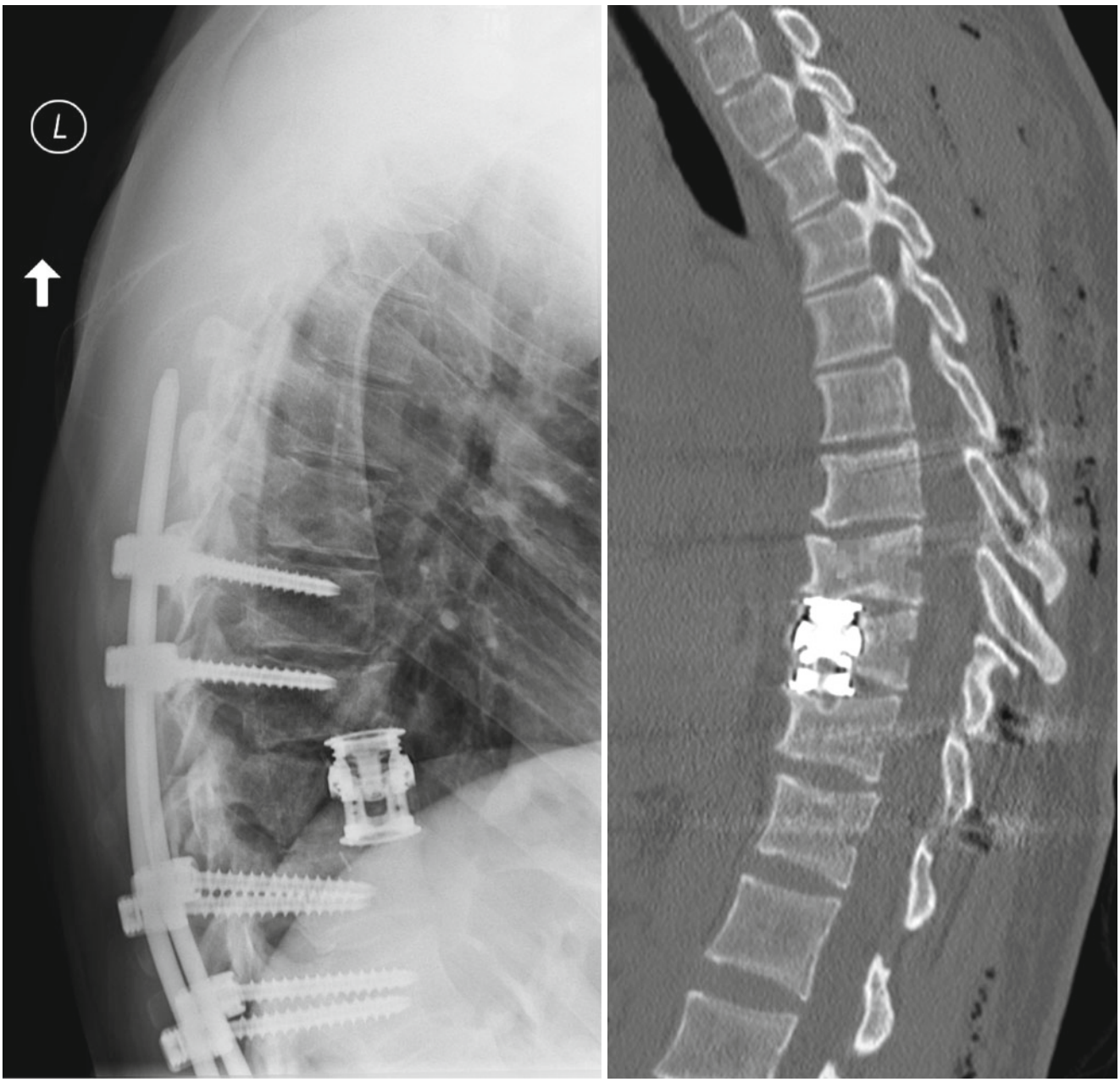

Fig. 11.6 (*Left*) Postoperative lateral X-ray thoracic spine and (*right*) sagittal slice of the thoracic spine demonstrating thoracic corpectomy with interbody expandable cage

osteotomes, curettes, and rongeurs are used to complete the bony resection. During the corpectomy, anesthesia should be counseled about aggressive volume repletion and potential for rapid blood loss. Except in cases of tumor, the anterior vertebral body wall should be left intact to protect the ventral thoracic vascular structures. After adequate decompression, the defect can be reconstructed with allograft, autograft, or synthetic structural cages (Fig. 11.6). The final ipsilateral pedicle screws and rods are placed percutaneously, compressed, and locked into place. Closure proceeds in standard fashion.

Pearls and Pitfalls

Important Points

A detailed understanding of surgical anatomy is critical to avoid disorientation in MISS approaches (e.g., when placing pedicle screws, keep in mind the thoracic pedicles are angled more medial at T1 and progressively become more straight at T12. Similarly, it is important to differentiate when the transverse process connects to the proximal rib as aggressive soft tissue dissection with monopolar electrocautery over the rib

may potentially lead to injury to the underlying pleura or caudally located neurovascular bundle).

Clinical/Surgical Pearls

- Prior to surgery always check for clinical symptoms and signs of cervical myelopathy. The cervical spine should be evaluated prior to any surgical intervention and treated accordingly.
- Confirmation of the surgical level of interest with fluoroscopy is critical to avoid becoming disoriented when working in a narrow surgical field.
- For localization: Always count the ribs or pedicles with anterior-posterior X-rays for mid-thoracic lesions. Lesions at the ends of the thoracic spine can be confirmed with lateral X-rays. When in doubt, perform intraoperative pedicle cannulation with a Jamshidi needle or a K-wire and take an X-ray image.
- Migration or misplacement of the dilators can lead to significant disorientation. Thus, the surgeon must be extremely careful during initial steps in localization and dilation.
- Drilling 2–3 mm of the ipsilateral superior portion of the caudad pedicle will improve medial visualization and access to the thoracic disc herniation.

Clinical/Surgical Pitfalls

- Caution must be used in the region of the medial interlaminar space to avoid inadvertent injury to the spinal cord or creation of a CSF leak.
- Do not angle the dilator medially when performing a posterolateral MISS approach until the working channel is placed to avoid "crossing-over" to the contralateral side.
- Avoid resecting the anterior vertebral body wall while performing the corpectomy to protect the ventral neurovascular structures.
- Do not retract the thoracic spinal cord for exposure as this may lead to permanent neurologic deficits. If necessary, resect more bone and tissue laterally to enable medial angulation of the tubular retractor and improve the exposure.
- During the "advancement" or "retraction" stage of tapping over the K-wire, an assistant should hold the K-wire in place with a locking metal instrument (Kocher) to ensure the K-wire does not migrate dorsal out of the vertebral body or ventral into the thoracic cage.
- During tapping or placement of percutaneous pedicle screws, it is important to maintain a parallel axis to the K-wire at all times. Any deviation from the K-wire trajectory can lead to misplaced pedicle screws or fracture of the K-wire.
- Once the pedicle screw is visualized on fluoroscopy as partially into the vertebral body, the K-wire should be removed to avoid potential fracture of the K-wire.

Avoiding and Treating Surgical Complications

Regardless of the surgical approach (MISS posterolateral vs. MISS lateral extracavitary), the surgeon must be comfortable with the surgical anatomy and potential complications. Working through a narrow access tube may decrease the disruption of normal anatomic structures, but also limits the surgeon's viewpoint and surrounding anatomy. In the MISS lateral extracavitary approach, there is always concern for a potential pleural violation. Gentle and meticulous subperiosteal dissection of the rib and associated fascia should minimize the incidence of pleural violation. If this occurs, a chest tube may need to be placed after surgery. During the corpectomy, the greatest concern aside from neurologic injury is potential harm to the thoracic great vessels. If there is any concern for potential vascular injury, the surgery should be aborted, alert anesthesia to maintain hemodynamic stability, and obtain an immediate vascular surgery intraoperative consultation.

Unintentional durotomies are difficult to repair primarily through the smaller MISS surgical tubes and are best treated with indirect techniques. We advocate placing a water insoluble layer on top of the dural defect (muscle, fat, fascia, or a dural substitute) and coating with a dural sealant (fibrin glue or TISSEEL). The patient is placed on flat bed rest for 24 h for small durotomies, but larger defects may require CSF diversion with a lumbar drain for a few days. The combination of a small incision and lack of "surgical dead space" has reduced clinically significant pseudomeningoceles or CSF leaks to negligible after a minimally invasive approach. When using larger tubes, such as for corpectomies, durotomies can be repaired directly.

Neurologic complications that may occur include direct injury to the nerve within the foramen or the spinal cord during decompression procedures. Unique to MISS approaches is the potential injury with the use of a K-Wire during localization. Initial placement should be localized with fluoroscopy, but inattention can easily lead to misplacement of the K-Wire medial to the facet into the interlaminar space (spinal cord injury). The K-wire must be controlled at all times and removed immediately after placement of the initial tubular dilator to minimize the potential migration of the K-wire into a "danger zone." With proper knowledge of the surgical anatomy and attention to detail, the MISS approach to the thoracic spine can be completed safely and quickly with minimal complications.

Wound Closure and Postoperative Care

After completion of the thoracic decompression, meticulous hemostasis is achieved with bone wax, bipolar cautery, gelfoam soaked in thrombin, or Surgifoam. The muscles and fascia are injected with local anesthesia for postoperative pain control, and the surgical field is then irrigated with copious amounts of antibiotic solution. In the MISS lateral extracavitary approach, close observation for "air bubbles" in the surgical site may indicate inadvertent pleural violation. Any doubt should lead to a chest X-ray and if there is evidence of a pneumothorax, a chest tube should be placed. Fascial closure is completed with 0 Vicryl sutures and the subcutaneous layer closed with inverted 3-0 Vicryl sutures. The superficial dermal layer is closed with a running subcutaneous nonabsorbable 4-0 suture and a skin adhesive (Dermabond, Ethicon Inc.) to complete the surgical procedure.

In the postoperative setting, systemic support and pain control are primary goals. The patient is admitted to the ICU overnight for close observation of cardiopulmonary function and neurologic checks. Postoperative lab draws should be performed at set intervals, and transfusion criteria should be proactive, as opposed to waiting for signs of systemic hypoperfusion or shock. Hemoglobin is often kept above 10.0, and platelets are kept above 100, with monitoring of coagulation profile and fibrinogen levels. Routine checks of troponin and EKG tracing are also valuable to monitor for signs of cardiac strain. A low index of suspicion should be utilized for echocardiographic evaluation of cardiac function. Depending on case length and transfusion requirements, extubation can be challenging in the immediate postoperative setting. Overnight intubation can be utilized to facilitate immediate postoperative pain control and equilibration of fluids and blood products. Close attention from intensive care is recommended prior to extubation. Patient controlled anesthesia is a common successful pain control strategy, with liberal employment of pain anesthesia consultation. We recommend liberal usage of basal rates and aggressive titration to minimize patient discomfort. Bracing is typically not required in the postoperative setting, and aggressive postoperative mobilization with physical therapy is essential once adequate pain control is achieved. Routine follow-up in clinic is 10–14 days after surgery.

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Lumbar Decompression Using a Tubular Retractor System

12

Sapan D. Gandhi and D. Greg Anderson

Indications for Procedure

Herniated discs and spinal stenosis can often compress the neural elements in the lumbar spine, causing debilitating leg pain (radiculopathy or neurogenic claudication). Typically, patient with symptomatic neural compression presents with complaints of pain radiating down the extremities in a dermatomal distribution. The patient may also complain of changes in strength and sensation. Lumbar microdiscectomy to remove compressive herniated disc fragments is the most common spinal surgery performed [1].

In elderly patients, stenosis in the lumbar spine is a common cause of back and leg pain and trouble with walking [1]. Spinal stenosis can cause compression of the lumbar nerve roots by a combination of degenerative changes including facet joint hypertrophy, ligamentum flavum thickening, and disc bulging [2]. Symptoms of lumbar stenosis are generally worse with standing and walking and improved with flexion of the spine or sitting. The patient may mention that leaning forward, such as on a shopping cart, may help their symptoms.

Nonsurgical therapies should first be exhausted before considering surgery for both herniated disc disease and lumbar stenosis. These may include nonsteroidal anti-inflammatory drugs, epidural steroids, and physical therapy. When nonsurgical methods fail to alleviate the symptoms, surgery may be considered. Surgical decompression has been shown to be quite successful in patients with persistent symptoms brought on by lumbar stenosis or herniated disc disease [1, 3, 4].

In contrast to traditional open techniques, minimally invasive surgical decompression has been shown to have a shorter patient recovery time and decreased blood loss [2, 5, 6]. This chapter will review the technique of performing lumbar decompression surgery using a minimally invasive tubular retractor system.

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Technique

A careful review of the preoperative studies (plain radiographs, MRI, or CT myelography) should be undertaken before surgery so that the surgeon has a thorough understanding of the location and causes of the patient's symptoms.

These procedures are most commonly done under general anesthesia. However, epidural or spinal anesthesia can be utilized depending on the preference of the patient, anesthesia team, and surgeon. Prior to initiating surgery, prophylactic antibiotics are administered and lower extremity compression stockings are applied. After the induction of anesthesia, the patient is placed prone on a radiolucent operating table to facilitate the use of fluoroscopic imaging of the lumbar spine (Fig. 12.1a). The surgical team should ensure that the abdomen is not compressed by the spinal frame prior to initiating surgery. A standard sterile prep and drape of the low back is utilized (Fig. 12.1b).

The authors prefer to clamp the tubular retractor on the side of the surgical approach. Because the C arm and microscope can be used from either side of the table, their positions can be determined by the layout of the room and the location of the operating room door.

Incision and Exposure

Before the surgical incision, palpable landmarks including the posterior superior iliac spines, intercrestal line, and spinous processes should be marked on the back as reference. Next, a spinal needle is introduced along the proposed surgical corridor (Fig. 12.2a). The spinal needle should be

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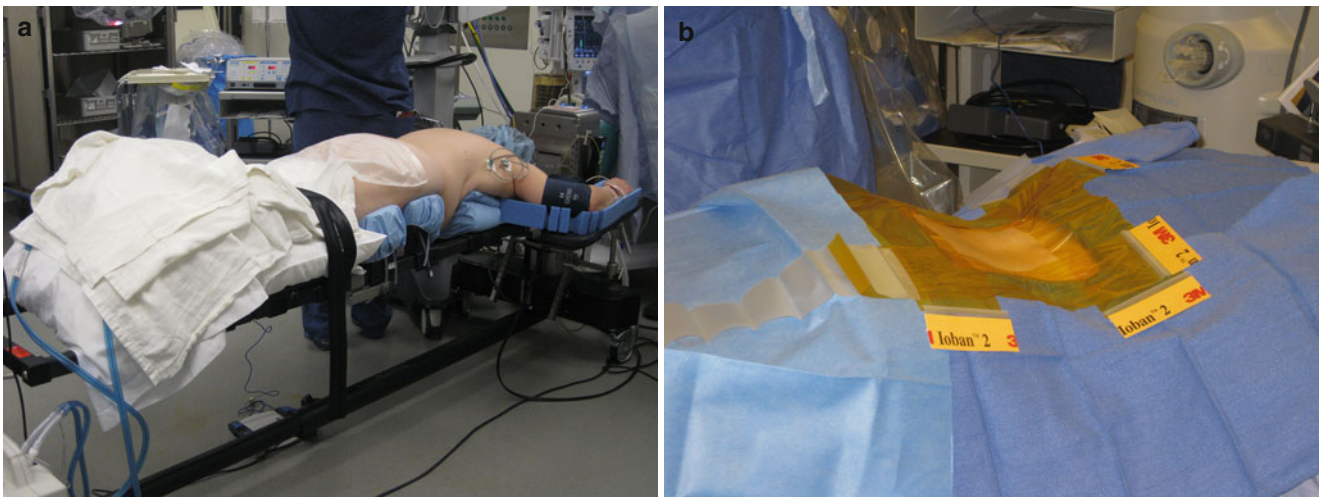

Fig. 12.1 (**a**) Positioning of patient prone on a radiolucent spine frame. Care should be taken not to compress the abdomen when positioning the patient. (**b**) A standard prep and drape of the low back

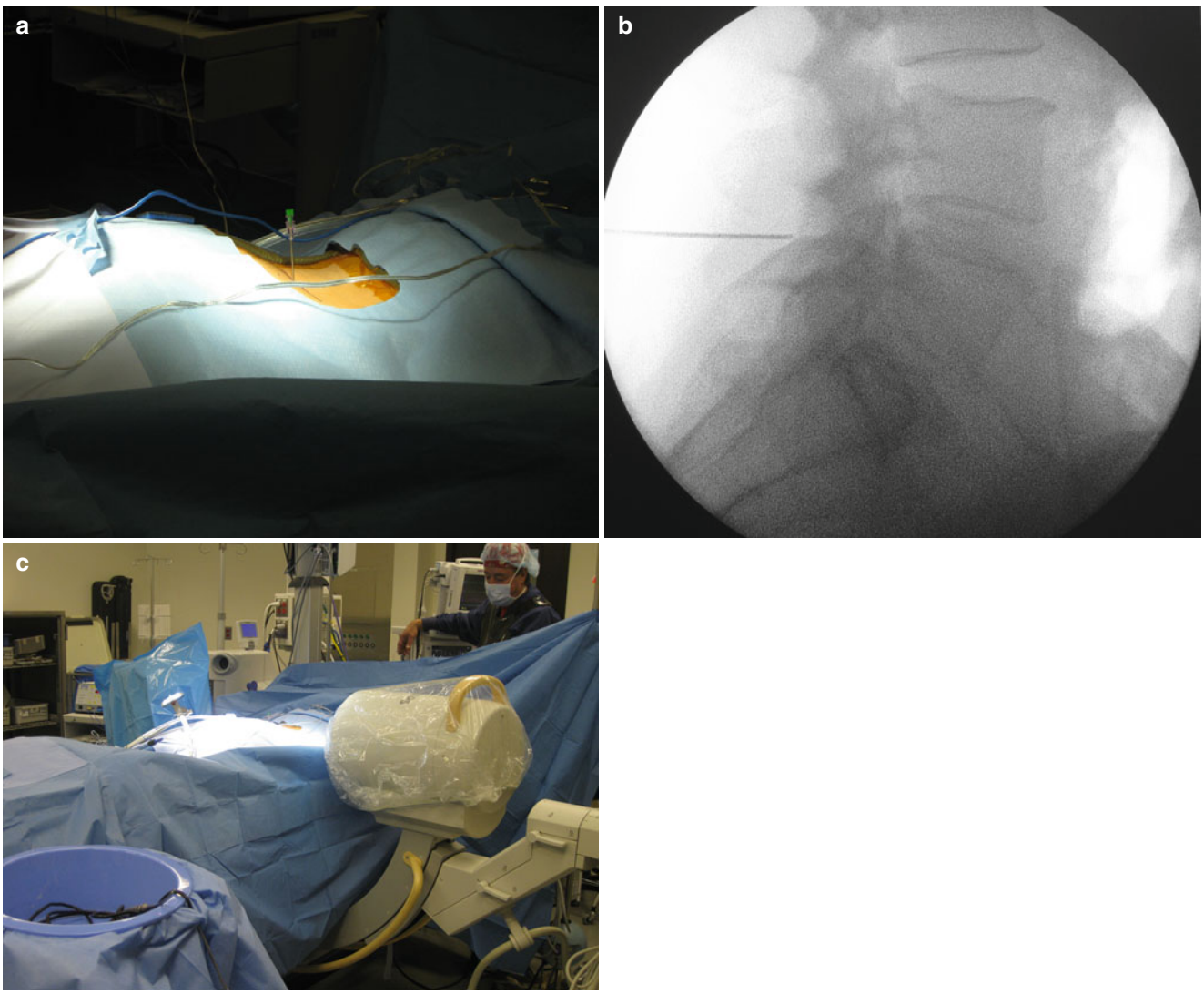

Fig. 12.2 (**a**) A spinal needle is introduced in the proposed trajectory of the surgical corridor. (**b**) Its trajectory is confirmed via C-arm fluoroscopy. (**c**) Positioning of the C arm around the operating table to confirm the trajectory of the spinal needle

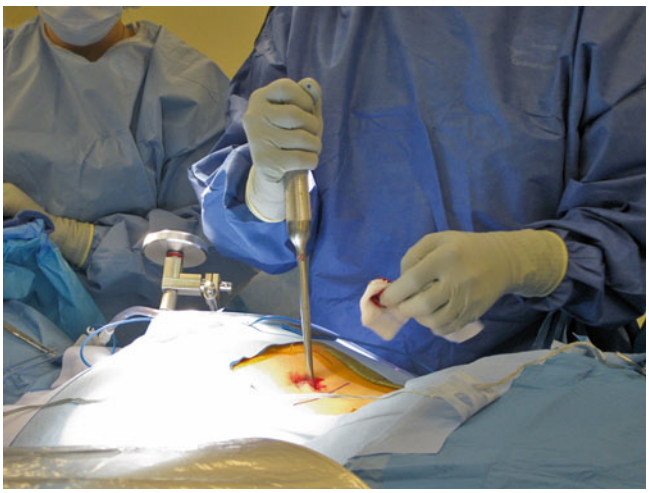

Fig. 12.3 A Cobb elevator is used to bluntly dissect the multifidus muscle from the underlying lamina

introduced lateral to the midline, aimed towards the facet joint to avoid inadvertent laceration of the dural sac and CSF leakage. Fluoroscopy is then used to confirm the level for the surgical incision and the trajectory of the spinal needle (Fig. 12.2b, c).

An incision equal in length to the diameter of the tubular retractor is then made lateral to the midline. The multifidus muscle compartment is then opened by incising the overlying fascia. When only an ipsilateral decompression is required, the incision should be positioned 1.5–2 cm lateral to the midline. In situations that require a bilateral decompression, the incision is made 3–4 cm lateral to the midline to allow angulation of the tubular retractor to the contralateral side. A more lateral incision may be necessary in heavier patients.

Blunt dissection of the multifidus muscle from the underlying lamina can be achieved using a Cobb elevator (Fig. 12.3). This step creates the docking site needed for the tubular retractor and thus will minimize the soft tissue resection required to perform the procedure. Alternatively this layer may be traversed by passing sequential dilators without formal dissection. The use of a K-wire as the initial step, prior to dilation, carries a risk of inadvertent dural puncture, and the authors avoid this step.

Sequential tubular dilators are then used to gently dilate and create the working surgical corridor (Fig. 12.4a). The smallest dilator is first used to palpate the underlying anatomy and dock along the caudal edge of the lamina. At this point, a tubular retractor of appropriate length is placed and the dilators removed. Selection of a tubular retractor of appropriate diameter and length is an important decision in minimally invasive decompressions. The authors typically use a 14–16 mm diameter tubular retractor for a microdiscectomy for herniated disc disease and an 18–20 mm diameter system for decompression of lumbar stenosis. In addition, the length of tubular retractor selected should be adequate to reach from the skin edge to the lamina.

Once the tubular retractor in its working position, the surgeon should secure the tube by attaching it to a table-mounted holder (Fig. 12.4b). Confirmation of the position of the tubular retractor should then be obtained using C-arm fluoroscopy (Fig. 12.4c). Any necessary adjustments should be made prior to the commencement of the procedure to ensure optimal access to the pathology. An operative microscope (or endoscope) is used for visualization of the surgical field.

Any residual soft tissue should be cleaned away with electrocautery to ensure good visualization of the bone landmarks. The facet joint capsule should be preserved during soft tissue clearance. During this maneuver, it is important for the surgeon to become oriented to the operative site by identifying the salient landmarks. These include the inferior laminar edge, ligamentum flavum, and the medial portion of the facet complex.

Ipsilateral Decompression

An ipsilateral decompression is utilized when symptomatic compression is isolated to only one side of the spinal canal. The technique after creating the tubular surgical portal is analogous to that used with other forms of surgical exposure.

First, the surgeon should use a curved curette to create a surgical plane between the ligamentum flavum and underside of the lamina. Next, portions of the lamina should be resected using a Kerrison rongeur or burr to expose the compressed neural elements. In addition, the ligamentum flavum should be resected adequately to expose the site of neural compression.

Palpation of the pedicle is a useful technique to confirm position within the spinal canal. In the case of a disc herniation, the dural edge should be identified and mobilized. Subsequently, a nerve root retractor is positioned to gently retract the nerve root, providing access to the ventral disc herniation. The posterolateral region of the disc, which is the most common site of herniation, is visualized and any required annulotomy is performed to expose the herniated fragment. Free disc material is then removed.

After excision of the visualized fragments, a long ball-tipped probe can be used to sweep the spinal canal to ensure an absence of additional disc material in a nonvisualized location. Annular incisions should be kept as small as possible to avoid subjecting the patient to a higher risk of recurrent disc herniation.

In those patients whose symptoms arise from lateral recess stenosis, the medial portion of the superior articular process is resected. A drill/burr may be used to thin or

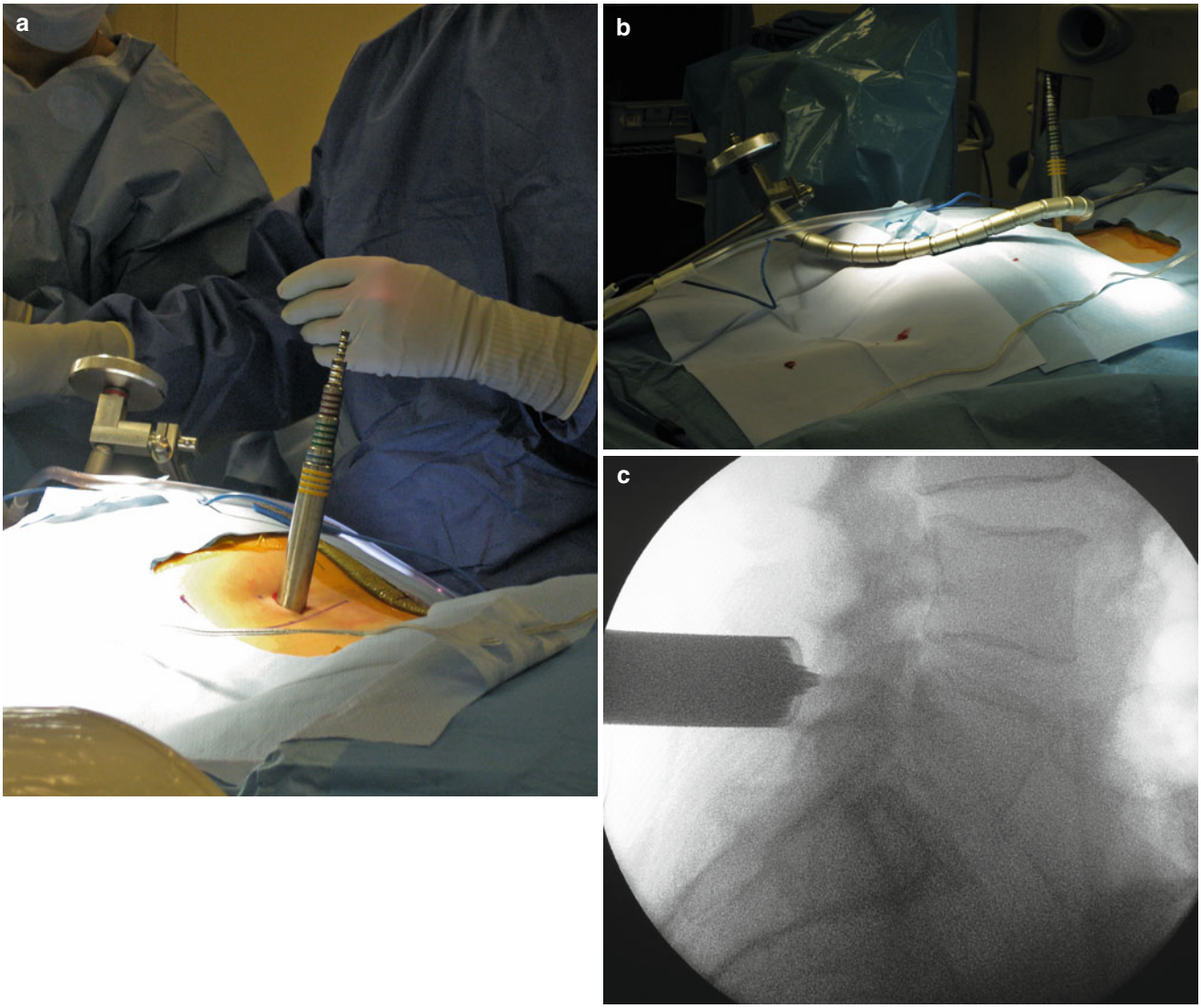

Fig. 12.4 (**a**) Sequential dilators are used to create the tubular surgical corridor. (**b**) The table-mounted holder is used to secure the tubular retractor. The authors prefer to mount tubular retractor holder on the same side as the surgeon. (**c**) The position of the tubular retractor is confirmed via C-arm fluoroscopy

remove the overlying inferior articular process; however, care should be taken not to thin the bone of the inferior articular process excessively, leading to an iatrogenic fracture or instability. Next, a Kerrison rongeur is used to trim the medial portion of the superior articular process until it is vertically flush with the medial border of the pedicle. The foramen can be opened up with the use of a curved tip "foraminotomy" Kerrison rongeur. The ipsilateral side can be difficult to visualize directly, so it is important to establish a plane above the nerve root by initial palpation with a ball-tipped probe and then work in the established plane using the Kerrison rongeur.

Once the surgeon is satisfied with the decompression of the neural structures, hemostasis is ensured and the tubular retractor is withdrawn.

Bilateral Decompression

When both sides of the spinal canal require decompression, bilateral decompression can be achieved from a unilateral approach.

Using a more laterally based incision (as described earlier), a laminotomy is performed on the ipsilateral side, leaving the ligamentum flavum intact [6]. The contralateral side of the spinal canal is then reached by "wanding" the tubular retractor and undercutting the spinous process region. When the tubular retractor has been properly positioned, the surgeon should be able to see the junction of the base of the spinous process and ipsilateral lamina. It is helpful to tilt the operating table away from the surgeon during this maneuver to decrease the angle of the

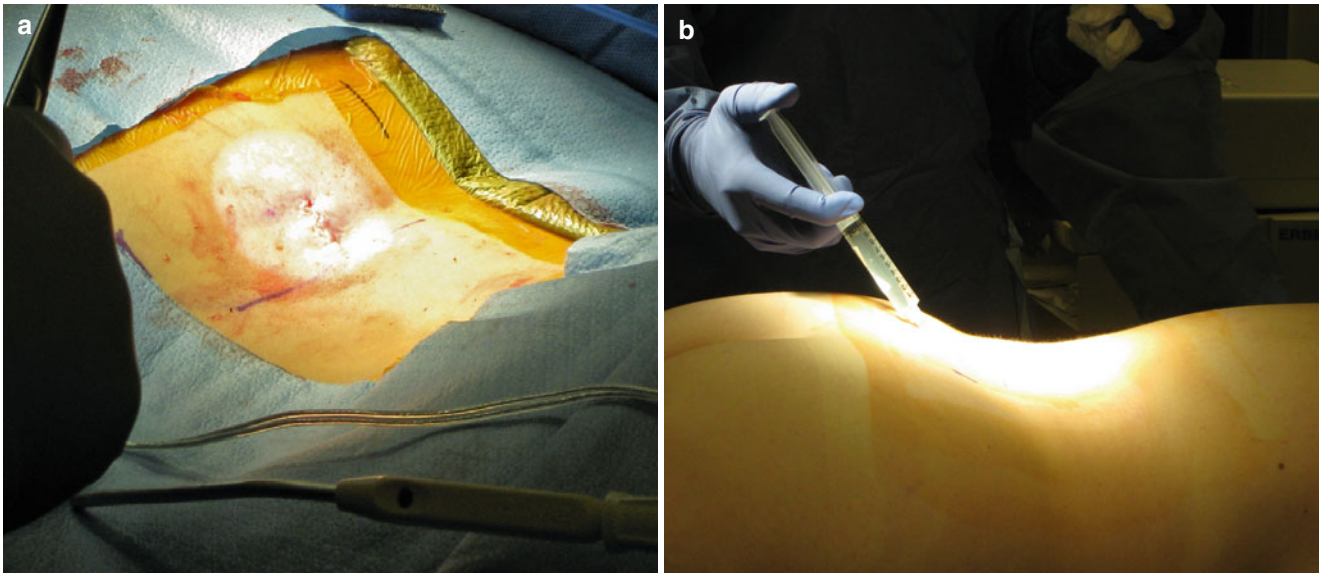

Fig. 12.5 (**a**) A skin sealant is used after wound closure to allow showering in the postoperative period. (**b**) A long-lasting local anesthetic is injected into the subcutaneous tissue to minimize pain in the postoperative period

microscope. This will improve the surgeon's visibility across the midline.

Next, the undersurface of the contralateral lamina is drilled away using a high-speed drill/burr. The surgeon should pay attention to the quality of the bone during this drilling maneuver. Initially, cancellous bone will be encountered at the base of the spinous process, and bone bleeding will be encountered. This should be controlled with bone wax. Next, cortical bone of the contralateral lamina will be encountered, and bone bleeding is generally minimal. As the surgeon begins to drill into the bone of the contralateral articular processes, a more cancellous-type bone will be encountered. The contralateral facet joint must be thinned until a Kerrison rongeur can remove the remaining medial portion of the facet to complete the decompression. During the drilling process, the surgeon should periodically release the ligamentum flavum from the undersurface of the lamina and facet.

It is useful to follow the ligamentum flavum across the midline to the undersurface of the contralateral facet, removing enough bone above the ligamentum flavum to provide an adequate working space for the surgical instruments.

After all the necessary bone drilling has been completed, the ligamentum flavum is removed by releasing the attachments of the ligament from the bone edges using a curved curette. After removal of the ligamentum flavum, direct visualization of the dural structures is then available and complete decompression of the contralateral lateral recess and foramen can be achieved.

After the contralateral depression has been completed, the surgeon should wand the tubular retractor towards the ipsilateral side. Then decompression of the ipsilateral side can be performed as described above.

At the conclusion of the decompression, a ball-tipped probe is used to confirm that an adequate decompression of the nerve roots has been achieved throughout. Adequate hemostasis is achieved, followed by removal of the tubular retractor and closure of the incision.

Wound Closure and Postoperative Care

The thoracolumbar fascia can be closed using interrupted sutures. However, if this is not possible to reach the fascia in an obese patient, the deep subcutaneous tissues are reapproximated followed by skin closure. Use of a skin sealant along the incision allows the patient to shower in the early postoperative period (Fig. 12.5a).

The subcutaneous tissues along the incision are infiltrated with a long-acting local anesthetic to minimize pain in the early postoperative period (Fig. 12.5b). A surgical dressing can be used according to surgeon preference. Early mobilization of the patient should be the goal following an MIS decompression. Most patients can be discharged from the hospital on the day of surgery.

Patients are encouraged to walk at least 30 min per day following surgery. Strenuous activity is allowed at the 4-week postoperative time point. Low-potency oral narcotics or over-the-counter medication such as ibuprofen or acetaminophen are generally adequate to manage pain in postoperative period. Physical therapy can be prescribed in selected cases for postoperative rehabilitation of the core musculature and lower extremities. Aerobic exercises are encouraged on an ongoing basis.

Pearls and Pitfalls

- The surgeon should be careful to avoid excessive thinning of the pars intraarticularis and the inferior articular process because of the risk of iatrogenic fracture.
- Palpation of the bone in the region of the pars intraarticularis with a #4 Penfield instrument is useful to ensure adequate bone is left in this region.
- The ligamentum flavum should be left intact until the end of drilling, to reduce the risk of a dural or nerve root injury.
- The operative microscope provides optimal visualization of the operative field during the surgical procedure and is encouraged for this type of surgery.
- After the ligamentum flavum has been removed, frequent palpation of the plane between the dura and the overlying tissue should be undertaken to reduce the risk of dural tear.
- Bleeding can be controlled with a combination of bone wax on bony edges and flowable hemostatic agents into the lateral gutters of the decompression.
- Revision surgery is complex and best managed by surgeons with substantial clinical experience in tubular-based surgery.

Complications and Management

The inherent risks to all lumbar decompressive surgery remain with tubular retractor-based surgery. The risks therefore include bleeding, dural laceration, nerve injury, iatrogenic instability, infection, and medical complications.

A learning curve should be anticipated in the early stages of a surgeon's experience with minimally invasive decompression surgery. During this phase, extra time for the procedures, careful technique, and a graduated approach to case difficulty are prudent. Cadaver experience, operative visitations, and formal mentored training can help to resolve learning curve issues. Published results support the positive effects of surgical mentorship when learning minimally invasive lumbar procedures [7].

Dural tears remain a challenge with minimally invasive lumbar decompression surgery. One report found an incidence of iatrogenic dural tear of 16 % [2]. Although dural tears can be minimized with careful technique, the surgeon should be prepared to manage a dural tear should it occur. Fortunately, the lack of significant wound "dead space" in minimally invasive procedures reduces the likelihood of a dural-cutaneous fistula in comparison to traditional open lumbar decompression. Small, stable dural tears may be successfully managed by placing a small amount pledgette of a hemostatic agent at the site followed by use of a dural sealant (e.g., fibrin glue). Larger tears may necessitate suture repair. Although suture repair can be technically demanding, it can be successfully achieved using a micropituitary instrument with a needle driver and an arthroscopic knot pusher [8]. When dural suture is performed, the author prefers to use a fine double-armed suture with an "inside-to-out" passage of the needles.

Infection is quite uncommon following tubular-based decompression surgery [9]. O'Toole et al. studied the rate of surgical site infection in 1,338 patients following decompression and fusion procedures performed through a tubular retractor system. In this cohort, there were 2 superficial and 1 deep infection at the surgical site. For simple decompression procedures, the rate of infection was 0.1 %, a rate that is approximately 10-fold less than comparable open surgical series [10]. In the event of a surgical site infection, traditional techniques of debridement and antibiotic therapy should be pursued.

Conclusion

Minimally invasive decompression can be used in selected cases with symptomatic herniated disc disease or lumbar stenosis where without findings of major spinal instability. Although a learning curve for minimally invasive decompression should be anticipated, tubular retractor approaches to lumbar decompression are able to achieve positive clinical results with reduced morbidity when compared to traditional open decompressive surgery [9, 11]. The surgeon learning curve is manageable for most surgeons by cadaver training, apprenticeship, and graduated exposure to case difficulty [7].

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Part IV

Surgical Techniques: Fusion

Minimally Invasive Posterior Cervical Fusion

13

Larry T. Khoo, Zachary A. Smith, Ian Johnson, and Xue Yu Hu

Evolution of the Minimally Invasive Technique

Various techniques have been developed over the years for the posterior internal fixation of subaxial cervical spine, including lateral mass metallic plates, interspinous wiring with bone graft, interlaminar clamps, hook plates, Daab plates, and Harrington rod constructs [1, 2]. In the past more commonly used technique for multilevel fusions involved interspinous wiring, where three wires were passed through holes made at the spinolaminar junction and around the rostral border of the rostral spinous process (Fig. 13.1a) [3–5]. The strength of this construct has been verified in biomechanical studies as well as excellent union reported in case reviews [6–9]. In cases where the dorsal spinolaminar sites were unavailable, such as in severe posterior column injury, Luque rectangles with facet wiring were often utilized (Fig. 13.1b). This triple-wire technique had several advantages such as the ability to bridge large dorsal column defects (e.g., after tumor resections), the capacity to perform segmental fixation at every level, and the provision of greater rotational and torsional stability [10, 11]. In 1979, a novel technique for posterior cervical instrumentation was described in which plates were fixed to the lateral processes of the cervical spine using screws, a technique that proved to be significantly stronger on biomechanical tests [12–17]. Subsequent authors described a 95–100 % fusion rate in cases of cervical trauma with this technique when autogenous bone grafting was performed [15, 18, 19]. Dissatisfaction with the quality of lateral mass screw fixation at lower cervical and upper thoracic spine subsequently led to the use of pedicle fixation for this region by several authors [1, 2, 20–26]. This transpedicular method was shown to have greater stability compared to other midcervical reconstruction systems [27].

More recently developed instrumentation systems utilize two rods and variable screw islets at each level. These systems vary by the angulation of their screws and in the degree of the constraint placed at the screw-rod interface. The polyaxial tulip or islet connectors of the screws are able to angle medially, laterally, and straight, with varying degrees of rotational freedom in each direction, thus making segmental fixation more readily achievable from a top-loading approach and allowing for the possibility of minimally invasive posterior cervical fixation possible.

With the advent of minimally invasive surgical techniques over the past decade, especially in the field of spine surgery, there have been significant improvements in the approach-related morbidities encountered compared to traditional techniques. Open surgery of the posterior spine requires subperiosteal muscle dissection which devitalizes the affected tissue and detaches crucial muscular and ligamentous insertions that, in turn, disrupt the posterior musculoligamentous dynamic tension band. Standard exposures can also cause substantial blood loss, muscular atrophy, and large cosmetic defects. This extensive dissection and stripping of the posterior musculature and ligaments is associated with considerable postoperative disability which may, in some cases, even exceed the intensity of the patient's preoperative symptoms.

The problems of the open approach are, for the most part, circumvented by the use of minimally invasive posterior approach technologies. While several systems are now commercially available, all of these instruments essentially involve fluoroscopic-guided placement of sequential dilators

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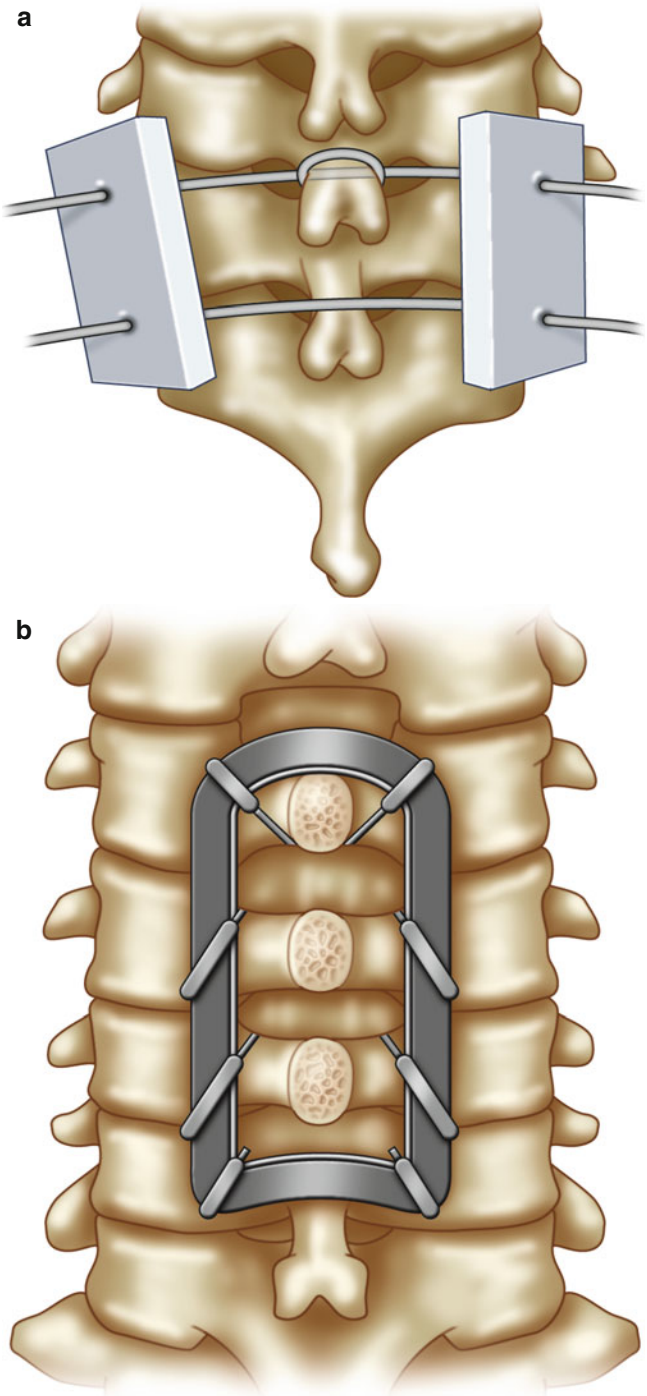

Fig. 13.1 Various posterior cervical fixation methods have been used over the years, such as the interspinous triple-wire technique (**a**) and sublaminar wiring which could be combined with a Luque-type construct (**b**). These semirigid constructs were eventually replaced by posterior lateral mass screw-plate fixation. The original unconstrained lateral mass screw-plate systems have since been supplanted by the more rigid screw-rod and polyaxial screw-rod constructs

through fascial and muscular structures—up to a final diameter of 14–24 mm. Visualization can then be accomplished through an operating microscope or via endoscopy through the established muscle-sparing working portal.

As an example of the superiority of the minimally invasive approach compared to the open technique, one can examine the evolution of the decompressive posterior cervical laminoforaminotomy for lateral recess and neural foraminal decompression. This procedure has been well documented as an effective treatment modality for patients who suffer from isolated radiculopathy from either a lateral disk or an osteophyte, achieving relief of symptoms in 93–97 % of patients [28–32]. Enthusiasm for this surgery, however, was tempered by the considerable cervical muscular pain and spasm that often followed, resulting in slower recovery, especially in cases where the use of a wider incision was necessary for adequate visualization. Microscopic and microendoscopic foraminotomy with a minimally invasive approach minimizes the amount of tissue trauma and muscle injury, thereby reducing the incidence of postoperative pain and muscle spasm with the similar clinical results as that of the classical open procedure [33, 34].

Through the same corridor of tubular access, the lateral mass of the posterior cervical spine can be readily visualized. Two adjacent lateral masses can typically be accessed through a 20 or 22 mm portal; and with the advent of some of the newer types of expandable access portals, up to three lateral masses can be instrumented through a single exposure. This allows for the placement of top-loading polyaxial screws through the tubular portals for the purposes of posterior cervical lateral mass fixation—a procedure successfully pioneered at our own institution and several centers nationally in 2001. Since that initial experience, this technique of minimally invasive posterior cervical fixation (MI-PCF) has been applied in several other cases requiring lateral mass fixation with excellent clinical and radiographic results [35, 36]. The widespread popularity of simple top-loading polyaxial screw systems has also greatly facilitated the MI-PCF procedure.

Minimally Invasive Posterior Cervical Fixation Technique

Anatomic Considerations

There are various methods for screw placement into the cervical lateral masses. The first report of the procedure described screw placement directed forward and outward 10° [12, 15]. Subsequent modifications recommended placing the screw at a point slightly medial to the center of the facet and directing it 25° laterally and 40–60° cephalad [37]. Other authors advocated for a technique in which the entrance point of the screw is 1 mm medial to the center of the lateral mass and aimed 15–20° cephalad and 30° laterally [38].

There are several advantages of lateral mass screw fixation over other techniques from C3 to C6 due to the typically

generous and broad size of the lateral mass. First, this method can be easily applied in cases where the posterior elements are compromised, such as lamina fracture and postlaminectomy, and when no competent spinous process is present. Furthermore, many pathological conditions of the cervical spine can be managed using this procedure, including neoplasms, posttraumatic or degenerative instability, and multilevel cervicothoracic stenosis. It is also biomechanically more resistant to rotation than constructs that use wires.

Although the lateral screw fixation method carries a risk of potential neurovascular injury, proper use of the technique is associated with an extremely low incidence of complication—4 to 6 %. A disadvantage of lateral mass plating, however, is that it is primarily an in situ fixator and cannot be reliably used for reduction of a significant kyphosis, which is why for major anterior compression, kyphosis, or cases with very poor bone quality in the lateral masses, an anterior approach is recommended with posterior supplemental fixation as deemed necessary to enhance stability and maintain the operative correction.

With regard to the surgical anatomy, the posterior neck musculature consists of three layers: superficial, intermediate, and deep. The superficial layer is composed of the splenius capitis, trapezius, and semispinalis capitis muscles. The intermediate layer is made up of the spinalis cervicis, levator scapulae, inferior oblique capitis, and longissimus capitis muscles. The deep layer is composed of the rotator cervicis longus, rotator cervicis brevis, and interspinalis cervicis muscles. The fibers for these muscles run in either the longitudinal or oblique direction which accounts for their primary role as the extensor, lateral flexors, or rotators of the neck. Due to this orientation of the muscle fibers, placement of sequential dilating tube retractors can be accomplished primarily by muscle splitting and stretching without the need for cutting, which minimizes tissue trauma and injury.

The minimally invasive technique for screw placement does not significantly differ from the open methods once the lateral mass is exposed. The exiting nerve root is more likely to be encountered by a screw trajectory that is aimed too low, and the vertebral arteries are more likely to be damaged by screw trajectories that are excessively medial. Thus, in order to avoid the neurovascular structures, the technique focuses on placing the screw into the upper lateral quadrant of each lateral mass. Screw length should allow for full penetration of the outer cortex and cancellous bone and, in case of trauma, bicortical screw penetration. The lengths typically vary between 12 and 16 mm but are affected by factors such as the patient's specific anatomy, the presence of dorsal osteophytes, and the exact screw trajectory. Although violations of soft tissues by an overly lengthy screw are seldom problematic if the trajectory is correct, preoperative measurements from CT scans can be helpful in determining the best screw length, especially if a bicortical screw purchase is desired.

Surgical Procedure

Anesthesia and Positioning

For the MI-PCF procedure, local anesthesia combined with intravenous sedation is inadequate due to the substantial risk of neurovascular injury in case of any accidental movement by the patient. Therefore, general endotracheal anesthesia is preferred for the operation along with the head rigidly affixed to the operating table using a three-point head holder. Depending on the exact nature of the pathology, consideration should be given to fiberoptic intubation if the neck manipulation necessary for a routine endotracheal intubation may considerably increase the risk of spinal cord injury. For cases with a high risk of venous air aspiration, a central venous catheter should also be placed into the right atrium and precordial Doppler monitoring should be used by the anesthesiologist in order to detect such air emboli within the atrium. This also allows for rapid infusion of fluid and blood products in case of heavy blood loss.

Patients may be positioned in either a prone or sitting arrangement; however, an intermediate semi-sitting position may be helpful due to the reduced epidural venous engorgement and consequent decreased intraoperative blood loss with a minimal risk of air embolic events. Prior to finalizing the head positioning, utmost care should be directed to ensuring that the cervical spine and neck musculature are not twisted or held in a grossly unusual position. Furthermore, the neck, chin, and chest must be allowed to remain loose and free of compression, and all routine pressure points should be adequately protected.

Intraoperative somatosensory evoked potential (SSEP) monitoring of the operated dermatome and distal distributions is highly recommended in order to monitor spinal cord integrity during surgeries where decompression is to be combined with fixation. Electromyographic recordings can also be used to assess motor integrity of the involved nerve root and can be used to stimulate the drills and screws to increase safety and accuracy. This requires that the anesthesiologist refrain from the use of neuromuscular paralytics following the induction in order to allow for improved feedback from the nerve root during the operation.

For most cases, a single intraoperative dose of either cefazolin or vancomycin is used for prophylaxis against infection. The role of methylprednisolone or other steroids for neural protection during the MI-PCF procedure has not been adequately studied; therefore, the use of these medications is not recommended.

Intraoperative real-time imaging is a necessity for the MI-PCF; therefore, a fluoroscopic C-arm should be brought into the surgical field. While lateral imaging is most commonly used for this procedure, the C-arm should be positioned in a manner that allows for easy rotation into various positions since visualization in other planes may

become necessary—for example, anteroposterior fluoroscopic images can be helpful during the initial localization. Whereas lateral mass fixation can be accurately performed using anatomic landmarks, cervical pedicles should be cannulated with the use of supplemental fluoroscopic confirmation whenever feasible.

Tubular Dilation and Exposure

While planning the skin incision for the MI-PCF procedure, one should take into consideration the ultimate trajectory of the working portal which should match that of the lateral mass screws—20–30° laterally and 20–30° rostrally. As such, lateral fluoroscopy is essential for safe and appropriate guidance and to ensure proper ergonomic placement of the working portal directly on target.

After the patient is properly positioned, a Kirschner wire (K-wire) is placed lateral to the neck to exactly parallel the facet of interest and determine the center of the skin incision. Typically, this skin entry point lies two to three segments below the target level in the sagittal plane and at the midline in the axial plane, which closely approximates the typical trajectory used during open lateral mass fixation.

Once this entry point is determined, under fluoroscopic guidance, the K-wire is inserted through the posterior cervical musculature and fascia to the target facet, taking care to remain parallel to the facet joint in the sagittal plane, with the pin trajectory directed in a superior and lateral direction, approximating the desired screw orientation. Particular caution should be taken at this point to ensure that the guidewire is docked on bone to avoid inadvertent damage to the spinal cord by penetrating the interlaminar space. To decrease the chances of this type of injury, it is recommended to aim more laterally than medially during this docking maneuver. The K-wire should ideally rest in the medial aspect of the facet complex—this can be confirmed through anteroposterior radiographic imaging.

Once the guidewire is docked on the facet in question, the skin incision should be extended above and below the K-wire entry point for about 1 cm in each direction and deepened sharply to just below the level of the fascia, taking care not to cut muscle fibers during this procedure to avoid unnecessary blood loss. This sharp opening of the fascia allows for easier passage of the sequential dilating cannulas. At this point, if a barrier such as Ioban® has been placed on the skin, it should be removed from the edges of the incision to prevent plastic sequestra that can occur during placement of the tubular dilators.

The dilators are then sequentially inserted through the soft tissues and docked on the facet of interest over which a final tubular working channel is inserted and docked at the junction of the lamina and the lateral mass. Real-time lateral fluoroscopic images should be obtained as often as needed to ensure a proper working trajectory throughout this process of serial cannula insertion. A variety of working channels are available, which includes fixed 20 or 22 mm portals. As an alternative, expandable cannulas can provide a greater working space and more flexible approach angles for hardware placement. In such instances, the portal can be distally expanded to encompass the target fixation levels. Once the position of the working channel is confirmed using fluoroscopy, it is attached to a flexible retractor affixed to the side rain of the operating table and locked in position.

Visualization can be achieved using loupe magnification, an operating microscope, or with an endoscope. Simple loupe magnification combined with an intratubular light source is especially recommended for cases of simple facet dislocation since it allows for multiple viewing angles that are needed for drilling of the facet, reduction of the dislocation, and placement of the lateral mass screws. For cases where extensive laminotomy, partial facetectomy, and foraminotomy are indicated, a high-quality operating microscope should be utilized. If employed, the endoscope should be white-balanced and an antifog agent should be applied to the lens following which the endoscope is attached to the tubular retractor via a circular plastic friction couple or mounting stage.

Instrumentation

For the placement of lateral mass plates, care must be taken to fully expose the facet joints and lateral borders of the lateral masses, which can be readily accomplished with a shielded monopolar cautery combined with pituitary rongeurs. While the capsular ligaments and soft tissue around the facets are removed, the facet joints above and below the involved ligaments should remain intact to prevent late instability or fusion at those levels. The monopolar cautery can be used to stop bleeding such as that from the venous plexus lateral to the lateral masses; however, caution should be exercised to avoid inadvertent injury to the vertebral artery by avoiding overly aggressive cautery in this region. Alternatively, gentle tamponade with Gelfoam® or Surgifoam® will often effectively stop bleeding from this venous plexus.

For cases where facet realignment is not necessary, the lateral mass screws can simply be placed in an in situ fashion. If open reduction is needed, a high-speed drill can be used to remove a portion of the superior articular process of the inferior vertebrae, and a Penfield-type instrument can then be inserted within the facet and rotated to elevate and posteriorly displace the subluxed lateral mass into proper anatomical alignment. An alternative method for open reduction involves disengaging the head holder after drilling of the facet edges followed by gentle in-line traction, appropriate anterior translation, and counterrotation opposite to the mechanism of injury for proper facet realignment. The head holder is then relocked and the facet complex fused in situ.

It is highly recommended that neural monitoring combined with nerve root surveillance at the pathologic level be used during such maneuvers.

For the screw placement, the entry point is approximately 1 mm medial to the center of the lateral mass. The outer cortex should be pierced either with an awl or a high-speed drill in order to prevent the drill from sliding over the lateral mass instead of entering the bone during screw placement. For C3 to C6 (and sometimes C7), it is recommended that the drill holes be made with a 15–20° cephalad angle and a 30° lateral trajectory. This rostral angle targets the transverse process and decreases the chance of damage to uninvolved joints. By starting the drill hole 1 mm medial to the center of the lateral mass and aiming laterally, there is less risk of damage to the vertebral artery which usually lies anterior to the junction of the lamina and the lateral mass. After drilling, the dorsal cortex can be tapped using the 3.5 mm cancellous tap. Because the majority of the new polyaxial screws are self-tapping, this step is not essential.

Should neural decompression be necessary, it is recommended that the screw sites be marked, drilled, and tapped prior to removing the laminae. This method protects the dura and spinal cord during the drilling process [35].

The joint cartilage from the facets should be removed prior to instrumentation, and the joint should be decorticated using a high-speed drill with a small bit. Although there is a wide body of literature demonstrating successful arthrodesis without the use of bone graft, it is generally recommended to use bone grafts—such as cancellous autologous bone from the iliac crest—within the facets as well as over the decorticated laminofacet junctions. Given the postoperative pain syndrome associated with iliac bone harvesting, as an alternative source of autologous bone, the dust obtained during facet drilling, laminotomy, and foraminal decompression can be used. This graft can then be combined in a one-to-one ratio with an appropriate bone extender, such as demineralized bone matrix or calcium triphosphate substitutes.

After denuding the facet and placement of bone graft, the appropriate length lateral mass screw is then inserted under both direct visualization and fluoroscopic guidance. Depending on the size of the lateral mass, 14 or 16 mm length, 3.5 mm diameter, screws are typically used. The exact size can be measured on the CT scan or estimated from lateral intraoperative fluoroscopy. The tubular retractor arm usually must be relaxed at this point to allow easy acquisition of the second screw trajectory following which the second screw is placed in the manner detailed above.

Since the C7 lateral mass is much thinner than that of the more rostral levels, placement of a lateral mass screw may prove to be excessively difficult; therefore, a pedicle screw may need to be used at this level instead. Furthermore, cervical pedicle screws may attain greater pullout strength than lateral mass screws due to the greater length and circumferential cortical penetration. Cervical pedicle screws may also be used in levels where the lateral mass is fractured or unusable. There is usually no vertebral artery in the transverse foramen at the C7 level which permits safer pedicle screw placement at this level and at T1. For C7 pedicle screw placement, the drill is generally angled 25–30° medially and perpendicular to the rostral-caudal plane. At the T1 level, the angle is usually 10–15° medially and 5° caudally. A careful examination of the preoperative CT scan is important in order to determine the pedicle size and to gauge the appropriate angle. Usually, a 4.0 mm cortical screw of 20–22 mm length is sufficient in size. A small laminotomy can be made to palpate the pedicle directly for safe placement of the screw.

Following placement of the screws, an appropriate-sized rod is inserted into the top of the polyaxial screws and locked into place (Fig. 13.2). The rod diameter generally varies from 3.2 to 3.5 mm, depending on the specific system used. Rod placement is more technically challenging when fusing three adjacent segments, but careful dorsal elevation of the tubular retractor system away from the facet joints usually creates adequate space for rod manipulation and placement. For this reason, the expandable retractors in conjunction with modern top-loading polyaxial tulip head fixation systems are particularly useful at providing a larger working space. For such third-generation posterior cervical instrumentation systems, there are subtle variations in the exact types of connectors, offsets, and locking devices used, all of which are explained in the individual instrumentation guides from each manufacturer. Once the rods are locked into place, the construct is completed. Appropriate lateral and anteroposterior fluoroscopy should be used at this point to confirm proper bony alignment and construct placement, following which the tubular retractor is removed.

For cases where bilateral fixation is needed, the above steps can be repeated through the same midline incision, using a contralateral trajectory.

Another method of posterior cervical fixation is through a transfacet approach using a facet compression device. For this procedure the optimum entry point for the screw is on the center of the lateral mass with a trajectory that is perpendicular to the facet joint (Fig. 13.3). As such, the incision should be placed more rostrally in order to allow for the insertion of the K-wire in such a manner that it docks at 90° to the facet and parallel to the spinous process. Once the entry point and trajectory have been confirmed, the K-wire is driven into the superior articular process to a depth that is determined by the length of the specific compression device to be used. Fluoroscopy should be used in order to insure appropriate depth and trajectory.

At this point the bone is drilled through the superior lateral mass, across the facet, and into the inferior lateral mass to a depth of about half to two-thirds of the inferior lateral

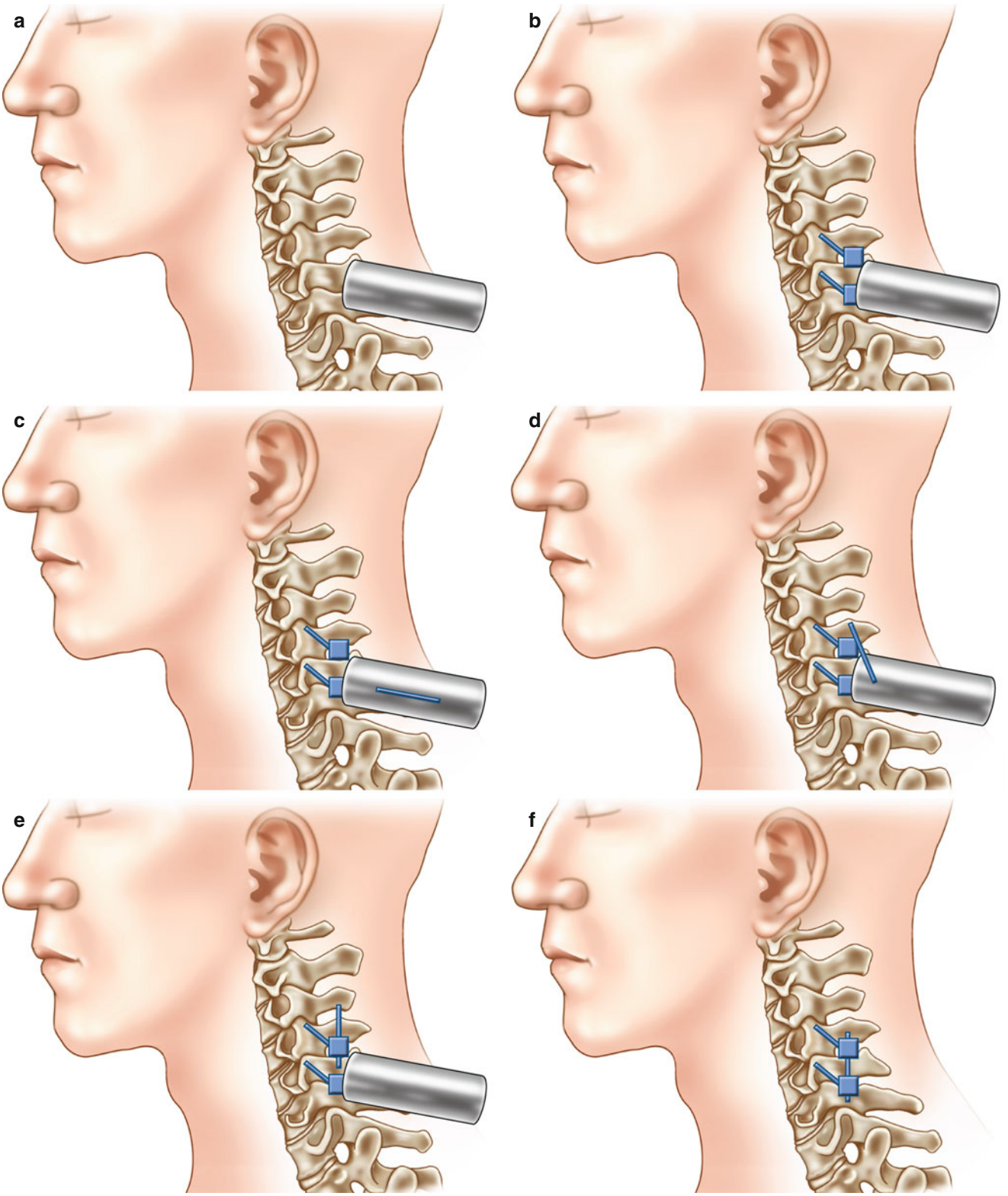

Fig. 13.2 Following placement of the lateral mass screw (**a**, **b**), the rod is advanced through the tubular dilator (**c**–**f**)

mass width as guided by lateral fluoroscopy. This procedure is facilitated by systems that supply cannulated drills with depth limiting contacts that are designed to be passed over the K-wire. For this system, after the proper depth has been achieved, the drill hole is tapped and the compression device is passed over the K-wire, engaged, and locked in place.

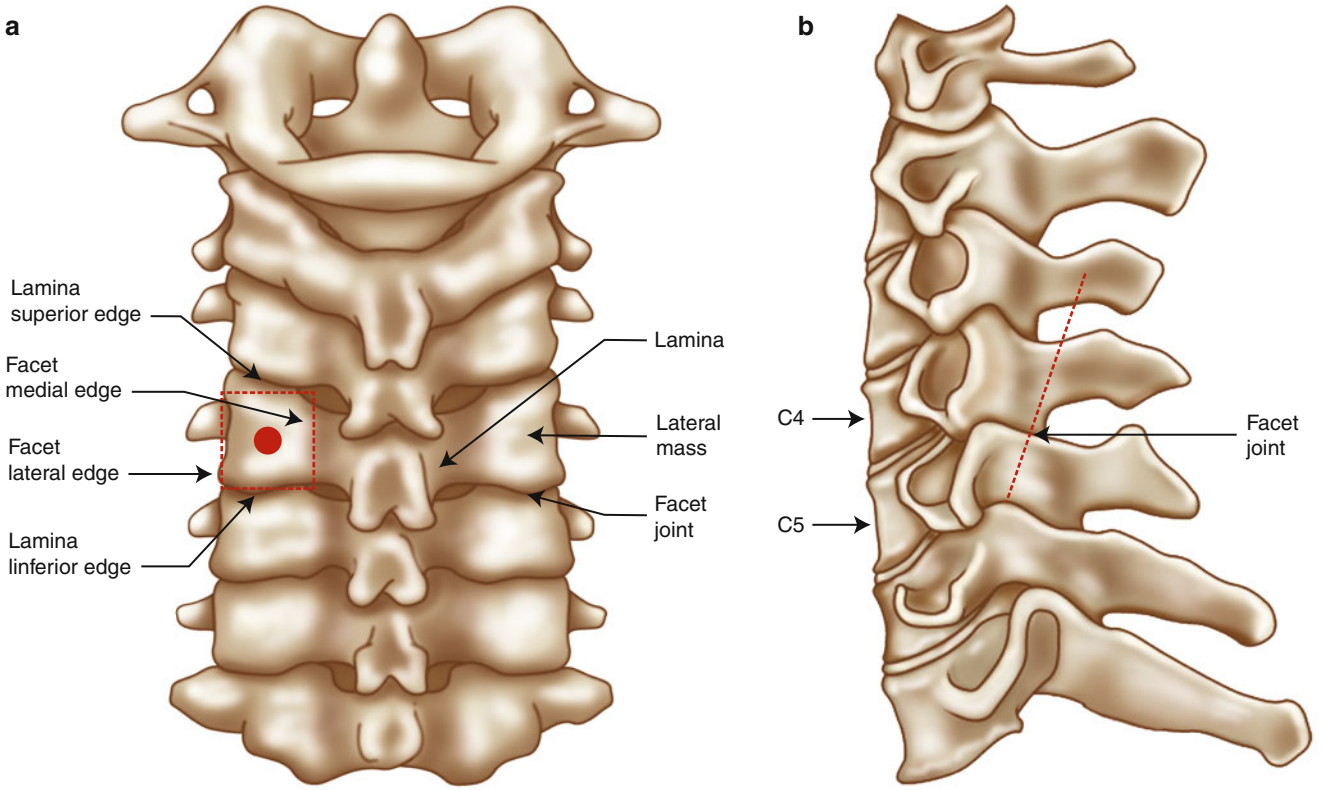

Fig. 13.3 The optimum entry point for the screw in the transfacet instrumentation approach is marked as the center of the lateral mass of C4 (**a**) with a trajectory that is perpendicular to the C4–C5 facet joint (**b**)

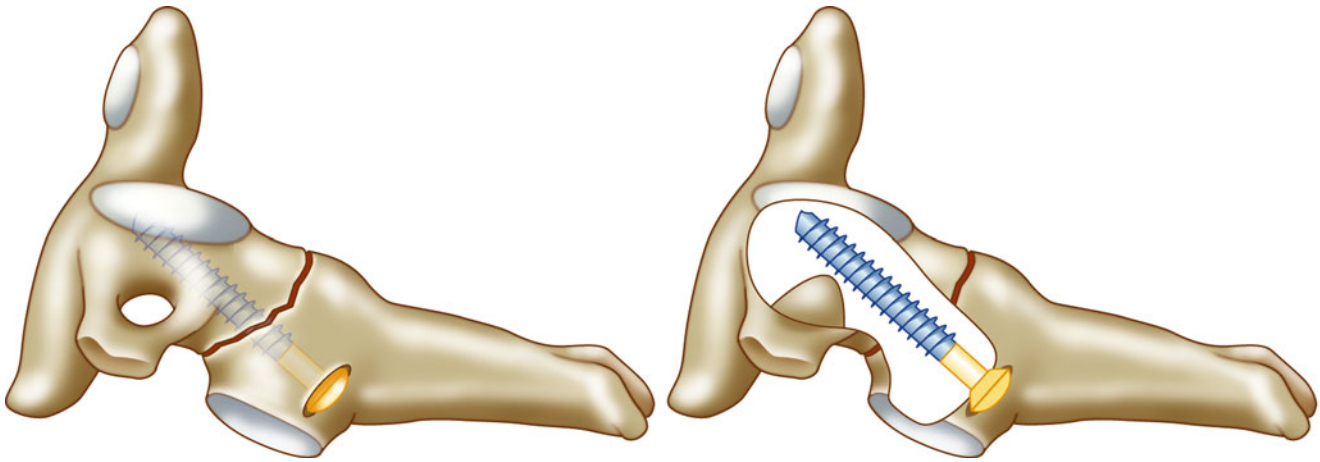

Fig. 13.4 Lateral and cutaway lateral image showing the entry point and trajectory of screw placement for Hangman's-type fracture

The K-wire is then removed and the procedure is repeated for the contralateral side in a similar manner.

While this transarticular fixation system allows for fixation at all cervical levels including C1 and C2, a modified version of the abovementioned procedure can also be used for arthrodesis in cases of trauma such as operative cases of Hangman's-type fractures. The initial approach for this type of surgery is similar to the transarticular procedure described above in that the entry point for the drill is at the center of the C2 lateral mass with a trajectory that is parallel to the spinous process in the lateral plain; however, instead of the device being aimed inferiorly, the trajectory in the cephalad-caudad direction is toward the superoanterior border of the C2 pedicle at a depth that allows for bicortical purchase (Fig. 13.4). Once this trajectory is confirmed by lateral fluoroscopy, the remainder of the operation is completed as described above.

Closure

Prior to closure, meticulous hemostasis should be obtained by a combination of bipolar cautery and gentle tamponade with thrombin-soaked Gelfoam® or Surgifoam®. The entire wound is then copiously irrigated with lactated ringers impregnated with bacitracin antibiotics. Although optional, a small pledget of Gelfoam® soaked with methylprednisolone can be placed over the decompression defects, if present in order to decrease local inflammation.

Following hemostasis, the tubular retractor and endoscope are cautiously removed, and the soft tissue corridor is washed with antibiotic irrigation prior to a routine closure of the fascia with one or two 0 Vicryl® or similar absorbable sutures. Because the defect is typically small, only a limited amount of closure needs to be performed, and a drain is not needed. Bupivacaine (0.25 %) may be injected into the skin edges and superficial musculature prior to closure in order to minimize immediate postoperative pain. Inverted 2-0 Vicryl® stitches are usually used to close the subcutaneous layer with a 4-0 Monocryl® subcuticular closure to meticulously reapproximate the skin edges. Either Steri-Strips® or Dermabond® can then be used to cover the skin. The latter is an attractive option since it keeps the skin edges closely approximated for a 7- to 10-day period, and it provides a waterproof barrier, allowing the patient to shower almost immediately after surgery, if desired.

When a CSF leak occurs, direct repair is often difficult because the durotomy is usually small and access is limited. Thus, the use of a lumbar drain is advocated in these cases for 2–3 days postoperatively, combined with elevation of the head of the bed, in order to help closure of the small dural tear. Such adjuncts as fibrin coagulation products, fat, or muscle grafts can also be used. Spinal headaches and nausea associated with the lumbar drainage can be treated symptomatically with nonsteroidal anti-inflammatory medications and bed rest. For large dural tears, direct repair can be attempted if specialized instruments are available for use through the endoscopic tube—fine-tipped needle holders and long forceps are particularly useful in this regard. In rare instances, conversion to an open procedure may be necessary to close very large dural violations.

Clinical Experience

The initial experience with minimally invasive cervical fixation at UCLA consists of 10 patients followed to radiographic fusion—6 patients underwent a single-level fusion and 4 patients with two-level fusions. Instrumentation was performed at the C3 to C7 segments with bilateral screw placement with the exception of 3 cases where lateral mass screws were placed unilaterally due to bony fractures on the contralateral side. Seven cases were posterior supplementations of anterior fusions, and three were stand-alone posterior constructs. Seven of the ten patients underwent surgery due to traumatic pathology with cervical burst fractures and fracture dislocations treated with combined anterior and posterior fusions. In three cases with bilaterally jumped facets treatment consisted of drilling and removal of the superior facet followed by intraoperative reduction and hardware placement with fusion. Three cases were posterior supplements to an anterior vertebrectomy for neoplasia.

All procedures were accomplished successfully with the use of 18–22 mm tubular dilator retractors. There were no complications or new neurologic deficits, and proper hardware placement was confirmed with a postoperative CT scan. In one case, the C6 screw was positioned fairly laterally with penetration of the lateral cortex of the lateral mass; however, no additional procedure or follow-up studies were deemed necessary as this was still thought to provide a stable construct. Fusion was confirmed in all cases with dynamic x-rays and CT scans.

Current tubular dilator dimensions limit the feasibility of this minimally invasive approach to one- or two-level fusions, since longer-segment constructs pose a problem with rod placement. However, the development of elliptical expandable tubular dilators may allow longer constructs to be placed safely. Furthermore, strategies similar to the arc rod systems and polymerizing connecting rods, which currently allow true percutaneous transpedicular instrumentation in the lumbar spine, may also prove to be beneficial in the cervical spine where it may ultimately allow for placement of longer-segment cervical constructs in a minimally invasive fashion.

Radiographic guidance is essential for safe screw placement, and fluoroscopic images may be inadequate for the lower cervical spine in patients with a short neck, large body habitus, or muscular shoulders. Image-guided systems surmount this problem and allow for virtual representation of the spine without the need for real-time x-rays. However, these systems are limited in accuracy with regard to the differences in the intersegmental relationships between vertebrae in preoperative image acquisition and final operative positioning. These inaccuracies are especially exaggerated in cases with abnormal intersegmental motion or in patients who require reduction of a fracture.

The emergence of three-dimensional fluoroscopic imaging allows for intraoperative acquisition of axial CT renderings of the spinal column. These images are less hampered by superimposed soft tissues, which allow access to the lower cervical spine for the purpose of minimally invasive screw placement. Furthermore, because the images are acquired intraoperatively, screw trajectories can be more reliably confirmed by guidewire placement prior to final instrumentation. Amalgams of 3-dimentional intraoperative imaging modalities with frameless navigation systems will ultimately make percutaneous placement of cervical instrumentation safe and accessible.

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Percutaneous Pedicle Screws

14

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Indications and Contraindications

Percutaneous placement of pedicle screws may be performed as an alternative technique of screw placement in practically any situation where open pedicle screw fixation is indicated. Thus, accepted indications for open pedicle screw fixation also apply for percutaneous fixation. It can be employed to provide supplemental fixation to interbody or posterior fusion procedures, to stabilize the spine in cases of infection or tumor, or as an internal brace in the setting of trauma.

The most obvious advantages of percutaneous over conventional open fixation relate to the minimal muscle dissection and stripping involved. This decreased approach-related morbidity has been shown to translate to reduced operative blood loss, postoperative pain, and narcotic medication requirement [1–3]. Other benefits include earlier hospital discharge [2], a milder spike in serum/urine levels of muscle breakdown products (e.g., CK-MM) [4], and greater preservation of paraspinal muscle (trunk) strength [2].

Another important advantage of percutaneous screw fixation is that it more easily allows optimal screw trajectory. With open screw placement, the paraspinal muscles often act as a mechanical impediment against screw medialization, predisposing to a lateral breach through the vertebral body. Furthermore, the muscles also frequently force the surgeon towards a more medial starting point, predisposing to cranial facet joint impingement. With percutaneous fixation, the muscles fibers are split rather than detached and retracted; this allows for easier medialization as well as a more lateral starting point right at the junction of the transverse process and the lateral wall of the ascending articular process. It should be noted, however, that published studies on facet joint impingement by percutaneously placed pedicle screws show inconsistent results, with impingement rates ranging from 11 to 58 % [5–8]. It is not clear whether this wide range may be reflective of a long learning curve, differences in technique of screw placement, or different criteria used in assessing facet joint violation.

Some patients have a form of lumbosacral transitional segmentation where the shape of the L5 vertebral body on the axial plane is more aptly described as heart shaped rather than round. These may provide a difficult challenge in pedicle screw placement, as a more medial trajectory is required to prevent a lateral breach (Fig. 14.1). Our preference in these cases is to place screws percutaneously rather than open for the advantages cited above. If the surgeon feels more comfortable performing other aspects of the surgery (e.g., posterior decompression, transforaminal lumbar interbody fusion) through an open midline approach, then percutaneous screw fixation can be performed in conjunction with a conventional open approach.

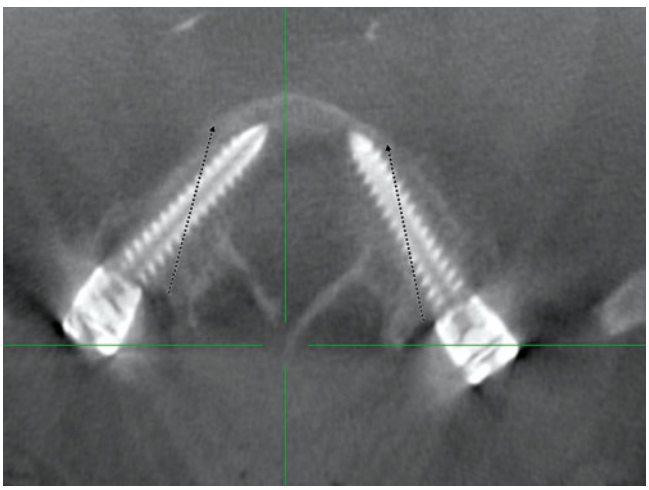

Fig. 14.1 Axial intraoperative CT scanner scan image of an L5 vertebral body demonstrating the projected pedicle screw trajectory in open technique (*dotted lines*) and actual percutaneously inserted screw. Because of a more lateral entry point afforded by percutaneous pedicle screw placement, the supradjacent facet joint can be avoided

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In percutaneous fixation, since direct visualization of anatomic landmarks is sacrificed in favor of a more tissue-friendly approach, one has to be able to make up for this in order to maintain accuracy. Typically, this is facilitated by the use of C-arm fluoroscopy [3, 9–13]. More recently, computer navigation (image guidance) based either on preoperative CT, intraoperative 2-D fluoroscopy, or intraoperative 3-D imaging has been increasingly utilized [14–17]. A major contraindication therefore to percutaneous screw fixation would be unavailability of these appropriate imaging modalities, as well as inability to obtain and interpret images of acceptable quality, such as could be encountered in obese and/or severely osteoporotic patients.

Concern over increased radiation exposure to the patient, and more importantly the surgical team, has been raised [18, 19]. This can be addressed by observing measures to reduce radiation exposure such as lead shielding, using pulsed image acquisition, and proper positioning in relation to radiation source. Lead aprons, thyroid shields, and lead-impregnated gloves and goggles should be made available in operating rooms and radiology suites. Awareness of scatter radiation near the beam source is also important. Using instruments to hold the needle, or taking one's hand away during image acquisition when an instrument is already firmly embedded in bone (aka "hands-off technique"), also helps reduce radiation exposure. Lastly, judicious use of imaging and eliminating unnecessary or superfluous image acquisition is good practice.

Surgical Technique

In this section, we will discuss the two techniques that we employ in placing percutaneous pedicle screws: 2-D fluoroscopy and intraoperative 3-D imaging computer navigation. Other techniques such as electromagnetic field (EMF) navigation [20], navigation using accelerometer technology [21], and robotic guidance [22] will not be discussed.

Percutaneous Pedicle Screw Fixation Using 2-D Fluoroscopy

The procedure is most commonly performed in the prone position, although it may also be performed in the lateral position. Prior to draping, it is very important to make sure that there are no obstructions to imaging. For example, if a regular operating table is used, the spinal region of interest should not be positioned over the table post; this would get in the way of the C-arm. We prefer to use a spinal table with radiolucent frames and pads and without a central bed post (Fig. 14.2).

The technique of 2-D fluoroscopy-guided percutaneous pedicle screw fixation is similar in many respects to the technique of needle placement described for vertebroplasty and kyphoplasty procedures [23]. First, true AP and lateral images of the operative levels are acquired. In a true AP projection, the spinous process is midline, the pedicle outlines are on the upper half of the vertebral body, and the endplates are superimposed (i.e., no double shadow). In a true lateral projection, the pedicles as well as the endplates are superimposed (Fig. 14.3a, b). In the process of obtaining true AP and lateral images, it is advisable to tilt the bed side to side (i.e., "airplaning") and leaving the C-arm in the 0°and 90° positions. Note that because of normal lordosis, the C-arm tilt (in the cephalocaudal direction) may need to be adjusted from one level to the next. This helps ensure that the pedicle screws would be parallel to the endplates.

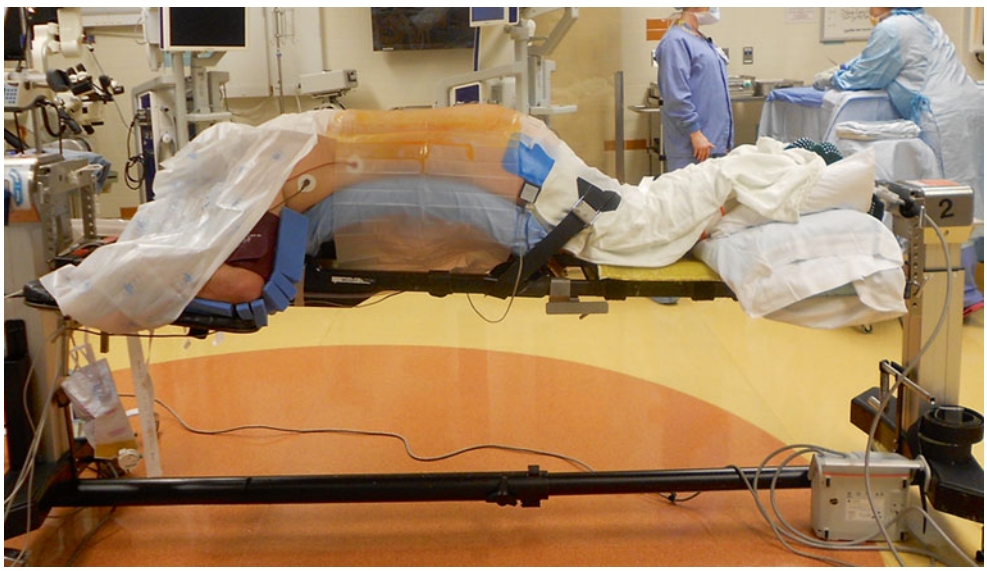

Fig. 14.2 Operative setup for percutaneous pedicle screw placement with the patient in prone position on a well-padded, radiolucent spinal table

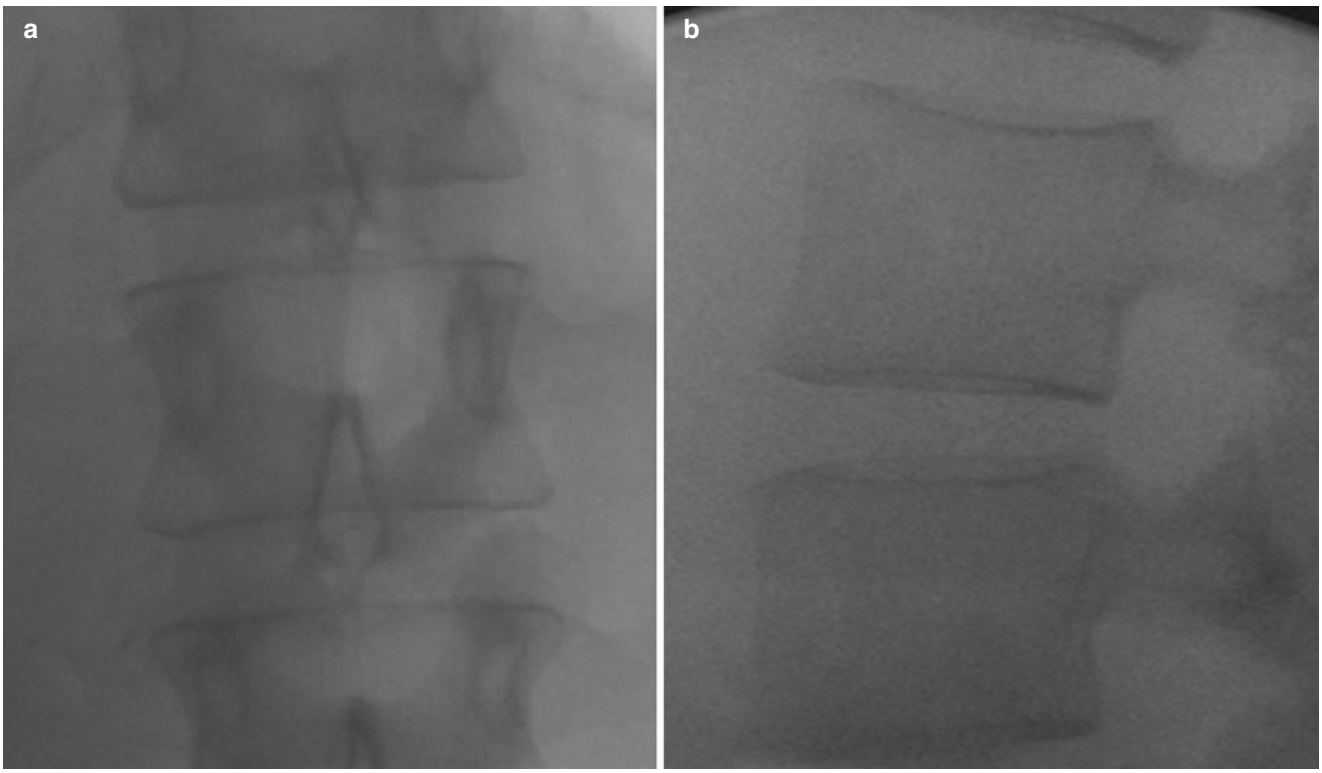

Fig. 14.3 Fluoroscopic images showing how vertebral bodies should look like in the AP (**a**) and lateral (**b**) views prior to percutaneous pedicle screw insertion

Some surgeons prefer to use the "owl's eye" view, which is an oblique C-arm view that looks down the barrel of the pedicle, and have reported good success rates [21, 24]. We do not routinely use this technique and would refer the interested reader to the references cited.

On the true AP image, the outlines of the pedicles are drawn on the skin. This is usually facilitated by using K-wires to trace the lateral and superior borders of the vertebral bodies. We prefer to trace the superior borders with the C-arm gantry in the true AP position for each level. Thus, in very lordotic segments, such as between L5 and S1, the two lines may be very close to each other. After this step, the surgeon then decides where to draw the skin incision on either side. One may choose to refer to the preoperative MRI or CT axial images and measure the distance from midline where the pedicle axis intersects with the skin. This distance varies among patients and is largely influenced by the angulation of the pedicle as well as patient size. Generally, the distance from midline increases with each level going down (Fig. 14.4). At the L5 and S1 levels, however, the iliac crest may limit the lateral extent of screw trajectory and thus the skin incision.

The surgeon may choose to make a single skin incision to place all the screws; this is usually the case in lordotic segments such as L5–S1. If the surgeon chooses to make separate skin incisions, we recommend that these incisions be made collinear such that they could easily be connected in a cosmetically appealing manner should the need arise. At this point, it is best for the surgeon to be familiar with the diameter of the dilators, screw extenders, and other instruments of the system being used, in order to gauge the length of incision necessary to place the screws. The incision is then carried down through the subcutaneous tissue until the

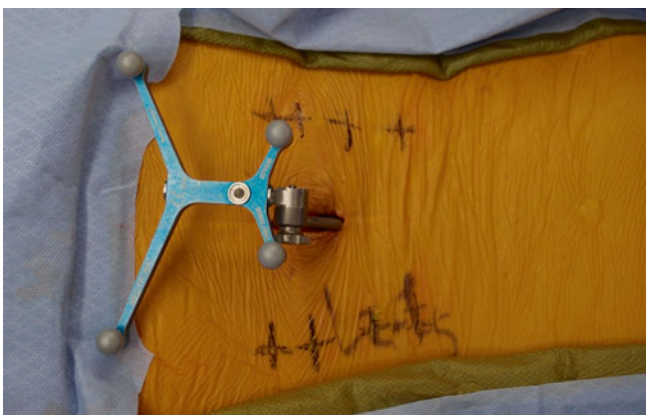

Fig. 14.4 Markings showing the skin entry site of the Jamshidi needle into the pedicle. Pedicle distance from midline typically increases from the upper to lower lumbar spine. This image also shows a reference frame attached to a spinous process for use in computer-assisted navigation procedures

dorsolumbar fascia is identified. At this point, the dorsolumbar and muscle fascia layers may either be incised or not. We prefer to incise the fascia longitudinally in line with the muscle fibers and the skin incision to minimize the subsequent tension on the K-wire and dilators. We then perform a blunt finger dissection splitting the muscle fibers down to the facet joint and the transverse process.

We guide the Jamshidi (bone biopsy) needle cannula down to the transverse process and use it to probe the rostral and caudal edges of the transverse process, staying at the midportion. We then "walk" the cannula medially until it hits a "wall," which would then correspond to the lateral wall of the superior articulating process. We prefer to initially slide only the cannulated portion of the needle down without the sharp trocar, so as to prevent perforating the glove of the guiding finger. Once docked on bone, we then insert the trocar through the cannula, taking care to maintain position. We then take an AP shot to verify the position of the needle as well as the operative level; we find the aforementioned technique very helpful in minimizing the number of C-arm shots required in getting to the optimal starting point.

During the pedicle cannulation process, the C-arm is kept in the true AP position; we only switch to the lateral position after all the pedicles have been cannulated and K-wires are in place. Others prefer the use of biplanar fluoroscopy with two C-arm units. In the true AP position, the ideal starting point is just outside the pedicle shadow, with the needle tip either in the 3 o'clock (right) or 9 o'clock (left) position [25]. We then gradually advance the needle by tapping with a mallet. We assume that the distance between the starting point and the level of the posterior vertebral body wall (i.e., length of the pedicle) is about one inch. We thus mark the needle (using a marking pen) about an inch away from the skin in order to determine that we have advanced the needle by an inch. The needle trajectory is forward and medial, aiming towards the 9 o'clock (right) or 3 o'clock (left) position. At about the one-half inch mark, we pause and take an AP shot to check the trajectory and needle position. The goal is that by the time we reach the one inch mark, the needle tip on the true AP view is within the pedicle shadow, approaching but not going beyond the medial border of the pedicle (Fig. 14.5). If these conditions are met, the needle is then presumed to be in acceptable position and a K-wire is advanced through the cannula, about 1–2 cm deeper into the vertebral body. The cannula is then removed, leaving just the K-wire. To prevent the K-wires from getting in the way while the rest of the pedicles are cannulated in the same fashion, they are held against the drape with use of a non-penetrating clamp. Care should be taken not to make an acute bend that would deform the K-wire (Fig. 14.6).

After all the K-wires have been placed, a true AP shot visualizing all of them is taken and saved onto one of the screens of the C-arm monitor (most fluoroscopy units have 2 screens that allow viewing of different pictures side by side). The C-arm is then switched to a lateral position, and a picture is taken. It is important for the surgeon at this point to assess each K-wire, correlating its position on both the AP and lateral images. K-wires that are not in acceptable position are then removed and reinserted by repeating the above procedure. If so, the surgeon should decide whether to use the same pilot hole and simply redirect the screw or to create a

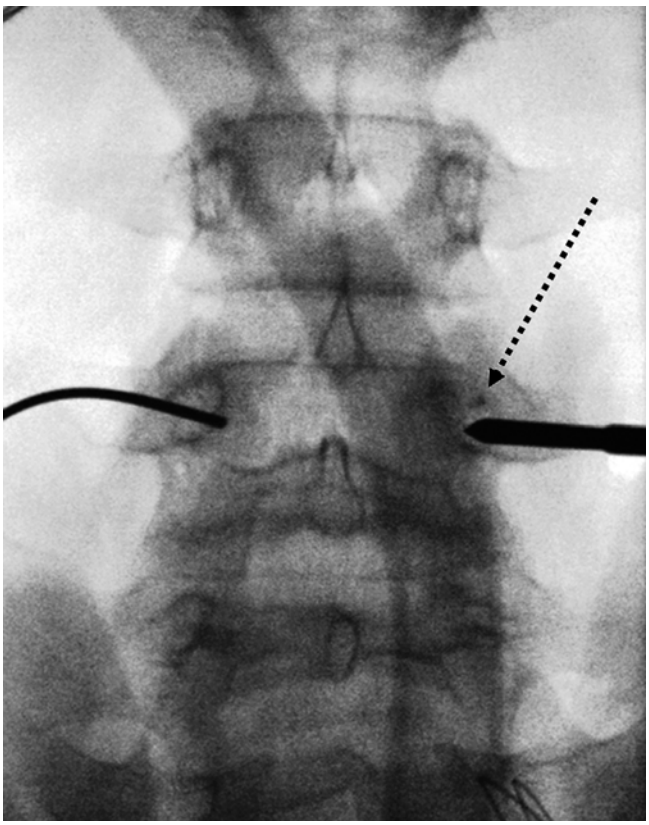

Fig. 14.5 A fluoroscopic image of the Jamshidi needle (*dotted arrow*) is shown at its half inch mark. Note that it has not yet reached the medial pedicle wall indicating that the needle is in the right position

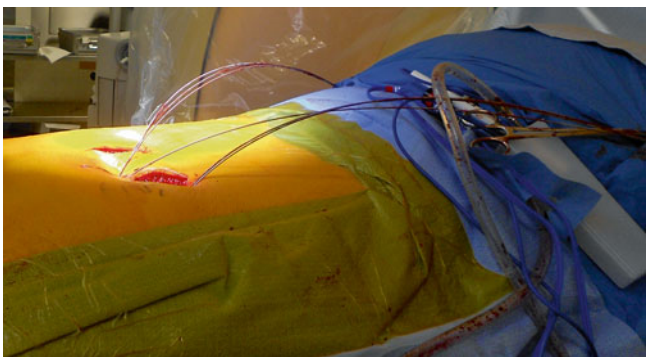

Fig. 14.6 K-wires are clamped into place to provide clearer fluoroscopic view and avoid inadvertent break in sterility by puncture of the free ends of the wire

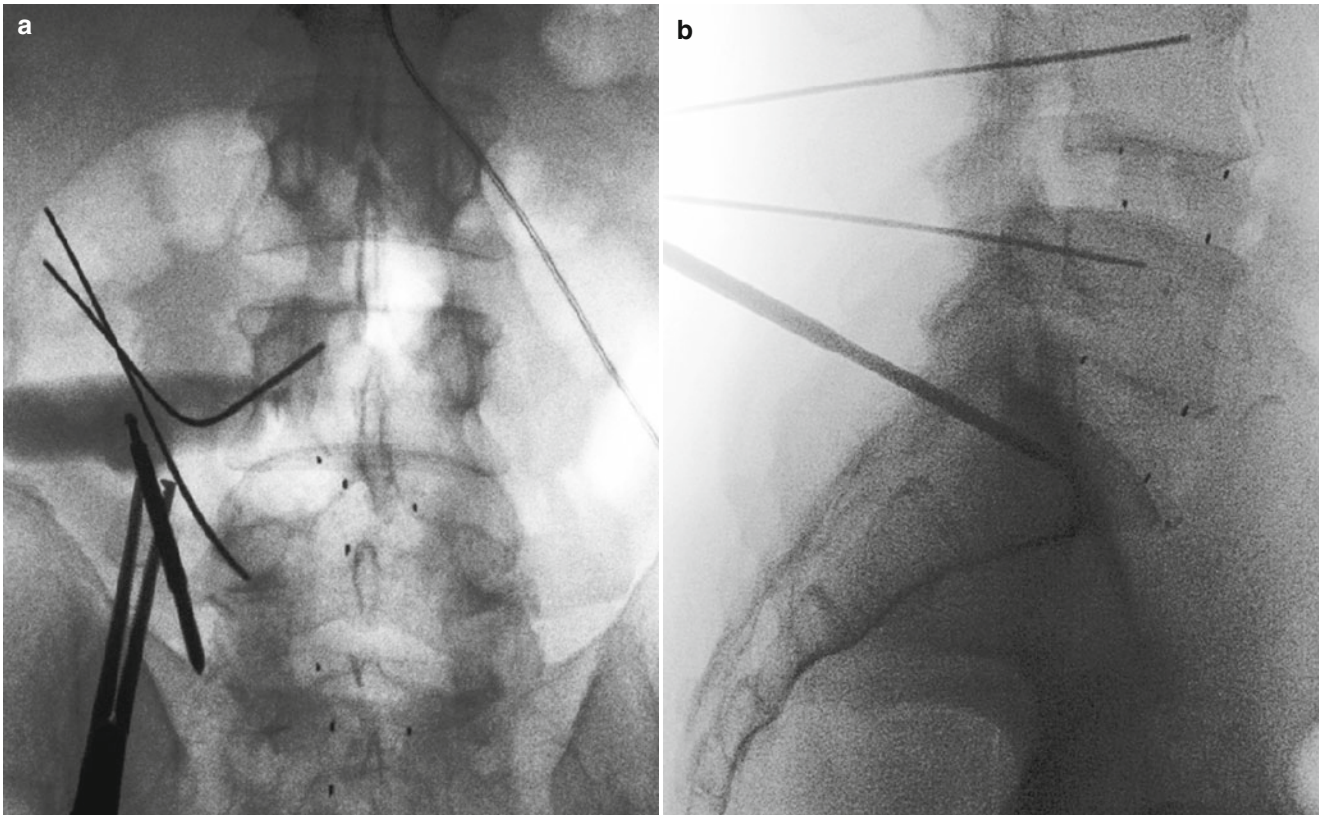

Fig. 14.7 An AP (**a**) and lateral (**b**) image of the operative levels should be taken to confirm that K-wires are in correct position

new starting point. On the other hand, K-wires that are in good position but are only through to the posterior half of the vertebral body may be advanced further until they are in the anterior half. When doing so, the surgeon should always keep in mind the 3-D structure of the vertebral body. A K-wire that is fairly lateral in position would likely break out of the anterior cortex even though the lateral image shows the tip to be well behind the anterior vertebral body wall; for this reason, we do not routinely advance the K-wire up to this point. However, we prefer to advance them deep enough to be in the anterior half of the body, so as to prevent inadvertent pullout, particularly when removing the tap (Fig. 14.7).

The next step is dilating and tapping over the K-wires. Different systems have different instruments for muscle dilation and soft tissue protection. It is important to make the skin incisions long enough to accommodate these instruments and prevent stretch/crush skin injury. If a plastic skin drape (e.g., Ioban) is used, it is also important to make sure that this is not inadvertently pushed into the wound. We prefer to use a tap 1 mm smaller (i.e., undertapping) than the planned screw diameter. This is advanced over the K-wire beyond the level of the posterior vertebral body wall, but not over the tip of the K-wire in order to avoid wire pullout. It is also important while advancing the tap to follow the K-wire trajectory as closely as possible in order to prevent binding and inadvertent advancement of the K-wire. We prefer to take a lateral C-arm shot after a few turns of the tap in order to verify its trajectory. We also mark the K-wire at the level of the handle of the tap (which may be unnecessary if the K-wire already has markings) and observe that it is not advancing with the tap.

If the surgeon desires to make small changes with screw trajectory in the sagittal plane in comparison to the K-wire trajectory, this may be accomplished by advancing the tap at the desired trajectory. Once the tip of the K-wire starts to bend on the lateral C-arm image, the K-wire is pulled out and a new wire is then passed through the tap; this new K-wire will then follow the new path [26]. When attempting to perform this maneuver, the surgeon should, however, make sure that inadvertent K-wire advancement does not occur. Furthermore, if substantial change in trajectory is desired, it is recommended that repeating the pedicle cannulation procedure be performed instead.

The pedicle screw is then inserted over the K-wire. Screw size is typically determined based on preoperative imaging studies. The surgeon may also elect to determine screw lengths based on intraoperative lateral images with the tap in place and knowing the depth of tap insertion. Again, it is important that the surgeon follow the same trajectory as the K-wire. Once the screw has good purchase within the

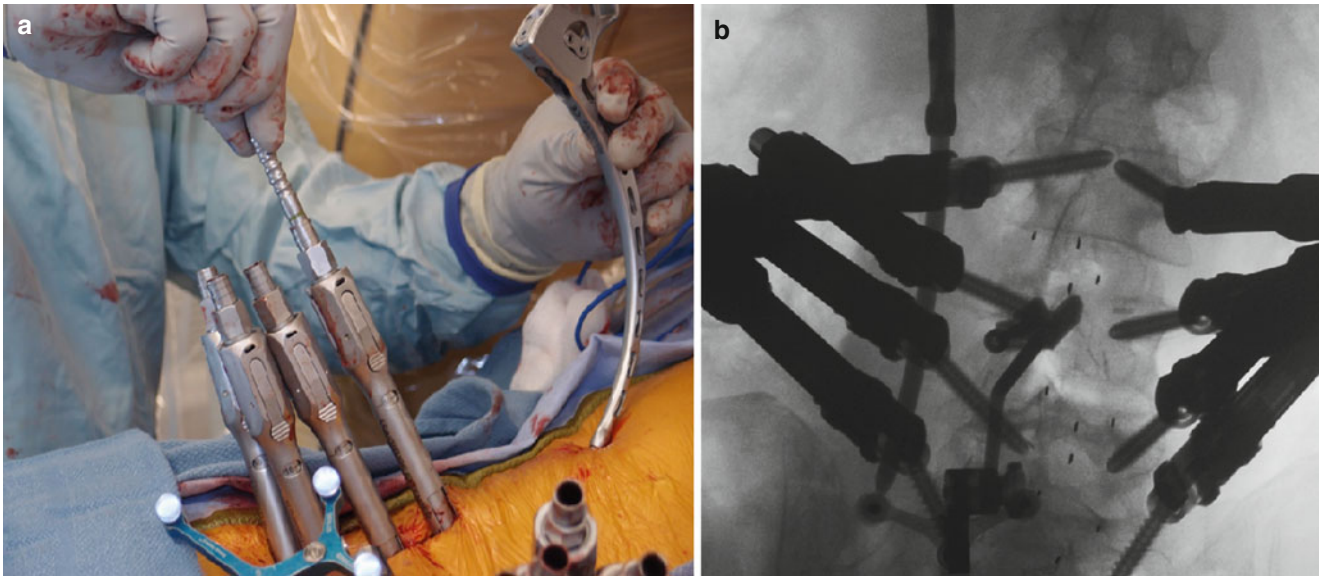

Fig. 14.8 An intraoperative image illustrating how a separate skin incision can be used as an entry point for rod insertion (**a**). A confirmatory radiograph should be taken to ascertain that the rod is properly seated on top of the screw heads (**b**)

vertebral body, the K-wire may be pulled out completely. Sometimes, the K-wire does not pull out easily, and the surgeon may need to exert a little more force to do so. Care should be taken especially in osteoporotic individuals where pulling hard on a K-wire that has bound on to a screw may end up pulling the entire screw. In order to prevent this, we recommend that a pair of pliers or vise grip be used to pull out the K-wire; instead of pulling straight in line with the wire trajectory, a rotational maneuver is performed, levering against the handle of the pedicle screw inserter, pulling and bending the wire in the process. This maneuver does not transmit a pullout force on the pedicle screw. Alternatively, the screw can be backed out 2–3 mm; the K-wire will then typically loosen and can be removed. Once the K-wire is removed, the screw is fully seated.

Make sure not to insert the screw too deep that it prevents the polyaxial screw head from angulating; this would make accommodation of the rod difficult. On the lateral image, the surgeon should try to achieve harmonious alignment of the screw heads so as to minimize stresses between the rod and the screws.

Next step is rod passage. Determining rod length may be facilitated by calipers and other measurement tools available in most systems. Most rods come prebent in some degree of lordosis. The surgeon may change this bend as deemed appropriate for the case. Depending on the system used and surgeon preference, there are different ways of passing the rod down to and through the screw heads. The simplest one is by direct vision through a single skin and fascial incision connecting the screw heads. This is commonly performed for single-level fixation and at the L5–S1 level where the screw heads are typically close to each other. Another method is to make a separate stab incision at a distance away from the skin incisions for percutaneous screw insertion. The rod is then tunneled subfascially through the muscle either using a jig or in freehand fashion until it goes through all the screw heads. The freehand technique is more useful for multilevel procedures. It is important to confirm that the rod has indeed engaged all the screw heads and with enough length both at the top and bottom of the construct prior to placing the locking/set screws and disengaging with the rod inserter (Fig. 14.8). A third method is passing the rod subfascially but through either the top or bottom incision, without making a new one. This requires a rod inserter that has the ability to angulate under surgeon control and may be more difficult for multilevel constructs.

Lastly, prior to locking the construct and removing the screw extenders and retractors, AP and lateral images should be taken to confirm acceptable screw placement, screw-rod engagement, and rod lengths.

We typically would place a drain only if a decompression was performed and there is open lamina or exposed dura. Closure is performed in layers; we prefer to perform fascial repair whenever possible.

Percutaneous Pedicle Screw Fixation Using Intraoperative 3-D Imaging Navigation

This method of screw placement replaces real-time acquisition of fluoroscopic images with virtual images based on 3-D images taken with an intraoperative CT scanner [14, 17, 27, 28]. Potential and documented advantages include (1) the ability to view axial images not available on

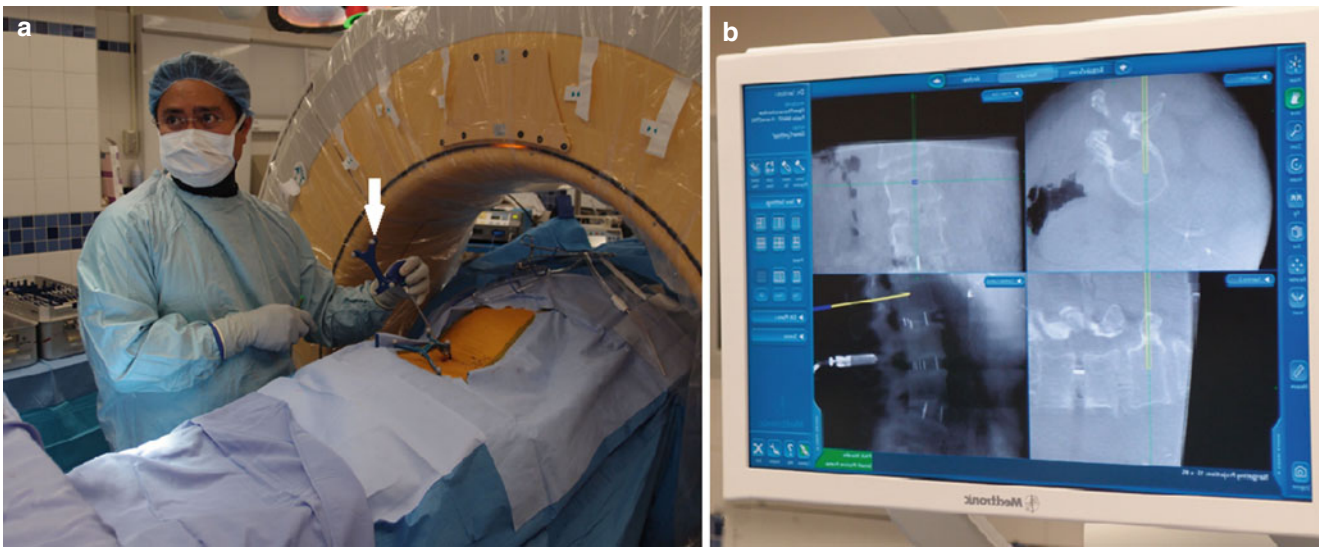

Fig. 14.9 Operative setup where the new generation intraoperative CT scanner gantry is "parked" at the head of the spinal table. To ensure clarity and accuracy of image, tracking spheres (*arrow*) must always be facing the camera (**a**). The surgeon determines the site of skin incision using three views (axial, sagittal, coronal) displayed on the screen (**b**)

2-D fluoroscopic imaging, which may help the surgeon avoid cranial facet impingement and more accurately place screws within the pedicle; (2) the ability to customize screw size (diameter and length) based on intraoperative virtual images taking into consideration screw position and trajectory; and (3) decreased radiation exposure to the surgical team [19, 29]. Regarding the radiation issue, while it is debatable whether patient exposure is increased or decreased, surgical team exposure is much decreased, since the team could step out of the operating room or hide behind lead-impregnated shields during 3-D image acquisition.

When using computer navigation based on optical tracking, a reference frame is attached to the patient. It is important that a direct line of sight be maintained between the navigation camera and the frame, as well as between the camera and the navigated instruments (e.g., probe, needle, tap, screwdriver, etc.). Considerations include the need for stable fixation of the frame and not getting in the way of the instruments. Typically, either a percutaneous pin into the iliac crest or a spinous process clamp is used (Fig. 14.4). If the latter is used, a midline incision is still made but only large enough to expose a single spinous process and accommodate the clamp.

After the frame is attached, the intraoperative CT scanner is brought into the field. New generation intraoperative CT scanners have a gantry that opens up to allow lateral entry, as well as built-in LEDs (light-emitting diodes) detectable by the navigation camera to facilitate automated image registration. Given the size of the scanner, it becomes all the more important that there is enough room around the patient's torso to accommodate the machine. It is strongly recommended that a spinal operating table be used for these cases. Once the machine is positioned and closed, AP and lateral images are taken to make sure that all levels of interest are within the imaging field. A 3-D scan is then obtained. During image acquisition, all members of the team are encouraged to be as far away from the radiation source as possible, either out of the room or behind lead shields.

After the scan, the surgeon may choose to let the scanner stay in the field and simply "park" it towards the head of the bed or to remove it from the field altogether. Some surgeons prefer to do the latter because of "space" issues and difficulty working beside a cumbersome machine. We prefer, however, to do the former, as we routinely take at least one other scan after screw placement to ensure optimal screw placement at every level (Fig. 14.9a).

Navigated instruments will need to be registered and verified to ensure accuracy; this is best done at the very beginning of the procedure to avoid delays. The surgeon is encouraged to double check the accuracy of the navigation by placing the tip of the instrument against a known and visible anatomic landmark and verifying on the computer screen that it shows the same information. Using different and simultaneous views on the computer screen (sagittal, coronal, axial), we use virtual projections/extensions of the instrument(s) in order to determine the ideal skin incision site for each pedicle screw (Fig. 14.9b). These sites are then marked with a pen. After all the sites have been marked, we then draw our skin incision (Fig. 14.4).

After incising the fascia and a blunt finger dissection down to bone, we then place our navigated bone needle on the desired starting point. Although some may consider the tactile feedback from probing unnecessary in the setting of navigation, this still serves to confirm the information

provided by the computer screen. Since there are many possible scenarios that may lead to navigation inaccuracies (e.g., inadvertent movement of the reference frame), it is important to repeatedly verify given information whenever possible.

The needle is advanced slowly by tapping with a mallet. An important adjustment compared to the previous technique is in regard to hand, arm, and body position by the surgeon. As mentioned, direct line of sight needs to be maintained at all times for navigation to work. The surgeon thus has to be mindful of directing the tracking spheres towards the camera and not covering the reference frame. By looking at the screen, the surgeon is able to visualize the needle position in the coronal, sagittal, and axial planes. After advancing the needle, the screen image may be frozen, and measurements made to optimize pedicle screw length and diameter (Fig. 14.9).

Once all the K-wires are in place, the surgeon should obtain AP and lateral images to verify positions. If there is any questionable K-wire position, we recommend that this be either repositioned or another 3-D scan be obtained.

When advancing the tap, the surgeon should also keep in mind that while the tap may be navigated, the K-wire is not. Precautionary measures as described earlier should still be observed in order to prevent inadvertent K-wire advancement or pullout. Lateral imaging should thus still be made available during tapping and screw placement (Fig. 14.10). In this regard, the intraoperative CT scanner may be used, although the circumferential gantry and the relatively small inner diameter present challenges in terms of space management. For this reason, some surgeons at this point would prefer that the CT scanner be removed from the field and a C-arm be brought in instead.

The navigation software may also be able to assist in selecting the appropriate rod length and perhaps in customizing the bend in the rod. Presently, however, we have not been using it for these purposes. In its present commonly used form, navigation also is not used for rod passage. Thus, 2-D fluoroscopy using either the intraoperative CT scanner or a C-arm is still needed (Fig. 14.8).

The reported accuracy rates of pedicle screw insertion with intraoperative CT scan and navigation ranges from 92 to 98 % [29–33]. With regard to the ability to avoid the facet joint, it has been shown that percutaneous insertion of screws with the aid of navigation can decrease facet joint violation rates compared to non-navigated percutaneously inserted pedicle screws and navigated screws inserted via the open technique [8].

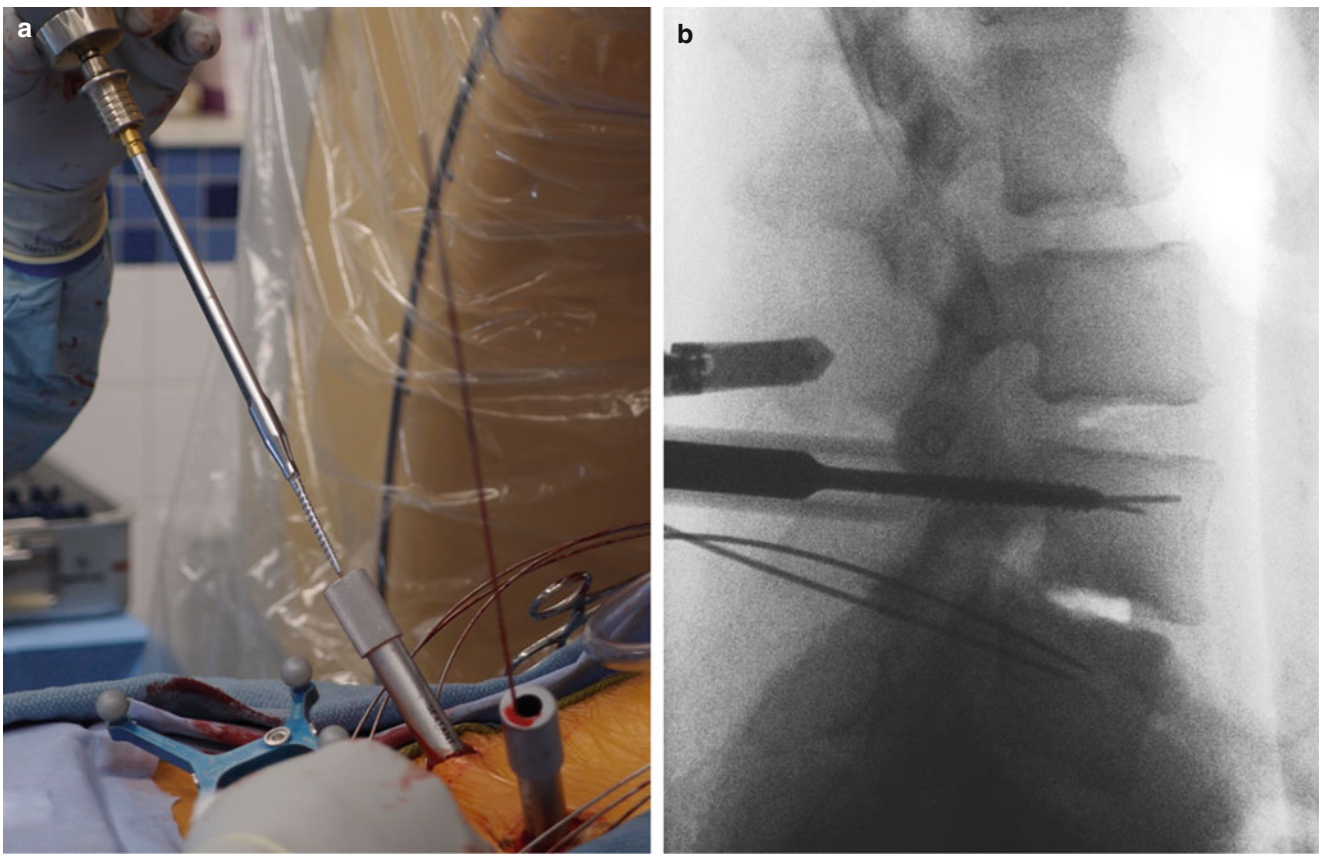

Fig. 14.10 Advancement of the cannulated tap should be in line with the K-wire (**a**) and this should be verified on a lateral fluoroscopic view (**b**)

Pearls and Pitfalls

Some of the pearls and pitfalls discussed below were already mentioned in the discussion of surgical technique, but are worth repeating for emphasis.

- Whether using an intraoperative CT scanner or a C-arm, it is important that clear unobstructed imaging be performed. Choice of surgical table and patient position on the table should be considered.
- In 2-D fluoroscopy, true AP and lateral images should be achieved (Fig. 14.3). For side-to-side tilt, leave the C-arm in 0°and 90° positions and tilt the operating table instead. For tilting in the sagittal plane to accommodate for lordosis/kyphosis, the C-arm gantry should be tilted; however, make sure that this is tilted in the sagittal plane without rotation of the gantry.
- In 2-D fluoroscopy, prefer to stand on the side of the image intensifier rather than the source, observe a "hands-off" technique, and use pulsed image acquisition mode. Also, make sure to wear at minimum a lead apron and thyroid shield; lead glasses and lead gloves are also recommended [18, 34].
- When drawing the planned skin incisions, make them in such a way that they could be easily connected should the need arise (Fig. 14.4). Alternatively, some surgeons prefer to make transverse skin incisions in order to obviate the need for connecting the incisions. We do not have experience with this technique.
- Use a finger to guide the cannula of the Jamshidi needle down to the transverse process. This places the needle in the vicinity of the desired starting point and helps minimize the number of C-arm shots required. When using this technique, take the trocar tip out of the cannula so as to prevent glove perforation.
- In 2-D fluoroscopy, perform pedicle cannulation and K-wire placement at all levels in the AP C-arm position. By following the "one inch" rule, estimating the position of the needle tip in relation to the pedicle walls could be reliably made. This saves time spent on switching back and forth between AP and lateral imaging.
- To prevent K-wire pullout, advance them to the anterior half of the vertebral body, but be mindful of its 3-D anatomy in order to prevent breaking through the anterior cortex.
- Be paranoid about inadvertent K-wire advancement. Keep your tap or screw collinear/coaxial with the K-wire (Fig. 14.10). Make marks on the K-wire (some systems have K-wires that already have markings on them) to verify that it does not advance with the tap or screw.
- If a K-wire does not pull out easily, use a rotational or twisting maneuver with pliers or a vise grip levering against the screwdriver handle. This prevents pullout of the entire screw.
- Do not sink the screw too deep in order to maintain the screw head's polyaxial capabilities. This facilitates rod passage.
- Verify on fluoro images that all screws are in acceptable position and that the rods are through all screw heads and with good length on both ends prior to locking the construct and removing all screw extenders and retractors.
- In 3-D navigation, make sure to maintain direct line of sight between the camera and reference frames on the patient and the instrument.
- In 3-D navigation, make sure that the patient reference frame is stable and well secured. Take care not to bump or cause any change in its position.
- In 3-D navigation, whenever possible, take every opportunity to verify information gleaned from the navigation screen.
- In 3-D navigation, remember that the K-wires are not navigated. Take all precautions necessary to avoid inadvertent wire advancement or pullout.
- In 3-D navigation, rod passage is not navigated. This step still requires fluoroscopic imaging confirmation (Fig. 14.8).

Avoiding and Treating Complications

Avoiding complications requires paying careful attention to detail. Surgeons should be knowledgeable about spinal anatomy and preferably are already adept at open pedicle screw placement prior, have observed an experienced surgeon performing percutaneous fixation, and have practiced on a cadaver prior to embarking on percutaneous pedicle screw placement. Because direct visualization is sacrificed in favor of reduced tissue disruption, the surgeon has to rely on tactile feedback, 2-D fluoroscopy images, and virtual 3-D navigation images to determine where the instruments and implants are in relation to the spine.

Although most systems in the market are adequate for the purpose of percutaneous pedicle screw fixation, each system has its own intricacies and nuances. It is thus important for the surgeon to familiarize himself/herself with the system that will be used prior to the operation.

When planning to use 3-D navigation, there may be occasions when the navigation system is not working properly. Thus, a backup plan such as using 2-D fluoroscopy instead should be made available. When 2-D fluoroscopy cannot be made to work, such as when good quality images cannot be obtained because of morbid obesity or severe osteoporosis, one should strongly consider switching to an open technique or aborting the procedure altogether.

The best time to revise a nonoptimally positioned screw is in the same surgical setting. Thus, it is important that 2-D or 3-D images be obtained and checked by the surgeon prior to the patient leaving the operating room. Images on the navigation screen are virtual images and should not be relied upon to tell the actual position of the screws.

As with open pedicle screw placement, vascular, visceral, and neural injuries may occur. These injuries may be incurred with the Jamshidi needle, the K-wire, the tap, the screw, the rod, or the set/locking screws. Careful control in manipulating the needle until it rests on bone is important; as well as confirming its position with imaging. Since the K-wire is the one temporary instrument that stays in the patient's body the longest and has the highest likelihood of migrating, it has the highest potential to cause injury to other structures. Vigilant K-wire management is critical in preventing inadvertent wire advancement and pullout. The tap and the screw should typically follow the K-wire's path; however, if the K-wire has moved in position, then the tap and screw could cause further injury. It is thus essential to take images regularly, particularly if there is any suspicion that the K-wire may have moved. Screw extenders normally should guide locking screws or nuts down to the screw heads to lock the rod and screw together. On occasion, however, these locking screws could fall off, migrate, and cause injury. It is thus important to follow the company's recommended technique when placing these.

When a major vascular injury is suspected, the surgeon should immediately alert the anesthesiologist. If there are accompanying changes in blood pressure and heart rate, it is advisable to get immediate help of a vascular or general surgeon, seal the wound, reposition the patient, and perform an emergent laparotomy to facilitate identification and repair of the injury. If the vital signs remain stable after a suspected possible injury, such as if a K-wire is inadvertently advanced beyond the anterior vertebral body cortex, one may elect to simply closely observe the patient.

Postoperative Care

Percutaneous pedicle screw fixation does not really require any special or additional postoperative care than for a regular spine surgical patient. Since stabilization had been performed, these patients typically do not require a brace and can be mobilized almost immediately after surgery. If a drain had been placed, these usually are removed on postoperative day number one. Depending on concomitant procedures performed (e.g., anterior lumbar interbody fusion) and patient's baseline condition, most patients are discharged on day two or three. Some authors have also reported performing minimally invasive lumbar fusion with percutaneous pedicle screw fixation on outpatient basis.

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Minimally Invasive Facet Screw Fixation

15

Isador H. Lieberman and Xiaobang Hu

Introduction

Although the new era in spine surgery is highly focused on preserving mobility, fusion is still an accepted way of treatment for a variety of spinal disorders. To stabilize the spine until a fusion consolidates, spine surgeons have used combinations of hooks, wires, and pedicle screws. The main problem with these implants is the need for extensive soft tissue dissection which may potentially contribute to an increased number of complications. To implant pedicle screws in a safe and anatomically correct position, the proximal facet joint of the segment adjacent to the fused level needs to be exposed and may well be damaged by the screw.

Facet screw fixation can be either translaminar or transfacet. The translaminar approach involves inserting the screws bilaterally at the base of the spinous process of the cephalad vertebrae, contralateral from the facet to be fused. The screw then passes within the lamina, crosses the facet joint, and ends at the confluence of the transverse process and the superior articular process of the caudal vertebrae. The transfacet approach involves inserting the screws bilaterally through the dorsal side of the facet of the inferior articular process of the cephalad vertebrae, across the facet joint and into the pedicle of the caudal vertebrae. Both these approaches can be executed in an open, mini-open, or even percutaneous fashion.

King described direct transfacet fixation as early as 1948 [1]. This technique was modified by Boucher in 1959 with further fixation into the pedicle of the caudal segment to be fused [2]. Magerl in 1984 extended the concept of transfacet fixation using a translaminar trajectory [3]. He described starting the screw on the contralateral side of the spinous process, drilling through the lamina, and aiming for the junction of the transverse process and facet joint (Fig. 15.1). The use of this implantation trajectory increases screw length as well as the potential stability of the fixation. The application of this technique requires minimal soft tissue dissection only to the outer side of the facet joint and requires only exposure of the facet joint of the involved level. The screws are flush with the bone and thus considered low profile. The earlier applications were performed by using standard 4.5 mm cortical bone screws, but today there are commercially available screws and tools designed for both direct facet fixation and translaminar facet fixation implanted both in an open fashion and percutaneous fashion [4–6]. Various studies have shown that facet screw fixation can provide good biomechanical stability and stiffness with relatively low operative time, blood loss, complication rate, and reoperation rate [7–9].

Indications

1. Degenerative conditions requiring a fusion with a stable anterior column (an end-stage collapsed disk with peripheral osteophytes)
2. Posterior stabilization after interbody reconstruction
3. To provide additional contra lateral fixation in thoracolumbar fusions treated with unilateral posterior instrumentation [10]

Contraindications

1. Isthmic spondylolysis or spondylolisthesis greater than grade 1
2. Deficient posterior elements (lamina, facets, and/or spinous process)
3. Anterior column deficiency
4. Severe deformities, such as scoliosis and kyphosis

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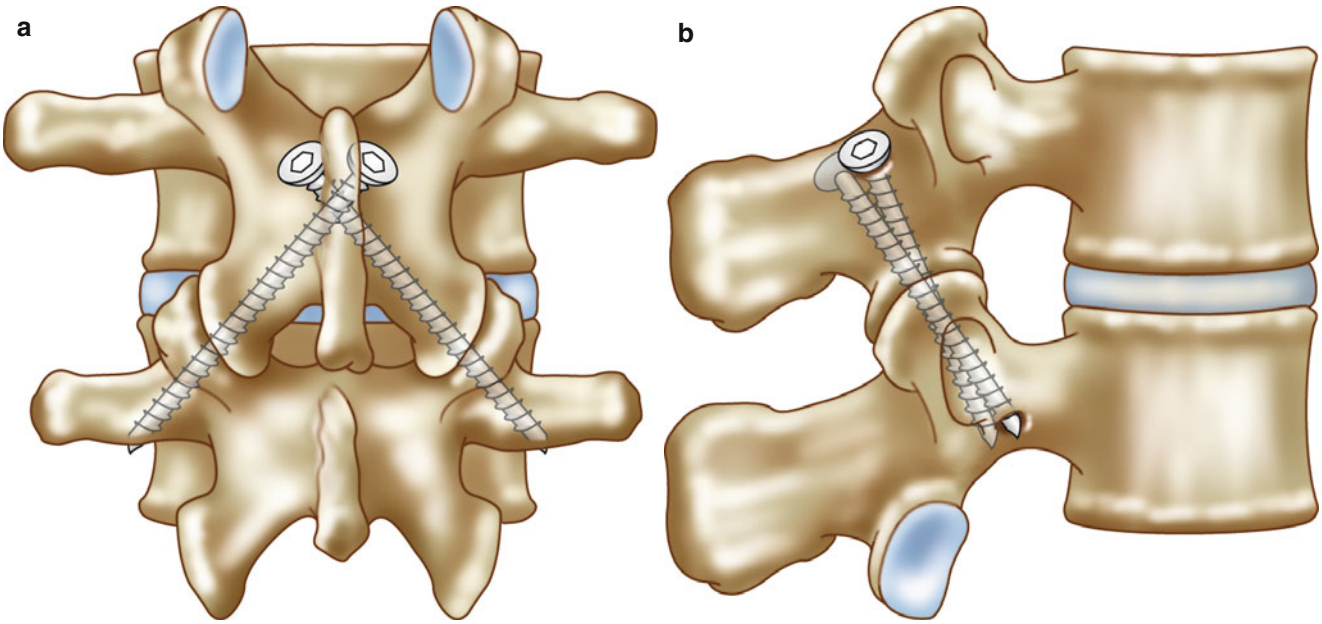

Fig. 15.1 Drawings demonstrating the Magerl method of translaminar facet screw fixation. (**a**) Posterior view showing the two screws crossing through the spinous process. (**b**) Lateral view showing the two screws at the junction of the facet joint and the transverse process

5. Severe osteoporosis
6. Patients who already or will require extensive decompression (the lamina and/or facets were or will be totally or partially removed)

Patient Positioning

The patient is positioned prone on a spinal surgery frame to facilitate the exposure and any use of guidance or fluoroscopy. The preparation and draping is carried out in accordance with the surgeon's usual technique, ensuring a wide enough and long enough sterile region especially if a percutaneous approach is being used. Intraoperative fluoroscopy or plain radiographs are used to identify the level of concern and are also used throughout the operation to judge positioning of the implants.

Surgical Technique

The most commonly used technique of translaminar or direct facet screw fixation involves a mini-open approach with or without a more lateral or more proximal second percutaneous skin incision to facilitate the screw trajectory. There have been methods described for fluoroscopic and computer-navigated implantation techniques; however, these have not gained widespread adoption and there are only anecdotal accounts of these approaches in the literature.

Mini-open Translaminar Facet Screw Fixation

The minimally invasive technique described below uses mini-open midline exposure of the posterior spine allowing the surgeon to directly visualize the translaminar passage of the screws (Fig. 15.2). Although the application of translaminar screws may be accomplished with a fluoroscopically guided totally percutaneous approach [11], we recommend that surgeons new to this technique use the mini-open approach for the first few cases to gain some experience and familiarity with the anatomy and with the "feel."

Through a small vertical midline incision, the spinous processes, laminae, and the facet joints are exposed in a standard fashion (Fig. 15.2). If decompression is needed, care should be taken to preserve the laminar arch and enough of the facet joints to accommodate the screws. This may mean working underneath the lamina to fully decompress the central and lateral regions of the epidural space. Consideration may even be given to first implanting the screws then proceeding with the decompression. Once exposed, the facet capsule is resected and the joint surfaces are denuded of their cartilage. Bone graft of the surgeon's choice is then packed into the facet joint.

A 3.2 mm drill bit is used to drill the base of the spinous process in line with the facet joint aiming to exit at the junction of the transverse process and superior articular facet of the level to be fused. This drilling can be done through the midline incision or through a second stab incision depending on the required trajectory and thickness of the patient (Fig. 15.3). It should be remembered that in

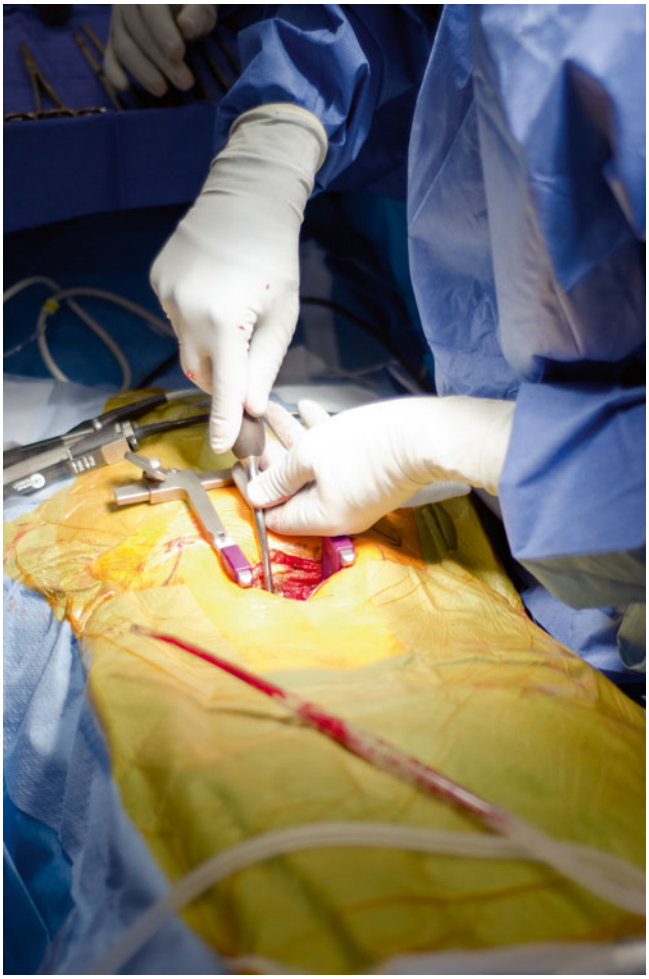

Fig. 15.2 Midline exposure of lamina and facet joints

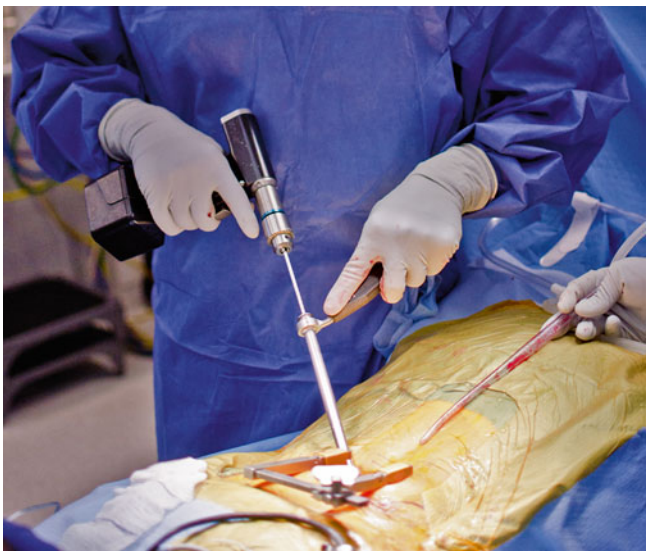

Fig. 15.3 Drilling the translaminar screw path through the lamina and across the facet joints

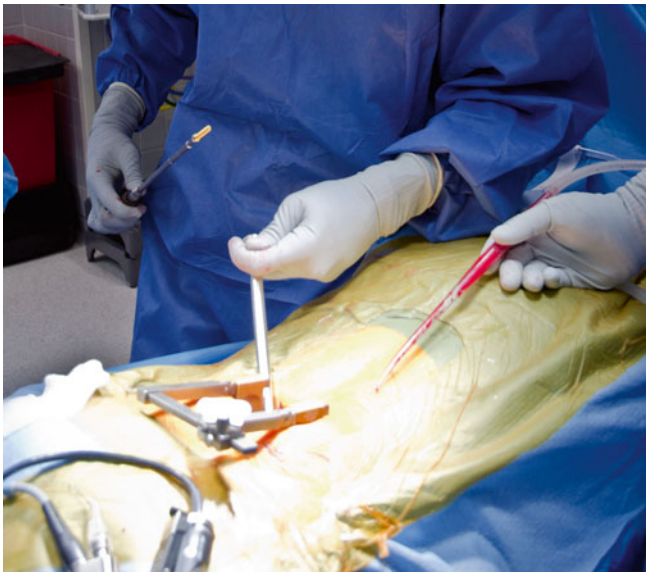

Fig. 15.4 Insertion of the 4.5 mm cortical screw

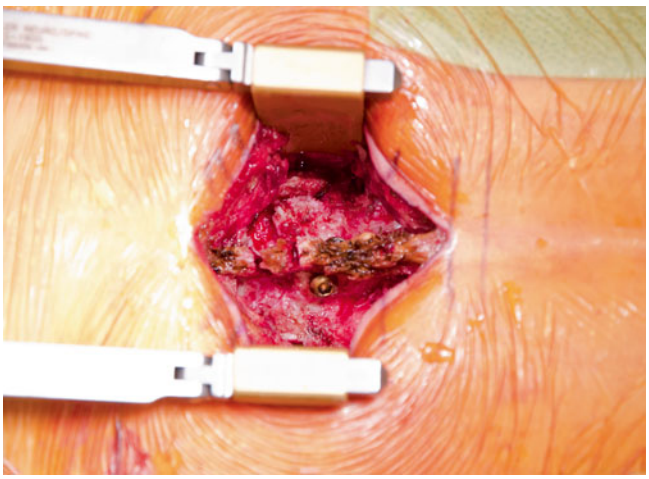

Fig. 15.5 The final position of the screws

order to place two screws through one spinous process, without the screws interfering with each other, one screw should be placed a bit more caudal and the other a bit more cranial (Fig. 15.1). If the trajectory of the lamina is followed, the risk of penetrating the epidural space and the risk of injuring the dura or neural structures is minimal. After drilling with the 3.2 mm drill bit, a 4.5 mm tap is used to tap the hole and then the length of the hole should be measured with a depth gauge. Finally, an appropriate length 4.5 mm screw is placed across the facet joint through the hole in the lamina (Fig. 15.4). The second screw is inserted in a similar fashion so the screws are crossing the spinous process (Fig. 15.5). Once both screws are inserted, intraoperative radiographs should be taken to verify the position of the screws (Fig. 15.6).

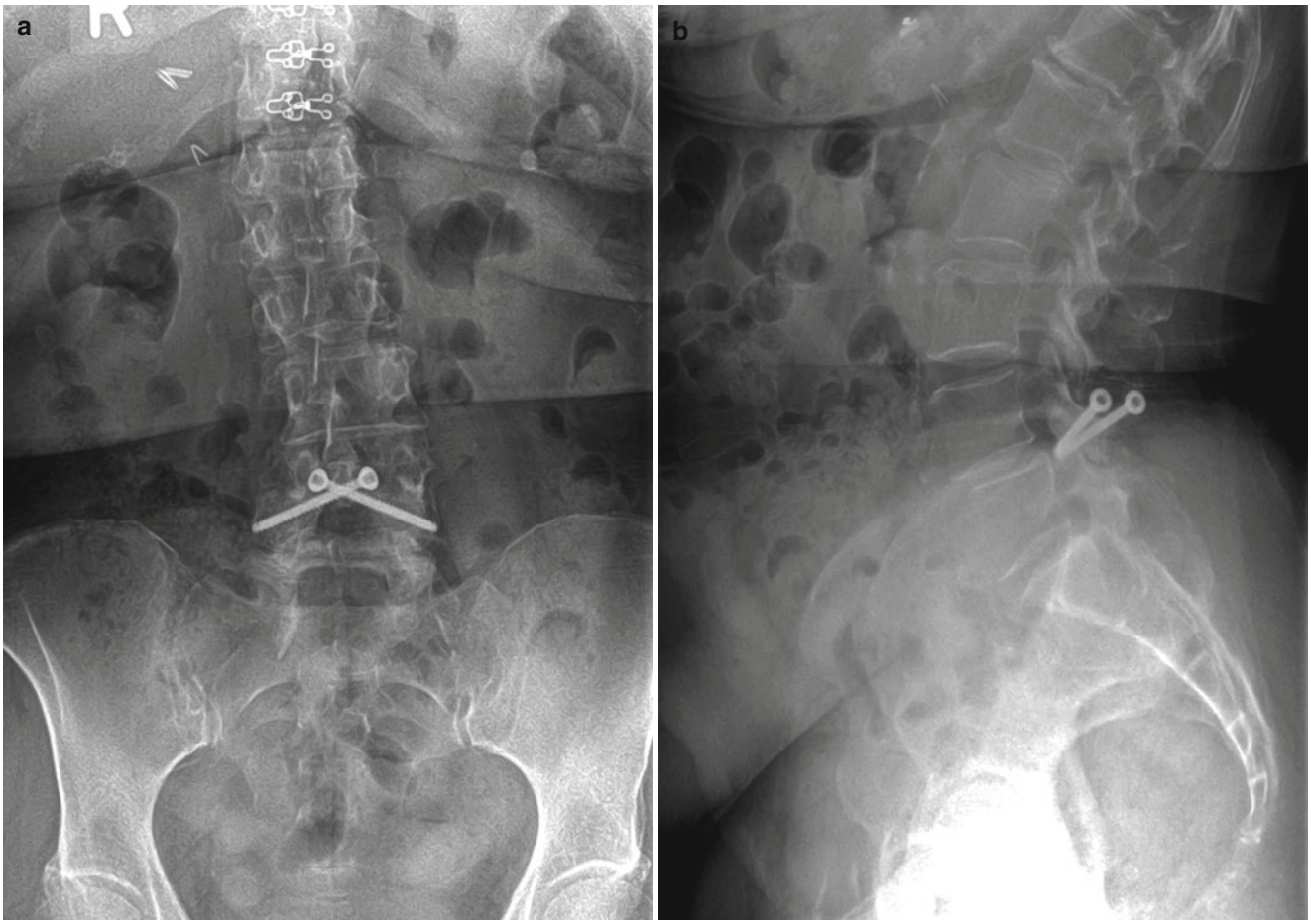

Fig. 15.6 Anteroposterior (**a**) and lateral (**b**) radiographs showing the proper placement of translaminar facet screws

Percutaneous Translaminar Facet Screw Fixation

Translaminar facet screws can be implanted percutaneously under fluoroscopic guidance or with navigation [11, 12]. Prior to percutaneous implantation, a preoperative axial MRI or CT scan is obtained to evaluate the trajectory and starting point on the skin. On the scans the lateral angle is drawn extending to the skin to measure the distance of skin entry from the midline (Fig. 15.7a). In the operating room, distance lines are drawn on the patient's back as two paravertebral vertical lines (Fig. 15.7b).

Then a bone biopsy needle is placed on the patient's skin to determine the caudal angle of the screw trajectory under fluoroscopy (Figs. 15.7c and 15.8a). A line is drawn from the pedicle of the upper vertebra of the motion segment to be fused, passing through the cranial one third of the base of the spinous process, to the superolateral quadrant of the opposite pedicle of the lower vertebra. The angle made by this line and a transverse axis of the spinal column is the caudal angle. The point of skin entry is at the intersection of the caudal angle line with the paravertebral line representing the distance from the midline of the spine.

A bone biopsy needle is then inserted into the skin through a stab wound at the entry point. The needle is introduced along the lateral angle and caudal angle until the tip of needle is anchored at the cranial one third of the base of the spinous process. The stylet is then withdrawn and a K-wire is inserted. Using an electrically powered drill, the wire is drilled toward the superolateral quadrant of the opposite pedicle of the lower vertebra, passing the lamina and the facet joint under fluoroscopic guidance. A cannulated screw, of the appropriate length, is inserted along the K-wire until the head of the screw engages the base of the spinous process (Fig. 15.8). The same procedure is then performed on the opposite side. Once both screws are inserted, intraoperative radiographs should be taken to verify the position of the screws (Fig. 15.9).

During insertion of either mini-open or percutaneous translaminar screws, the surgeon must remember that these screws are not meant to be a lag screws; they are stabilization or neutralization screws. Any attempt to compress the facet

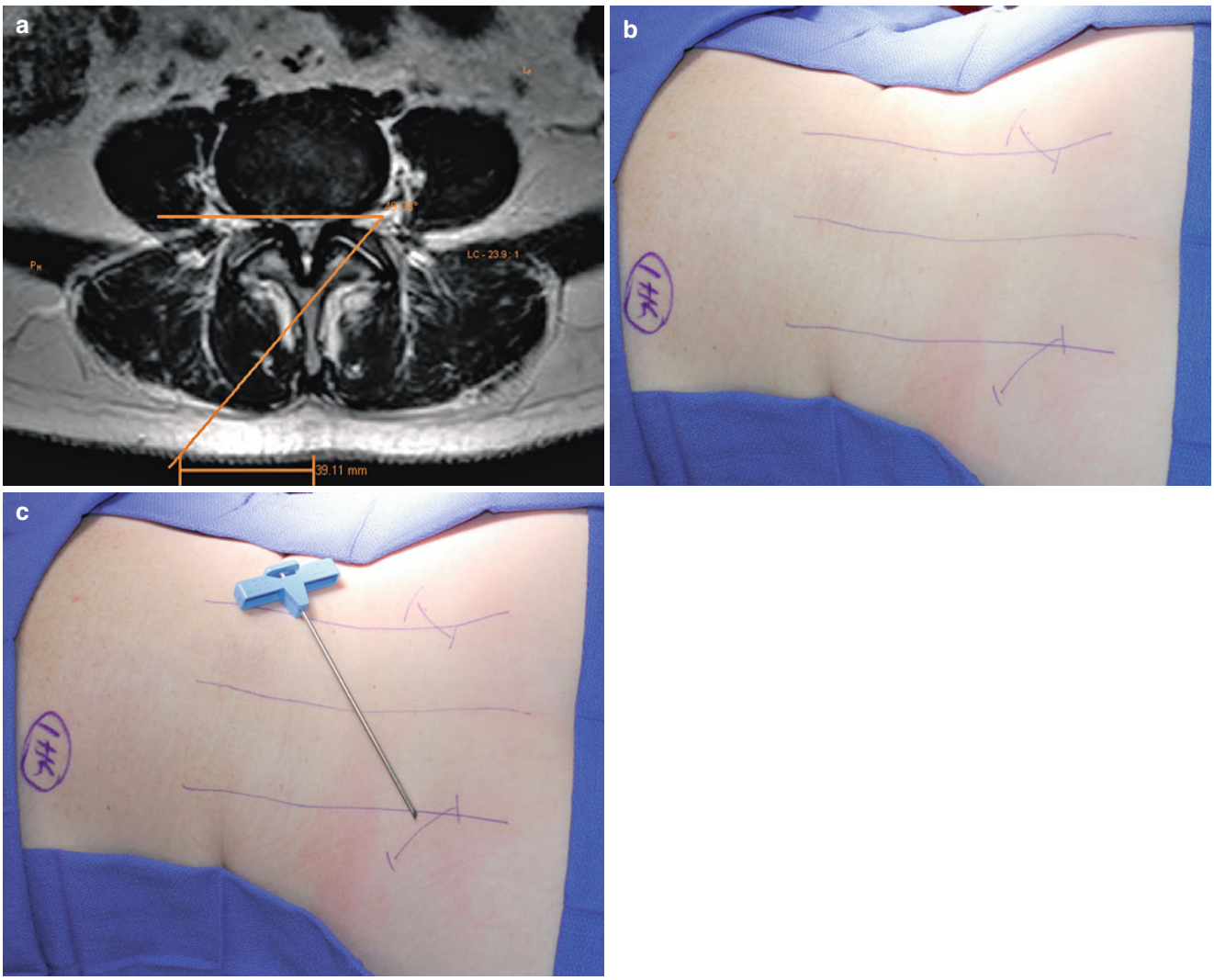

Fig. 15.7 (**a**) The lateral angle is measured by a preoperative axial CT or MRI scan. The line of the angle is extended to the skin level to measure the distance of skin entry from the midline. (**b**) In the operating room, the distance lines are drawn on the patient's back as two paravertebral vertical lines which are at same distance from the midline. (**c**) A bone biopsy needle is placed on the patient's skin to help determine the screw path

joint will only result in either facet fracture or spinous process fracture.

Percutaneous Transfacet Screw Fixation

Posterior transfacet screw placement is another option that can be used to facilitate arthrodesis after interbody graft insertion [13–15]. It can also be done through a mini-open incision or percutaneously.

A small midline incision is made over the spinous process at about two levels above the disk space of interest. On the AP view, the entry point lies at the intersection of a vertical line drawn at the medial aspect of the pedicles with the inferior endplate of the superior vertebra to be fused. A lateral view is used to confirm the proper angle of the Jamshidi needle through the facet joint and into the pedicle of the inferior vertebra. In the lateral plane, the tip of the screw will end at the transition point of the pedicle and vertebral body and at the inferolateral corner of the pedicle in the AP plane. The screw will result in a ~30° caudal angulation and a ~15° lateral angulation.

Once the incision is made, the fascia adjacent to the spinous process bilaterally is opened with electrocautery. A Jamshidi needle is docked onto the aforementioned entry point using AP and lateral fluoroscopic imaging and secured in position with a mallet. The inner stylet is removed and a Kirschner (K) wire is driven across the facet joint and inferior pedicle using AP and lateral views. A series of dilators are inserted over the K-wire and the

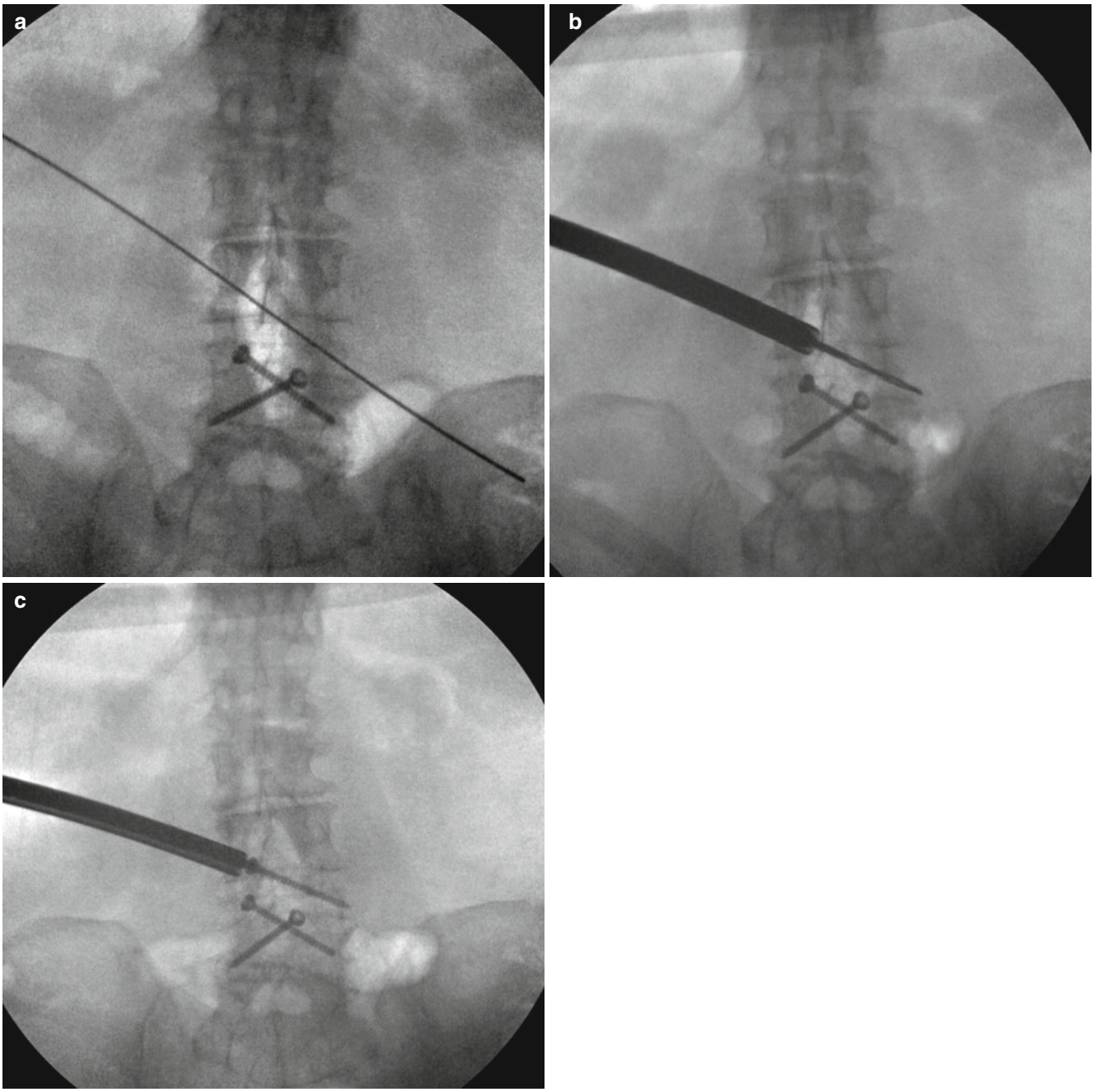

Fig. 15.8 (**a**) The caudal angle of the screw path is determined by placing a bone biopsy needle on skin in a way that the needle in fluoroscopic view is passing from the pedicle of upper vertebra to superolateral quadrant of the opposite pedicle of the lower vertebra. (**b**) A K-wire is inserted using a drill. (**c**) A cannulated lag screw is inserted until the head engaged the base of spinous process

outer dilator is kept in situ. A cannulated drill and tap are passed over the K-wire followed by the insertion of the cannulated transfacet screw (Fig. 15.10). After x-ray imaging confirms proper positioning, the K-wire is removed and the contralateral transfacet transpedicular screw is inserted through the same incision. Once both screws are inserted, intraoperative radiographs should also be taken to verify the position of the screws.

Postoperative Care

There is no need for any special postoperative care. The patient is generally discharged in 1–2 days. At the surgeon's discretion, a lumbar corset can be used to provide immobilization as needed. Return to work is generally dependent on the patient's motivation and job specifications.

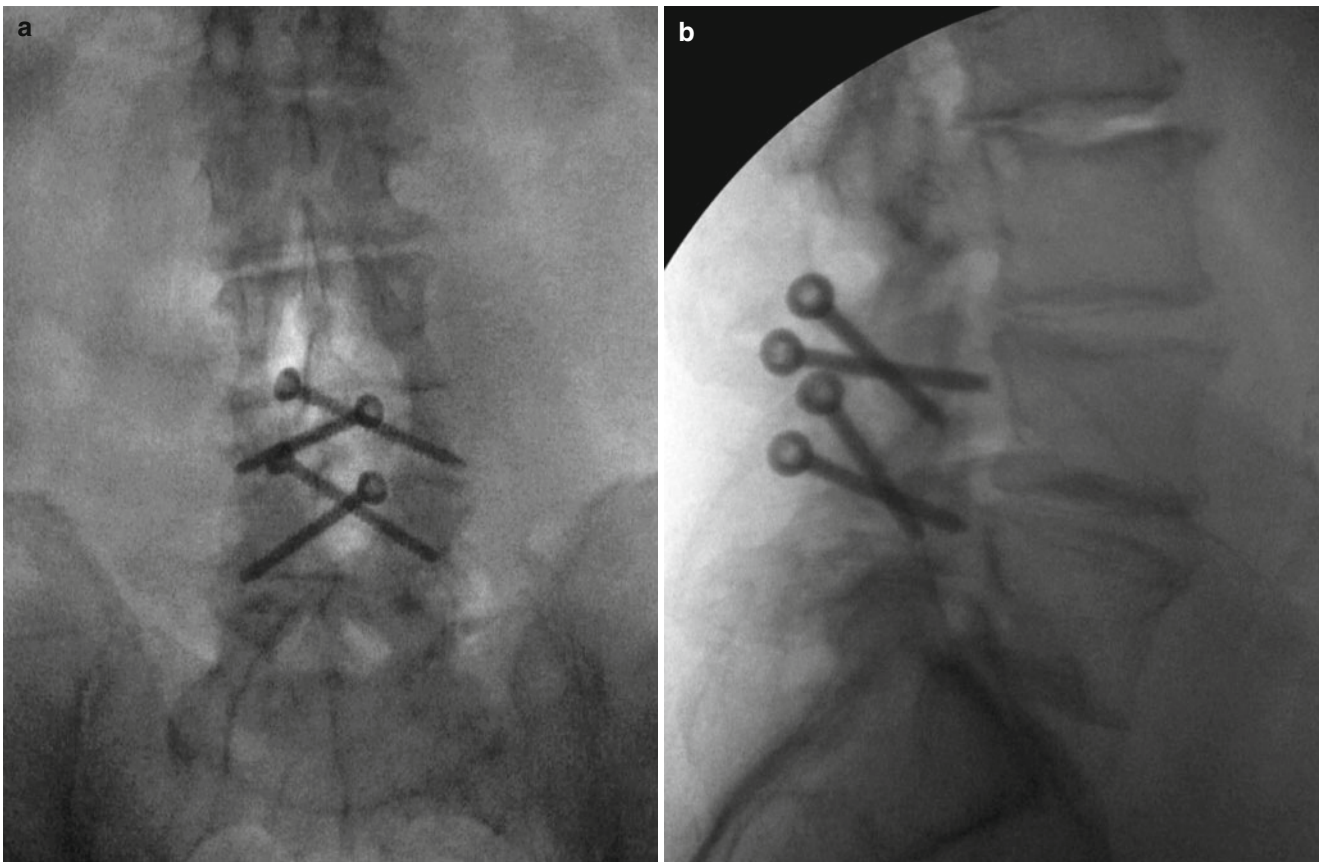

Fig. 15.9 AP (**a**) and lateral views (**b**) of fluoroscopic images showing trajectories of the screws

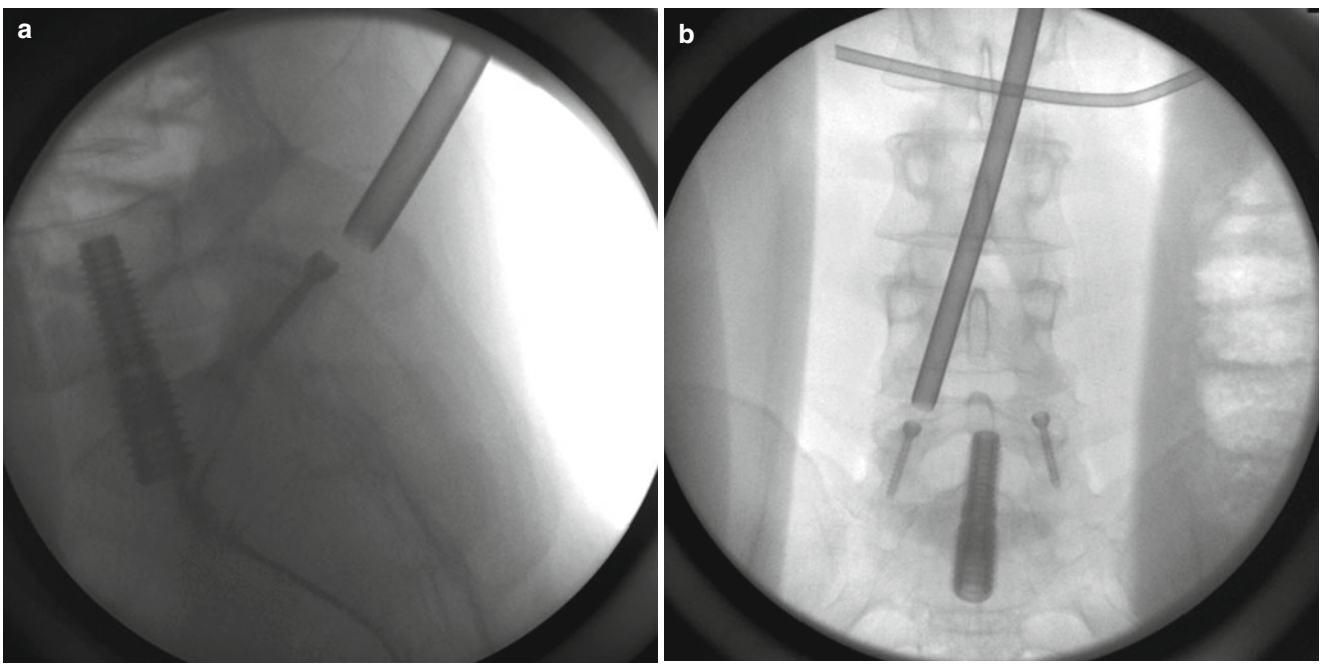

Fig. 15.10 Intraoperative fluoroscopic images showing lateral (**a**) and AP (**b**) views of facet screw placement. This patient also had an AxiaLIF procedure

Potential Complications

Although translaminar and direct facet screw fixation are relatively simple fixation techniques, as with all surgical procedures, they are not free of complications. Prior to surgery it is important to inform the patient that in the event that the translaminar or transfacet screws cannot be placed, then, as a salvage, transpedicular screws may need to be used.

The potential complications include:

- Foraminal violation and nerve root irritation by the drills if the trajectory is not ideal or by screw malposition. In this case the misplaced screws should be removed and or repositioned.
- Inadequate decompression.

The spine surgeon should never sacrifice a good decompression in order to preserve bone for fixation. If too much bone is resected, other methods of spinal fixation should be employed.

Clinical Studies

There are multiple reports describing the clinical and biomechanical outcomes of translaminar and direct facet screw fixation (Table 15.1). It can be seen from the table that these methods have proven to be a safe form of posterior stabilization with high rates of fusion when adhering to the appropriate indications and when applied with the appropriate technique.

Summary

Minimally invasive translaminar and direct facet screw fixation is a cost-effective, safe, and efficient procedure for the segmental stabilization of the lumbar and lumbosacral spine. It is a technically easy way to improve fusion rate with a low complication rate. This technique is ideally suited to one- or

Table 15.1 Brief summary of various clinical studies about translaminar facet screw fixation and their clinical results

Author/year	No. of patients	Follow-up	Clinical result	Fusion rate (%)	Fusion time	Complications
Jacobs et al. (1989) [16]	43	16 months	93 % improvement	91	6 months	Neurological – none
Grob et al. (1992) [17]	72	24.4 months	76 % satisfied	94.5	–	Screw breakage – 5 5 screws were not transfacet Diskitis – 1 Back pain – 2 Dural tear – 1 Wrong level – 1 Neurological – none
Reich et al. (1993) [18]	61	24 months	93.4 % excellent to good, 6.6 % unsatisfied	98.4	5 months	Neurological – none
Grob et al. (1998) [9]	173	68 months	99 good, 70 satisfactory, 4 bad	94	–	3 % loosening Screw breakage – 2 Diskitis – 1 Dural tear – 1 Temporary quadriceps weakness – 1 Wrong level – 1 Nerve root irritation – 1
Thalgott et al. (2000) [19]	46	24 months	75.5 % good, excellent or total pain relief	93.2	–	Neurological – none
Jang et al. (2003) [12]	18	6 months	100 % excellent or good	–	–	No malpositions and no other complications
Yin et al. (2004) [10]	30	10 months	97 % anterior, 98 % posterior edge restoration	100	4.3 months	3.4 % correction loss
Jang et al. (2005) [20]	44	28 months	90.9 % excellent or good	95.8	–	ALIF cage subsidence at 4 fusion sites
Shim et al. (2005) [11]	20	19.5 months	80 % good to excellent 20 % fair to poor	100	–	10.8 % lamina violation 15.4 % minimal screw malposition Articular process fracture in 1 level

(continued)

Table 15.1 (continued)

Author/year	No. of patients	Follow-up	Clinical result	Fusion rate (%)	Fusion time	Complications
Best et al. (2006) [21]	43	>24 months	–	95.3	–	4.7 % reoperation
Grob et al. (2009) [8]	57	24 months	78 % good	–	–	Bleeding in spinal canal – 1 Wound infection – 1 Anemia – 1
Aepli et al. (2009) [22]	476	10 years	74 % good 26 % poor	–	–	4.4 % new sensory and/or motor deficits 0.4 % broken screws 0.2 % screw loosening 0.2 % persistent pain at the iliac crest donor site for the bone graft 0.4 % postoperation site infection

two-level fusions in patients with a mechanically stable anterior column where the posterior lamina and facets are able to accommodate 4.5 mm screws. The screws can be applied in an open, mini-open, and percutaneous fashion.

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Minimally Invasive Transforaminal Lumbar Interbody Fusion

16

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Introduction

Minimally invasive (MIS) posterior approaches allow for restoration of lumbar lordosis, provide pain relief from a multitude of pathologies, and allow for earlier rehabilitation [1–7]. These approaches provide the ability for a thorough decompression with minimal muscle trauma. Additionally, the application of an interbody arthrodesis allows anterior column stability increasing arthrodesis rates and potentially eliminates the disk as a pain generator [8–10]. Two of these posterior approaches include the direct posterior lumbar (PLIF) and transforaminal lumbar (TLIF) techniques. The MIS PLIF approach to the disk space is more medial in orientation and leaves a portion of the facet, which typically necessitates neural element retraction for discectomy and interbody graft placement [11]. The MIS TLIF approach involves a complete facetectomy and thereby allows for a more lateral exposure to the disk space obviating neural retraction.

The choice for a TLIF or PLIF should be made with regards to experience and comfort of the surgeon. In either approach, bilateral decompression can be performed if severe bilateral radicular symptoms are present or if the patient's preoperative imaging studies reveal central or contralateral lateral recess stenosis. This chapter specifically describes the MIS TLIF approach from preoperative stages to postoperative care. In order to enhance patient outcomes, pearls and pitfalls associated with learning this technique are also described.

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Biomechanical Goals

Biomechanically, 80 % of the weight-bearing load is transmitted through the anterior column [12]. The TLIF approach provides anterior column support theoretically improving arthrodesis rates. The approach restores disk space height and improves sagittal alignment of the lower lumbar segments. The interbody graft in the disk space shares the axial load with the dorsal pedicle screw construct [13].

Surgical Indications

Indications for an MIS TLIF are numerous and are the same as the traditional open, midline technique [12]. Grade I or II spondylolisthesis with or without radiculopathy is an ideal indication. Mechanical low back pain due to spondylolisthesis is also an indication. Other indications include recurrent disk herniation, lumbar spinal stenosis, discogenic low back pain caused by degenerative disk disease, postlaminectomy kyphotic instability, spinal trauma, pseudarthrosis, and synovial cysts with associated spinal instability.

Relative contraindications to an MIS TLIF are grade III or IV spondylolisthesis, a conjoined nerve root within the foramen, active or systemic infection, acute spinal fracture, extensive epidural scarring, severe osteoporosis, spinal metastasis, pregnancy, and gross obesity [14]. These contraindications are relative and are largely dependent upon the familiarity and mastery of the technique.

Preoperative Planning

Imaging: Preoperative anteroposterior (AP) and lateral radiographs allow for evaluation of sagittal alignment, disk space height, and osteophytes. Flexion and extension views may allow for evaluation and detection of any instability.

Magnetic resonance imaging (MRI) is used to detect stenosis (central, lateral recess, and/or foraminal). All patients

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have a preoperative MRI unless a specific contraindication is present whereby a CT myelogram or plain CT could be used instead. CT myelography with a water-soluble contrast can be helpful to identify structural problems and spatial association among soft tissues and bony anatomy. It also improves visualization of foraminal and lateral recess stenosis with axial and reconstructed images [11]. Thin slice (1.5–3 mm) CT scans help in visualization of bony detail to distinguish between neural compression due to soft tissue or bony structures.

Surgical Anatomy

The anatomical working zone of a transforaminal lumbar interbody fusion is bounded by the traversing nerve root and thecal sac medially. The exiting nerve root and the cranial vertebra above the disk of interest represent the superior border. Finally the pedicle of the caudal vertebra below the disk of interest represents the inferior border of the working space.

Musculature of the posterior lumbar spine has been described as three layers of superficial, intermediate, and deep groups [15]. The superficial layer consists of the latissimus dorsi and thoracolumbar fascia. The intermediate layer is comprised of serratus posterior and erector spinae muscles. Specifically, these erector spinae muscles consist of the iliocostalis, longissimus, and spinalis. Lastly, the deep layer is compromised of the multifidus and rotator muscles [13].

The paraspinal (Wiltse) approach uses the natural plane between the multifidus and the longissimus part of the sacrospinalis muscle from the midline at the level of the spinous process of L4 [16]. Natural fibrous tissue is encountered between these two muscles. This approach spares the natural posterior tension band created by the interspinous and supraspinous ligaments. The muscular attachments of the paraspinous musculature on the posterior elements of the contralateral side are also preserved [17].

Surgical Technique

Patient Positioning

A Jackson table is used with the patient in the prone position. The table must be radiolucent to allow for appropriate imaging [18]. The monitor and C-arm fluoroscopy should be set up on the opposite side of the patient to which the surgeon is standing allowing for easier visualization for the operating surgeon. The axillary region must be well padded to protect from potential brachial plexus palsy. Other pressure points that should be well padded include the anterior thighs, knees, and chest. Neuromonitoring in the form of somatosensory-evoked potentials and motor-evoked potentials can be used to assess for potential changes in the nerve roots or cord which would require patient repositioning [13]. EMG (electromyography) monitoring is also used for pedicle screw placement [19].

Approach

AP fluoroscopy is used to identify the level involved with the sacral pedicle (tear drop) serving as a reproducible level for counting. It is critical to obtain a true endplate view of the cephalad pedicle to be cannulated. This ensures that the proper orientation and angulation are achieved for the sequential muscle dilators and subsequent pedicle screw placement. In addition, the spinous process should be centered perfectly in between both pedicles (Fig. 16.1a). Three vertical lines are drawn (center spinous process and bilateral pedicular lines). A horizontal line is then made midpedicle at the cephalad level. An incision is made 1 cm lateral to the junction of the vertical and horizontal midpedicular line. The incision is made extending caudal approximately 2 cm.

Pedicle Screw Cannulation

A Jamshidi is used to penetrate the fascia down to the junction of the transverse process and superior articular facet joint. The tip of the needle should be docked on the lateral wall of the pedicle at the 10 or 2 o'clock position confirmed via a true AP fluoroscopic image (Fig. 16.1b). The Jamshidi needle is gently advanced 15–20 mm. A Kirschner wire (K-wire) is then advanced an additional 10–15 mm. An AP fluoroscopic image is used to ensure that the K-wire does not cross the medial wall of the pedicle. In addition, a threaded K-wire is used allowing for easy advancement. Any resistance to advancement suggests that there is impending violation of the medial wall. Once advanced 10–15 mm, the C-arm is then switched to a lateral view. The K-wire tip should be across the pedicle-vertebral body junction. This confirms that no violation of the medial wall has occurred. This step is then repeated at the caudal level. The K-wires are then gently bent outwards on each end of the incision.

Incision and Dilation

A series of tubular dilators are used to create a muscle-sparing surgical corridor to the level of the facet joint of interest. The dilators are placed in between the space formed

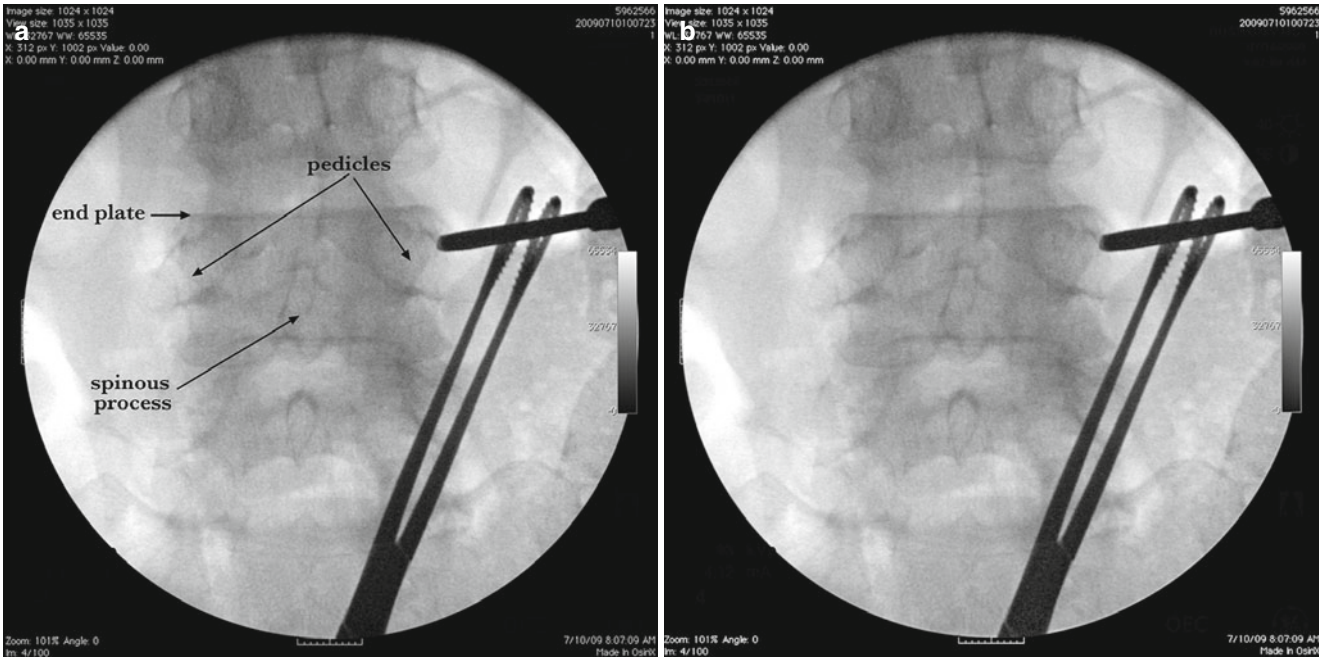

Fig. 16.1 (**a**) It is critical to obtain a true endplate view of the cephalad pedicle to be cannulated (**b**) The tip of the Jamshidi needle should be docked on the lateral wall of the pedicle at the 10 o'clock or 2 o'clock position

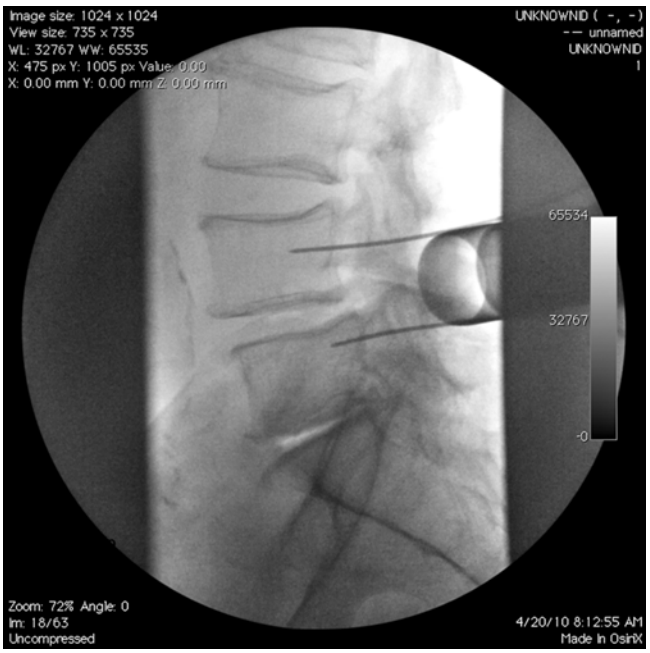

Fig. 16.2 This lateral fluoroscopic image shows the final largest dilator placement between the cannulated K-wires at the L4–5 interspace. This creates a muscle-sparing surgical corridor to the level of the facet joint of interest

within the cannulated K-wires. After the final largest dilator has been placed, a 22-mm-diameter tubular non-expandable retractor is placed over the dilator and locked into final position to the table. The correct position of the retractor is directly on the facet joint and angled with a trajectory parallel to the intervertebral disk (Fig. 16.2). Loupes or microscope is used for visualization into the tube. A light source is positioned within or over the retractor to permit visualization of the surgical field.

Laminectomy, Facetectomy, and Foraminotomy

Bovie cautery and rongeurs are used to remove any residual soft tissue over the facet. A thorough facetectomy and laminectomy are accomplished using a high-speed drill. When indicated, the decompression is extended superiorly and to the contralateral side. The decompression is complete when the entire flavum can be resected. Flavum is not removed until the entire bone decompression is accomplished. A curved curette is used to release the flavum (Fig. 16.3). The facetectomy is accomplished using a burr and extending the superior extent of the decompression to the level of the pars. The superior and inferior articular processes are removed. Bone is collected in a Luken's bone trap and saved for placement into the cage and intervertebral disk space.

Disk Space Preparation and Interbody Graft

The interbody space is identified, and a series of endplate cutters, pituitary rongeurs, and curved curettes are used to remove the disk material. An annulotomy is typically made

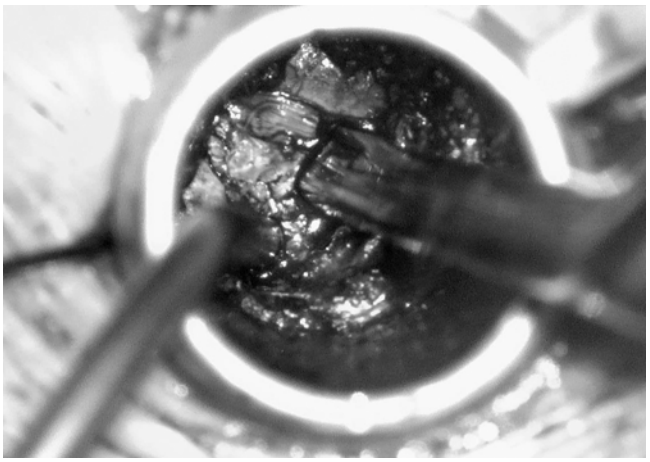

Fig. 16.3 This view is looking down the tubular dilator and shows a curved curette, which is used to release the ligamentum flavum

with the aid of an osteotome under lateral fluoroscopy. One can use a Kerrison rongeur within the annulotomy to release the posterior longitudinal ligament as far to the contralateral side as possible. This technique aids in visualization and helps to make the disk space more mobile for distraction. Paddle distractors and endplate shavers should be used sparingly until a thorough subtotal discectomy is accomplished. Early use of endplate shavers and paddle distractors may lead to endplate violation and ultimately cage subsidence. Trial sizers are used to find the appropriate interbody device size to restore adequate lumbar lordosis and allow for proper neuroforamen distraction (Fig. 16.4). After the correct size is determined via lateral fluoroscopic views, the interbody device is filled with one of a variety of osteobiologics/graft enhancers mixed with locally harvested bone graft (Luken's bone trap) and local bone marrow aspirate harvested from the pedicle at the time of pedicle cannulation with the Jamshidi. The cage is then gently impacted into the interbody space and placed directed across the midline with the aid of lateral fluoroscopic visualization. Care should be taken to ensure that no pressure is exerted on the exiting nerve root or the dorsal ganglion superior to the disk space.

Pedicle Screw Placement

Polyaxial extended-tab titanium screws can be used to facilitate a less invasive approach and efficient rod placement (Fig. 16.5). A 1-mm undersized tap is used. The tap can be electrically stimulated and serve as a reference for possible medial wall violation. Once the screws are placed, an appro-

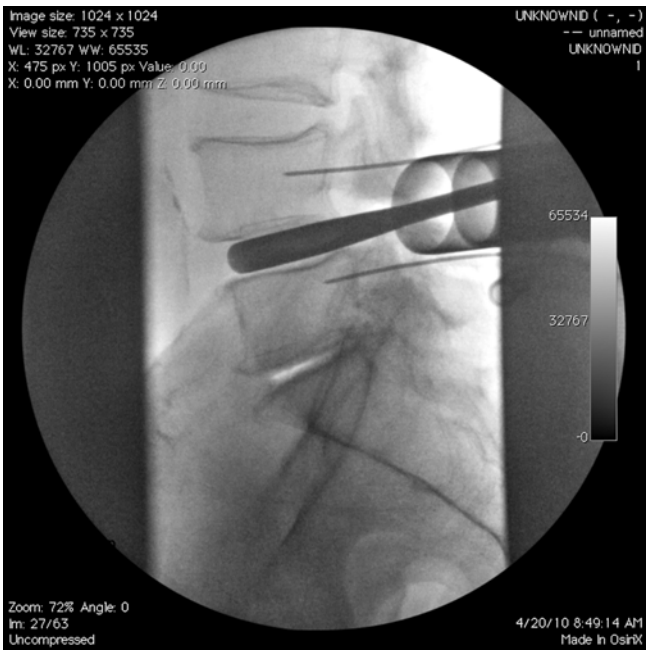

Fig. 16.4 Lateral fluoroscopic view of a trial spacer inserted into the L4–5 disk space before final cage placement. This helps in determination of the final implant dimensions

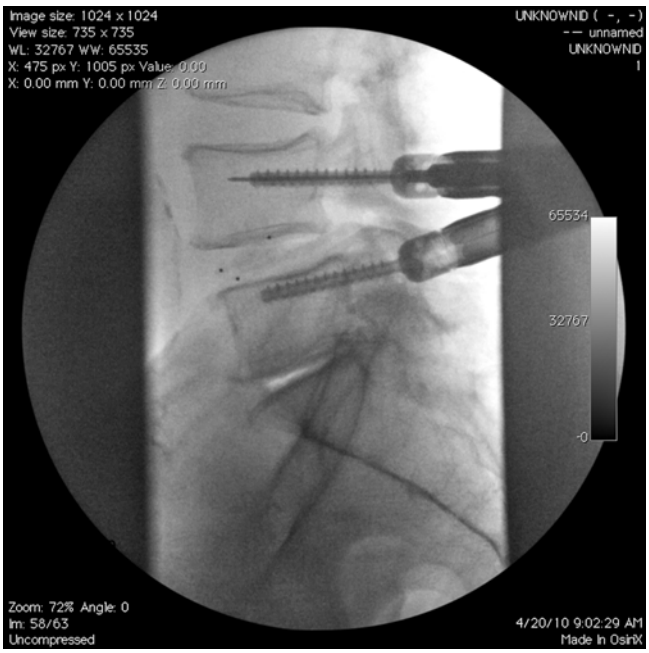

Fig. 16.5 Lateral fluoroscopic view of unilateral polyaxial pedicle screw placement with use of two 1-mm undersized taps inserted within the L4 and L5 vertebral bodies. Note the tap/screw assembly is engaged within the retaining bonescrew driver. The guidewire can be removed once the pedicle screw is engaged in the vertebral body (caudad pedicle screw in figure has had the guidewire removed)

priately sized rod is then inserted. Compression is placed across the pedicle screw construct as well as the bone construct within the middle column. Final rod contouring and rod tightening occurs via a torque wench (Fig. 16.6).

Posterolateral Fusion

If a posterolateral fusion is to be attempted the tube is wanded laterally to visualize the transverse process. This step should be performed prior to placement of the screws. The transverse processes are decorticated as well as any pars defect. An osteobiologics/graft enhancer is placed into the posterolateral gutter. This step is not mandatory and left to the discretion of the surgeon. Care should be exercised to ensure bone material does not compromise the exposed neural foramen.

Wound Closure

The wound must be copiously irrigated particularly if BMP-2 is utilized as this may serve a chemical irritant of the neural elements. Additionally, bone wax can be applied to the back end of the cage and annulotomy defect in an attempt to reduce the potential for postoperative radiculitis and neuroforaminal bone growth that may occur with the usage of BMP-2. The incision is closed in layers. Dermabond and sterile dressings are applied. Long-acting local anesthetic may be injected intramuscularly to relieve postoperative pain.

Postoperative Care

The patient is mobilized the same day of surgery [20]. The patient is typically discharged on postoperative day 1 or 2 An LSO brace is not routinely required but may be used according to surgeon preference. Muscle spasms are more common after MIS TLIF technique and can be managed with use of muscle relaxants (cyclobenzaprine, baclofen) [11].

Pearls and Pitfalls

General Considerations

A significant learning curve is associated with the minimally invasive surgical technique [21–24]. Thus, any surgeon undertaking work in this area should truly master the open technique before the attempt is made. Mentorship under a more experienced surgeon can be extremely helpful to learn nuances and to gain specific tips. As discussed earlier, the

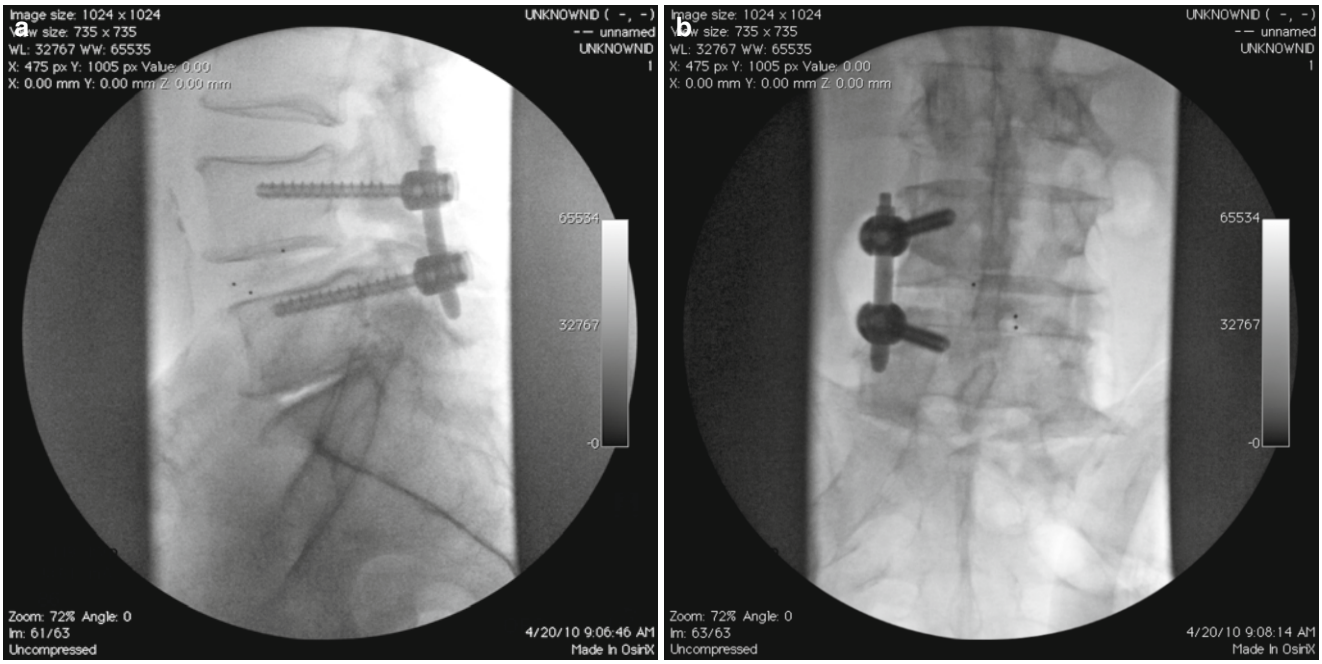

Fig. 16.6 (**a**) Lateral and (**b**) anteroposterior fluoroscopic images display unilateral pedicle screw fixation at the L4–5 interspace with the lordotic rod appropriately positioned and the interbody device in place

surgical space is constrained within the access system; thus the surgeon must have a thorough knowledge of the three-dimensional surgical anatomy. The surgeon also needs to be able to manipulate longer, bayoneted instruments [13]. Lastly, the surgeon needs to be able to efficiently use fluoroscopic imaging to keep radiation exposure to a minimum [25].

Although less common, cerebrospinal fluid leaks may occur. Some surgeons attempt to directly repair the durotomy down the tubular retractor via a small needle driver and dural suture. An alternative and easier method is to treat these leaks indirectly with a collagen sponge, fibrin glue, or other dural sealants. The lack of a dead space and thorough fascial closure in most instances may make a formal dural repair unnecessary.

In the recent literature, concerns of the deleterious effects of rhBMP-2 used during TLIF including vertebral body osteolysis, pseudarthrosis, and neuroforaminal bone growth have been expressed [26–29]. Neural foraminal bone growth is thought to occur due to the posterior egress of rhBMP-2 and concentrating of the postoperative seroma due to the lack of postoperative dead space in the constrained surgical field. A simple prevention technique is to apply bone wax to the annulotomy defect that seals the intervertebral space from the spinal canal. In addition, rhBMP should be packed anteriorly within the disk space.

Outcomes and Literature

The past several years have seen an increase in the publications reporting on the outcomes of minimally invasive spinal procedures [17, 30–32]. Many of these are focused on comparison to conventional open techniques. Karikari et al. recently reviewed the published literature on comparison of the open TLIF to the MIS TLIF approach [30]. Average duration of surgery ranged from 156 to 348 min for the MIS TLIF versus 142–312 min for the open TLIF technique. Average blood losses were less in the MIS TLIF group (range 150–456 mL) versus the open TLIF group (range 366–1,147 mL). Length of postoperative stay ranged in the MIS TLIF literature from 3 to 10.6 days and from 4.2 to 14.6 days for open TLIF. These short-term results suggest that the MIS TLIF approach provides benefits in the perioperative and immediate postoperative period.

According to some reports, surgical site infection may also be less with the MIS TLIF approach [33]. In comparison of 10 MIS TLIF cohort studies (comprised of 362 MIS TLIF patients) and 20 open TLIF cohorts (comprised of 1,133 patients), cumulative surgical site infection rates were reported at 0.6 % versus 4.0 % ($p=0.0005$) for the two groups, respectively [33]. More recently Parker et al. retrospectively reviewed 120 open-TLIF-treated patients and reported a 5 % (six patients) surgical site infection rate. Additionally the authors asserted that the mean cost ($29,110) of treating these surgical site infections represents a costly complication [33].

Other studies have addressed the costs associated with MIS procedures [5]. Adogwa et al. compared 15 MIS-TLIF-treated patients to 15 open-TLIF-treated patients and found that 2 years postoperatively, the MIS TLIF group showed lower length of stay days, lower postoperative narcotic use, and less return to work days [34]. These parameters may reduce both direct medical and indirect costs of lost work productivity associated with TLIF procedures. In a direct comparison study by the same authors, 2-year costs associated with the MIS and open TLIF techniques displayed average costs of $35,996 and $44,727, respectively [35]. Although the small sample size of the study ($n=30$) prevented statistical significance ($p=0.18$), the authors suggest that the $8,731 costs savings along with QALYs (quality-adjusted life years) gained from the MIS TLIF approach warrants serious consideration for its incorporation into surgical practice.

Since minimally invasive approaches are still in their infancy, long-term follow-up studies are limited. Rouben and colleagues assessed clinical outcomes, reoperation rates, and fusion status in 169 MIS-TLIF-treated patients with an average follow-up of 49 months [36]. The patients showed significant improvements in ODI and VAS scores ($p<0.01$). Additionally a 99 % fusion rate was assessed at final follow-up. Another study assessed the MIS TLIF approach for use as a revision surgery [37]. Twenty-five MIS TLIF patients were compared to 27 open TLIF patients at an average of 27.5 months postoperatively. Although clinical and radiographic results were similar between the two groups, less blood loss and less postoperative back pain scores of the MIS-TLIF-treated groups suggest that the approach can be used as an effective treatment for revision surgeries. These two studies suggest the long-term durability and expanded applications of the MIS approach.

The unilateral pedicle screw approach outlined in this chapter has also been explored as a viable and possible cost savings procedure in the literature. Advantages of the unilateral approach include preservation of the contralateral musculature, decreases in blood loss, decreases in operative time, and lower risks of intraoperative complications [38, 39]. These operative parameters are also speculated to translate to earlier mobilization, less pain, earlier discharge, and earlier return to work [40]. Other studies suggest that indications for the unilateral MIS TLIF approach even extend to obese patients and smokers [41, 42]. More long-term studies are needed to truly verify these results.

Conclusion

The minimally invasive transforaminal approach is a viable technique for a multitude of degenerative spinal maladies. It represents a robust and durable approach that provides anterior column reconstruction, stability, and relief of patients' pain symptoms. As the learning curve is surmounted, the spine surgeon should expect to see significant patient improvements as well as both direct and indirect cost savings. Careful preoperative assessment, precise surgical technique, and adequate follow-up can restore function to a variety of patient groups.

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Mini-Open Anterior Lumbar Interbody Fusion

17

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Introduction

Before 1930, anterior approaches to the spine were primarily involved in the treatment of spondylolisthesis and tuberculosis [1, 2]. The first use of anterior lumbar surgery for the treatment of lumbar degenerative disc disease had been described by Burns in 1933 [3]. In 1957, Southwick and Robinson [4] described a lateral extracavitary thoracoabdominal approach for the treatment of lumbar disc disease. They reported no serious complications and few cases of postoperative ileus as related to the retroperitoneal approach [4].

Overtime, the anterior retroperitoneal lumbar approach has developed into a common alternative of treatment for a variety of lumbar conditions. Minimally invasive methods such as mini-open, endoscopic, and laparoscopic approaches have been introduced in order to optimize the anterior lumbar interbody fusion (ALIF) procedure. As compared to traditional approaches, minimally invasive methods are accompanied by shorter hospital length of stays, shorter operative room time, minimal blood loss, and smaller incisions. As such, this approach has the benefit of being more cosmetically pleasing, having reduced postoperative complications, and a faster early recovery with equivalent fusion results [5]. It also allows for the eradication of disc material with a wide exposure of disc space, excellent interbody preparation, the use of a large graft and/or stable interbody device, lordosis correction, high fusion rates, and no posterior muscle injury [6–8]. Despite the advantages to this approach, there is still a risk of damage to the large blood vessels leading to catastrophic blood loss [6]. In addition there is a risk of retrograde ejaculation in males reported in literature from 0.1 to 45 %, specifically when the L5–S1 level is involved [5, 6, 9, 10]. Other disadvantages of an anterior lumbar retroperitoneal fusion include instability when used as a stand-alone procedure, pseudarthrosis, or poor extension stability when used without supplemental instrumentation and no direct neural decompression [7, 11, 12].

Indications

Broad indications exist for mini-ALIF which include mechanical low back pain often attributed to symptomatic degenerative disc disease of one or two adjacent levels of the lumbar spine, degenerative or isthmic spondylolisthesis, spinal or foraminal stenosis, tumors, deformity, reconstruction of the anterior column, iatrogenic segmental instability, lateral listhesis, pseudarthrosis, specific vertebral fractures usually from trauma, and sagittal malalignment [2, 13–16]. Other indications include revision of failed posterior procedures, postdiscectomy collapse, additional support for long fusion, and spinal infections [2, 15, 17].

Clinical and Radiographic Evaluation

The patient's history should be reviewed and a proper physical exam should be conducted. Preoperative planning includes imaging such as standing anteroposterior and lateral radiographs with flexion, extension views, magnetic resonance imaging (MRI), or computed tomography (CT) scan. Preoperative imaging can increase surgeon knowledge of patient anatomy which can indicate instability, end plate sclerosis or osteophytes, loss of lordosis or disc space, and/or disc dehydration and location of peri-spinal vessels [2, 15]. When indicated, discography may be appropriate. Discography remains controver-

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sial; internal disc disruption should be undertaken with caution as results are inconsistent in the literature [15]. Patient selection remains key to successful fusion.

Relevant Anatomy

An understanding of anatomy can lead to an avoidance of potential complications such as vascular injury and retrograde ejaculation. When accessing the retroperitoneal space anatomic structures to identify and avoid include: sympathetic and parasympathetic plexi, aorta, vena cava, superior hypogastric plexus, psoas muscle, ilioinguinal nerve, genitofemoral nerve, ureter, iliolumbar vein, and common iliac artery and vein.

Commonly the use of a vascular or general surgeon both for preoperative evaluation and intraoperative exposure is recommended in order to limit complications [10]. The L4–L5 level is most commonly associated with vascular injury due to vessel retraction and injury to the ureter [2, 9, 15]. The iliolumbar vein commonly arises from the posterolateral side of left common iliac vessel but can sometimes emerge from the inferior vena cava. The iliolumbar vein is commonly observed as a single vein; however, it is possible to observe two or more veins upon approach. [18] When accessing the L4–L5 level, it is important to double ligate and transect these vessels in order to avoid tearing while retracting the major vessels towards the patient's right side [2] (Fig. 17.1).

Caution should be taken at the L5–S1 approach as access to this disc space is between the bifurcation of the iliac vessels. Certain conditions can cause this bifurcation to occur at or below the L5–S1 disc space, rendering access to this disc space potentially troublesome or making that level impossible to access. Furthermore, the middle sacral artery and vein usually span the L5–S1 disc space anterior to the anterior longitudinal ligament and should be ligated before attempting to perform an annulotomy. The superior hypogastric sympathetic plexus lies directly anterior to the L5–S1 disc space. The use of monopolar electrocautery dissection should be avoided in an attempt to reduce the incidence of retrograde ejaculation in male patients, due to potential injury to this plexus [2, 15]. Sacral inclination should be taken into account in regard to its location and angle in the pelvis. The incision should be relative to the operative level for removal of the disc material and graft placement [13]. Preoperative imaging should be reviewed when accessing the L4–L5 or L5–S1 level in order to observe the presence of any anterior osteophytes and vascular calcification [19]. Careful vessel manipulation must be performed to avoid any tearing of these vessels on these bony projections [2, 19].

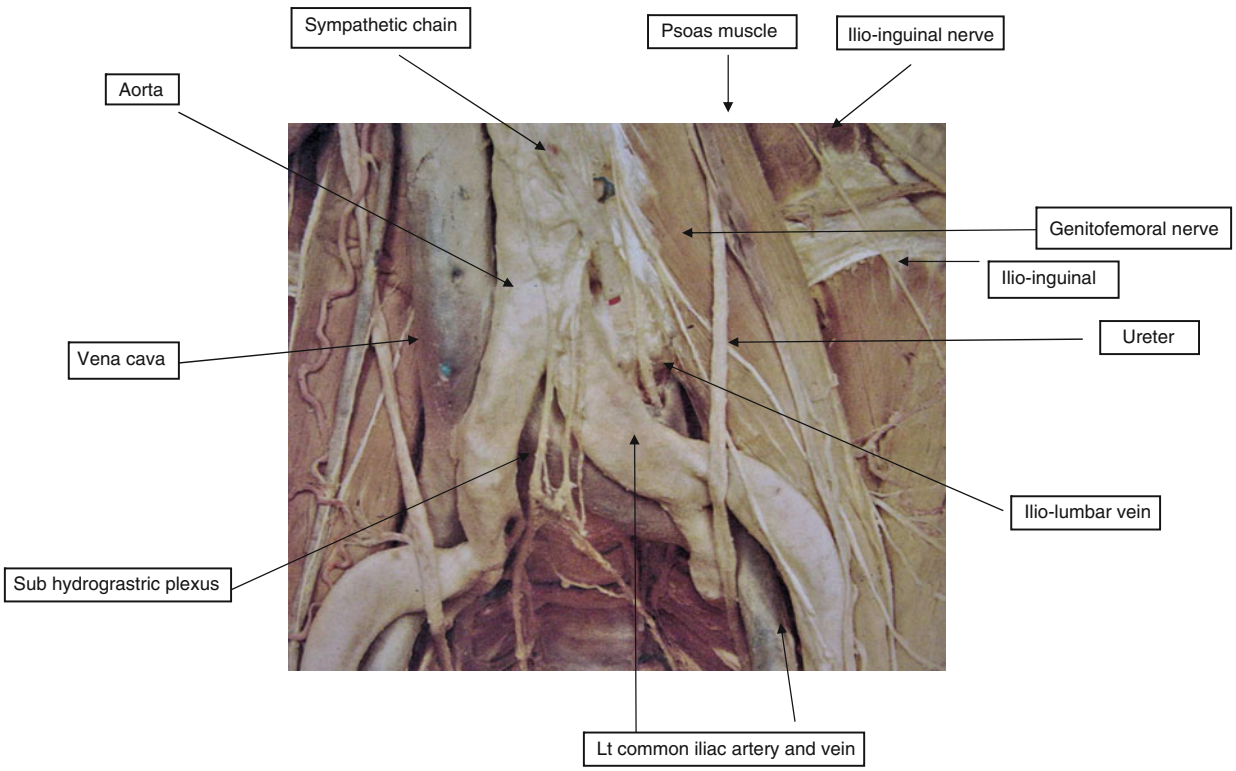

Fig. 17.1 Intraoperative photo of the retroperitoneal anatomy

Contraindications

Anterior access for lumbar fusion may have contraindications: such as significant sacral inclination, high-grade spondylolisthesis, vascular disease or vessel disease with calcification, or morbid obesity [13, 15]. Osteoporosis or osteopenia can be contraindications for a stand-alone mini-ALIF procedure due to potential for implant or graft subsidence or vertebral body fracture [14]. Prior abdominal surgery such as previous anterior lumbar surgery or reconstruction of the abdominal wall or the presence of retroperitoneal pelvic fibrosis can make the anterior approach more difficult [13, 15]. In such cases, patients should be evaluated and counseled on the potential risks of a repeat exposure. Alternatives would include an opposite-side retroperitoneal exposure (most commonly right sided) or a direct lateral transpsoas approach above L5–S1 or the need to access the spine via a transperitoneal approach.

Avoiding and Treating Complications

The mini-ALIF approach has a range of associated intraoperative and postoperative complications including vascular, neural, or gastrointestinal complications. Prior to proceeding with surgery, patient comorbidities should be evaluated medically in order to reduce the incidence of intraoperative and postoperative complications.

Preoperatively, the presence of osteoporosis should be evaluated in order to reduce the incidence osteoporotic fractures and graft dislodgment or subsidence postoperatively. The use of a preoperative DEXA scan assists in the prediction of the presence of osteoporosis. Osteoporosis is usually characterized by a femoral neck or spinal (L2–L4) T-score of less than −2.5 [20]. Preoperative imaging should be assessed in order to identify any instability and determine whether supplementation with posterior instrumentation is required. If serious concerns exist in determining whether to use a mini-ALIF approach, it may be appropriate to consider an alternative approach.

Intraoperative complications include vascular injury, most commonly at the L4–L5 level, that can result in laceration of the left common iliac vein, inferior vena cava, or iliolumbar vein, requiring treatment by obtaining hemostasis with manual compression and repair with suture or double ligatures [2, 9, 15]. Prolonged retraction of the common iliac arteries can lead to left iliac artery thrombosis, thereby diminishing arterial flow resulting in left-sided thrombosis and potential limb ischemia. While treatment of this complication is considered an emergency using either bypass surgery or thrombectomy, prevention of thrombosis can include intermittent release of retractors and detection can be achieved by intraoperative pulse oximetry on the great toe [2, 9, 21].

Postoperative complications include gastrointestinal issues, graft subsidence or displacement, iatrogenic fractures, pseudarthrosis, infection, nerve damage, deep vein thrombosis, dural injury, cerebrospinal fluid leak, postoperative weakness or numbness, hardware failure, or death.

Gastrointestinal complications most often include postoperative ileus and acute colonic pseudo-obstruction, also known as Ogilvie's syndrome. Postoperative ileus, specifically reduced gastric motility, results from three common factors that can manifest with a clinical presentation of increased abdominal distention, increased abdominal discomfort, and decreased flatus. Neurologic, immunologic, and pharmacological factors can all contribute to decreased gut motility [9]. As constipation can progress to ileus and further to Ogilvie's syndrome, immediate response to clinical and objective diagnosis is warranted. Patients should be placed NPO (nothing by mouth), intravenous fluids should be restarted, and bowel rest and the avoidance of narcotic medication are warranted as initial conservative management. One might also consider the placement of a nasogastric tube to lower intermittent wall suction and repeat imaging studies along with serial physical exams. Once the symptoms of an ileus resolve, an aggressive bowel regimen, including continued use of laxatives, along with the slow advancement of the patient's diet should facilitate return to normal bowel habits.

Direct interaction with the parasympathetic nerves to the colon and the insult to the blood supply of the pelvis in transperitoneal and retroperitoneal approaches in a mini-ALIF can result in acute colonic pseudo-obstruction [22]. If symptoms of pseudo-obstruction are suspected, plain abdominal radiographs and CT or contrasted enema should be ordered and evaluated in order to assess for the presence of colonic dilation from the cecum to the splenic flexure and exclude a mechanical obstruction. In addition to imaging, laboratory results should be evaluated in order to determine if leukocyte numbers are elevated or if any other metabolic discrepancies exist including abnormal levels of sodium, potassium, bicarbonate, creatinine, magnesium, and blood urea nitrogen. Second-line management is typically intravenous neostigmine, which has shown an efficacy long-term response rate of 64–100 % [23]. Further development of colonic dilation or the presence of Ogilvie's syndrome should be taken into serious consideration. General surgery consultation is indicated, and a high suspicion for colonic rupture should be kept in mind when evaluating such patients [9].

Subsidence, end plate fractures, and graft displacement can result from poor exposure and inadequate or improper disc space preparation thus leading to improper cage placement or improper cage sizing [2, 9, 15]. Maintenance of

midline orientation with the use of fluoroscopy should be stressed in order to avoid poor implant placement [15]. Implants should be directly visualized centrally in the disc space. Aggressive end plate disruption should be kept to a minimum [15]. Appropriate preoperative radiographic measurements and intraoperative sizing of implant trials should assist in determining the appropriate interbody implant size. Postoperative graft displacement can result from poor bone quality, instability, or improper cage sizing [15]. In patients with isthmic spondylolisthesis, it is generally recommended that posterior instrumentation be used in addition to increase sagittal stability thereby decreasing the risk of graft dislodgement [24]. It is important that patients with a history of diabetes and long-term nicotine abuse and elderly patients undergo complete preoperative medical evaluation in order to reduce perioperative complications. Further consideration for posterior fixation should be made for patients in these demographics [2]. Supplementary fixation includes anterior plates, pedicle screw systems, and translaminar screws. The use of a larger cage in conjunction with an adequate central opening for bone graft placement and proper end plate preparation may improve fusion rates [24].

The choice of biologics in a mini-ALIF approach is largely dependent on surgeon preferences. The use of bone morphogenetic protein (BMP) has been shown to increase fusion rates when used in the proper environment [2, 9]. Currently, the only spinal procedure for which the use of BMP (recombinant human bone morphogenetic protein-2 (rhBMP-2) [Infuse; Medtronic Sofamor Danek, Memphis, TN, USA]) is currently FDA approved is for a ALIF approach in conjunction with an LT-CAGE, Lumbar Tapered Fusion Device (Medtronic Sofamor Danek, Memphis, TN, USA). Although many surgeons use BMP in other off-label applications, the safety of rhBMP-2 in these procedures has not been conclusively demonstrated, and there have been concerns raised regarding complications stemming from off-label use of these products [25]. One of the most significant risks associated with BMP involves the formation of ectopic bone outside the desired fusion bed [26]. Another risk is retrograde ejaculation/male sterility which has also been cited with the ALIF procedure and the use of rhBMP-2; however, there are many studies demonstrating no significant difference in complication rates when using rhBMP-2 in other procedures [27, 28].

Surgical Technique

The patient is placed on an operative table in a supine position. A padded lumbar bolster may be placed at the operative level in order to create appropriate lordosis in the lumbar spine. All bony prominences should be well padded, and the hips should be flexed to decrease any tension on the femoral nerve. Utilizing a radiolucent table, anteroposterior and lateral fluoroscopic images are used to determine placement of the incision and to assure that the patient is level in the surgical plane. Understanding patient anatomy is crucial for proper incision placement. A skin incision (transverse, vertical, or oblique) should be made a few centimeters to the left of the midline. Subcutaneous dissection is carried down to the rectus sheath, entering the retroperitoneum through the abdominal wall by splitting the rectus muscle.

Mobilization of the rectus abdominus should be performed from medial to lateral to preserve the innervation. Identification is then made of the carcuate ligament followed by dissection of the peritoneum from the posterior rectus sheath. The posterior rectures sheath should be released cephalad enough to achieve exposure. Tense reflect the retroperitoneal contents from left to right [7], identify psoas muscle ureter and vessels, and [8] place retractors.

L5–S1 Exposure

Further exposure to the disc space is specific for each level being accessed. In order to expose the L5–S1 level, the surgeon should continue dissection of the peritoneum from the lateral abdominal wall; the psoas muscle should be identified and retraction of the peritoneal contents can continue from left to right. The left ureter should be identified and retracted with the peritoneum. Care should also be taken to avoid electrocautery close to the sympathetic plexus which often lies to the left of the disc space, in order to reduce the incidence of retrograde ejaculation. Radiolucent retractors or surgeon-specific retractors are placed anteriorly to the sacrum, fully exposing the L5–S1 disc space (Fig. 17.2). Identification and mobilization of the middle sacral vessels

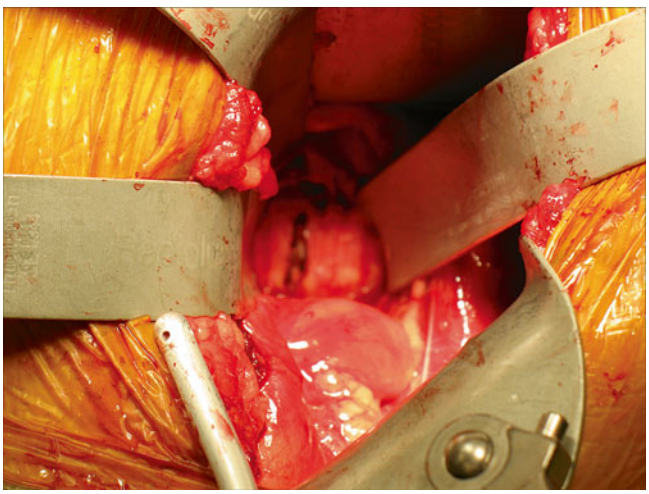

Fig. 17.2 Intraoperative photo of the retroperitoneal exposure of the L5–S1 disc space with retractors in place

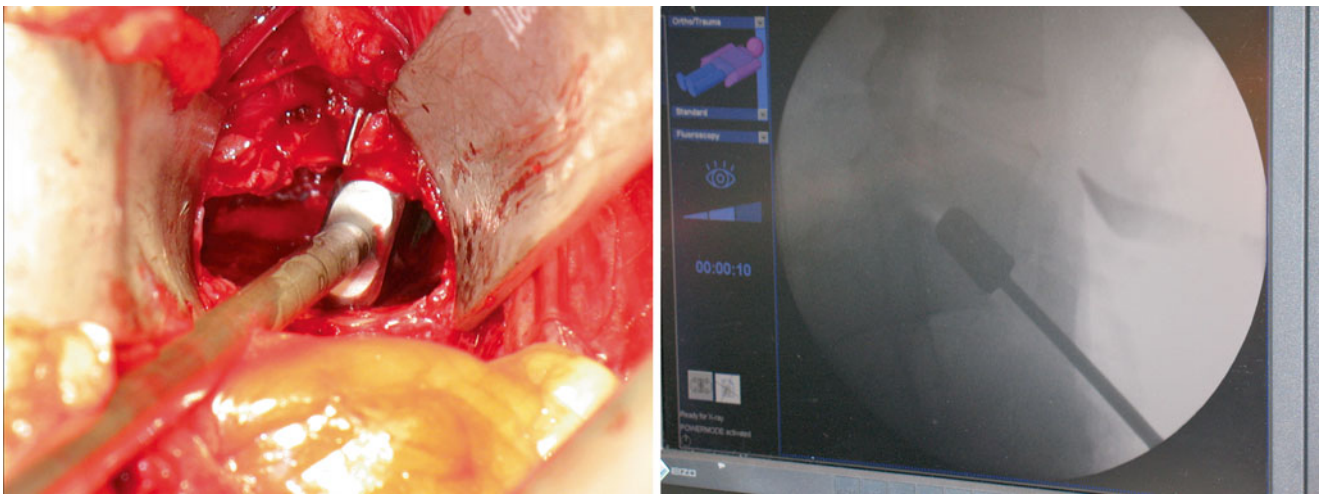

Fig. 17.3 Intraoperative photo (*left*) of paddle distractor in the disc space after complete discectomy is completed. Radiographic lateral intraoperative image (*right*) demonstrating paddle distractor in position

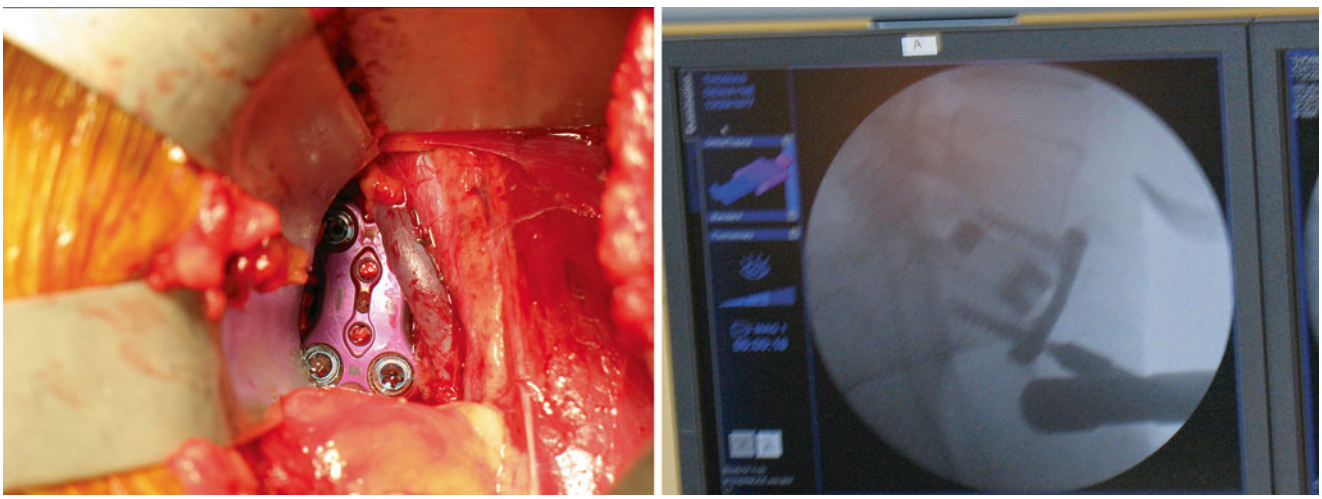

Fig. 17.4 Intraoperative image (*left*) demonstrating position of plate and secured to the L5–S1 vertebral bodies with fixation screws. Intraoperative lateral x-ray (*right*) displaying the interbody cage and anterior plate of L5–S1

and iliac vessels is critical for appropriate visualization of the L5–S1 level.

Once the correct level is identified, the discectomy is performed and must be carried out to the posterior longitudinal ligament, at times releasing the posterior annulus, which allows for better mobilization of the vertebral segment and distraction of the disc space (Fig. 17.3). End plate preparation is critical in the exposure of bleeding bone from both end plates. This is achieved with a series of curettes to remove the disc in its entirety. We then use a rasp to further prepare the end plates being careful not to remove subchondral bone to prevent subsidence of the implant. Punctate bleeding is then elicited from the end plates using currettes, taking care not to violate the endplate integrity. Distraction is applied to the disc space in order to restore proper disc space height and proper sagittal alignment.

It is important to note that there is a wide variety of hardware, biologics, and cage options available for mini-ALIF procedures. Most commonly utilized cages include polyether ether ketone (PEEK) interbody device, ceramic devices, and titanium devices (threaded or cylindrical). Biologics commonly utilized include structural femoral ring allograft, INFUSE (rhBMP-2 [Infuse; Medtronic Sofamor Danek, Memphis, TN, USA]), iliac crest autograft, and demineralized allograft bone matrix.

Hardware and biologics are then placed according to the details for the insertion of the specific implant. Proper hardware and interbody implant placement is visualized using fluoroscopic imaging (Fig. 17.4). Upon careful review of implant placement, retractor blades can then be removed. Careful inspection and proper hemostasis is obtained as retractors are removed, and each layer is then closed

including re-approximation of the anterior rectus sheath, subcutaneous tissue, and skin—using suture dependent on surgeon preference.

Superior Lumbar Levels of Exposure

Anterior exposure to the L4–L5 level requires visualization of the patient's vascular anatomy, achieved by preoperative assessment of the MRI. At L4–L5, the vascular anatomy includes the division of the aorta into the right and left iliac arteries, while the inferior vena cava can remain as a single vessel or separate into the iliac veins. Skin incision and development of the preperitoneal space is achieved similarly to the L5–S1 exposure using the placement of radiolucent retractors. Blunt dissection should expose both the left common iliac artery and vein allowing possible mobilization across the disc space. Vessel mobilization should be done bluntly and carefully so as to avoid injury to such vessels. This can be done with vein retractors and blunt-ended instruments. However, it is critical in order to mobilize the vessels at the L4–L5 disc space that the surgeon must divide the iliolumbar vein and possibly the segmental vessels which arise from the posterior aspect of the left common iliac vein and then traverse under the psoas muscle, prior to retraction of the vessels. This division allows for safer and easier vessel mobilization and retraction across the disc space. Disc removal, preparation of the disc space, and implantation of the appropriate interbody device at the L4–L5 level, similar to the L5–S1 level, should be done expeditiously and with great care in order to prevent injury to the great vessels. The same approach may be utilized when anteriorly exposing the L3–L4 disc space.

Postoperative Care

Patient should be ambulatory as soon as declared stable and may wear a brace as needed. It is important to observe and expect ileus; therefore, begin bowel protocol. Routine wound care and suture removal will follow patient discharge from the hospital. Appropriate postoperative imaging studies should be obtained to ensure the implants are intact, and the patient may begin physical therapy for core and abdominal strengthening along with aerobic conditioning.

Outcomes

Clinical and radiographic successes have been cited at varying levels for mini-ALIF procedures. Subach et al. [29] retrospectively reviewed the radiographic findings of 53 patients that had received single lordotic titanium cages with rhBMP-2 in a single-level stand-alone ALIF. The study demonstrated that subsidence reduced significantly when a wider cage was placed thereby permitting an increased surface area exposure for interbody fusion [29]. Quirno et al. [30] retrospectively evaluated the surgical and clinical outcomes of 23 patients that underwent anterior interbody fusion with a femoral ring allograft or iliac crest bone graft supplemented by posterior instrumentation for treatment of low-grade spondylolisthesis. The study noted improvements at 10-month follow-up in Oswestry Disability Index (ODI) and Visual Analog Scale (VAS). The average slip percentage was reported as 23.2 % preoperatively to 19.0 % postoperatively. Overall, the authors reported good clinical outcomes associated with the use of an ALIF combined with posterior supplementation [30].

Shim et al. [8] reported a 91.3 % fusion rate in 23 patients that underwent ALIF with instrumented posterior lumbar fusion (PLF) compared to a fusion rate of 76.9 % in 26 patients who underwent ALIF with percutaneous posterior spinal fusion (PSF) at a 2-year follow-up. The study found no significant differences between the complication rates for both groups [8]. Strube et al. [12] prospectively compared the clinical outcomes between 80 patients that underwent stand-alone ALIF or an anteroposterior lumbar fusion (APLF). ODI and VAS scores were reported to be significantly improved through the follow-up period for the ALIF group as compared to the APLF group. Both groups maintained improvement through the 24-month follow-up period. The study also reported a significantly higher patient satisfaction of those that had undergone ALIF as compared to the APLF group. At 12-month follow-up, CT evaluation demonstrated a fusion rate of 68.7 % in the APLF group and 70.6 % in the ALIF group. These findings were not significant between the groups over the follow-up period [12]. Ohtori et al. [31] prospectively compared the clinical outcomes of 22 patients that underwent stand-alone ALIF to 24 patients that underwent instrumented PLF. The study reported no significant difference in bone union success or patient-reported outcomes (i.e., VAS and ODI). The ALIF patients were found to have experienced a greater improvement in low back pain, significantly less blood loss, but much longer length of hospital stay compared to the PLF group [31].

Pearls/Pitfalls

- Proper training in exposure techniques or use of a vascular or general surgeon to assist with exposure.
- Proper knowledge of patient anatomy utilizing MRI visualization preoperatively.
- Appropriate use of osteoinductive, osteoconductive, and osteogenic materials to ensure fusion and avoid pseudarthrosis and subsidence.

- Risk of retrograde ejaculation.
- Specific attention to anatomy, pathology, and biomechanics; consider supplemental fixation after mini-ALIF with mobile spondylolisthesis or high sacral slip angles.
- When accessing the L5–S1 level, sacral inclination should be taken into account in regard to its location and angle in the pelvis. The incision should be relative to the operative level for removal of the disc material and graft placement [13].
- Patient selection is key to successful fusion.

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18 Minimally Disruptive Lateral Transpsoas Approach for Thoracolumbar Anterior Interbody Fusion

Jeffrey A. Lehmen and W. Blake Rodgers

Introduction

Conventional Surgical Approaches

The minimally disruptive lateral approach for thoracolumbar interbody fusion was developed as a less-invasive alternative to conventional anterior (ALIF) and posterior (PLIF/TLIF) lumbar interbody fusion approaches. The ALIF procedure provides a wide exposure to perform an extensive discectomy and place a large intervertebral graft, which promotes a healthy fusion environment as well as enables segmental realignment, but has several notable drawbacks. The approach itself is generally performed through an open anterior incision (though mini-open alternatives have been proposed [1]) with mobilization of the great vessels to expose the anterior disc space. In most cases, ALIF is a somewhat easier approach for L5–S1, below the bifurcation of the great vessels. At L4–5, where the vessels bifurcate, the risk of vascular injury is higher. The incidence of vascular injury during ALIF procedure has been reported as high as 18 % [2, 3], though most authors have found the rate to be much less, between 2.2 and 6.7 % [4, 5]. Additional risk considerations for ALIF include the potential for visceral injury (5 %) [4, 5], reproductive complications (9.6 %) [4], and difficulty with revision due to the potential for scar tissue formation on the interface between the great vessels and anterior border of the spine. From a procedural standpoint, ALIF requires sectioning of the anterior and, possibly, the posterior longitudinal ligaments (ALL, PLL) for graft placement, which may destabilize the segment, necessitating either internally fixated devices or for the patient to be repositioned for posterior instrumentation placement. Overall complications have been reported as high as 29 % [6] to 76.7 % [7] in ALIF with posterior fixation [7].

Posterior procedures for interbody fusion generally rely on a direct decompression to treat stenosis, with placement of a small graft(s) in the interbody space that is limited in its ability to increase disc height, effect segmental alignment, and provide indirect decompression due to a limited working window from posterior, accessing the anterior column adjacent to the cauda equina and exiting nerve roots. As a result, while posterior approaches allow for single-incision surgery to perform an interbody fusion, direct decompression, and placement of posterior fixation, the requirement to retract the cauda equina in PLIF and work adjacent to the nerve root in TLIF may put the root at risk [8]. Scaduto et al. in 2003 found a 13 % rate of new postoperative motor weakness following PLIF with pedicle screw fixation [5]. Similarly, Okuda et al. found in 251 PLIF patients with complete facetectomy, a neurologic injury rate with resulting motor deficit of 8.3 %, with 43 % of those classified as severe and 19 % permanent [9]. In TLIF, several studies have shown 7–10.9 % rate of new-onset radiculitis postoperatively on the side ipsilateral to the approach, indicating a relatively high rate of nerve root irritation or injury during the transforaminal approach [10, 11]. Additionally, damage to the multifidus muscle during traditional open posterior approaches, namely, dissecting its tendon origin(s) from the spinous process, results in substantial muscle damage, functional loss, and scar tissue formation [12–15]. This single factor has been posited as the differentiating factor between true minimally disruptive and non-minimally invasive approaches for posterior procedures [13, 14]. Procedurally, the ability to prepare the disc space, maximize fusion area, and place an interbody graft to markedly increase disc height is somewhat limited using posterior approaches.

The morbidity in these conventional surgical approaches for spine surgery has led to the development of minimally invasive techniques which minimize traditional

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approach-related morbidity. Early iterations of minimally invasive anterior approaches in spine surgery primarily used endoscopes for spinal access [16]. While endoscopic spine surgery has largely been successful at limiting exposure-related complications (blood loss, infections, incisional pain, etc.), there have been several challenges which have resulted in its limited use in current spine surgery. These adoption challenges include expensive instrumentation, the requirement for specialized surgical staffing, extended learning curves (as high as 150 patients) [17], the visualization of a three-dimensional field in two dimensions (monitors), difficulty in placing implants and instrumentation in segments requiring realignment, and the relative difficulty in managing intraoperative complications without converting emergently to an open exposure [16–21]. In the late 1990s, endoscopic approaches for lumbar interbody fusion began being performed from an anterolateral orientation taking a transpsoas approach on the anterior margin of the psoas muscle. This approach required dissection of the aorta and vena cava off of the anterior spine. Initially, no neuromonitoring modalities were recommended. Perhaps consequently, in their early series of 21 patients, new neural deficits were observed in 30 % of cases, 66 % of which resolved within 4 weeks, the other 33 % persisting at last follow-up in the study [22].

Mini-Open Lateral Transpsoas Approach

These challenges slowed the adoption of endoscopic procedures, and then, starting in the late 1990s and early 2000s, the modern mini-open lateral retroperitoneal transpsoas approach for lumbar interbody was pioneered by Luiz Pimenta with early reports appearing in the literature in 2006 [23]. The procedure was designed to leverage the advantages of anterior approaches through a mini-open incision under direct visualization and minimize the complications common to ALIF, namely, vascular, visceral, and reproductive injuries. Compared to posterior approaches, the lateral retroperitoneal transpsoas approach leaves bony, ligamentous and structures intact, does not require nerve root or cauda equina retraction, and allows for the placement of a large interbody graft. Other benefits of the procedure minimize collateral soft-tissue trauma through a muscle-splitting retroperitoneal approach using blunt dissection, maintenance of the ALL and PLL, allowing for disc height restoration while maintaining natural stability and alignment correction through ligamentotaxis [24], and the ability to place a large interbody cage across the lateral borders of apophyseal ring with wide apertures for fusion. Additionally, while the placement of posterior instrumentation requires a second incision, anterolateral plating allows for single-incision interbody fusion and fixation, and a variety of posterior instrumentation can be placed without repositioning the patient from the lateral position, including ipsilateral pedicle screws, unilateral and bilateral transpedicular facet screws [25], and interspinous plating.

In early reports of the procedure, it has been shown that placement of a large interbody implant through the lateral approach results in significant indirect decompression of the central canal and neural elements [26], with little perioperative morbidity in large-series studies [27, 28]. Similar or, possibly, improved long-term outcomes and fusion results to conventional surgical approaches for lumbar interbody fusion [29–33] even in high-risk patients with significant baseline comorbid factors like obesity [34] and advanced age [34, 35] have been reported.

Surgical Indications and Contraindications

Indications include any disease requiring interbody fusion in the thoracolumbar spine above the L5 level and below approximately T4. Specific indications may include degenerative disc disease (DDD) with instability [29], recurrent disc herniation, degenerative spondylolisthesis (≤ Grade II) [29, 36], degenerative scoliosis [37, 38], pseudoarthrosis, DDD sequelae following discitis, total disc replacement (TDR) revisions [39], post-laminectomy instability, and adjacent segment disease [40]. Relative contraindications to the approach include instances where L5–S1 is indicated, where the approach is limited by the position of the iliac crest, and where a level cranial to approximately T4 is indicated, where vascular anatomy and the position of the scapula limit access for the approach. Other relative contraindications include patients with bilateral retroperitoneal scarring (e.g., prior kidney surgery), patients with anomalous vascular anatomy interfering with the lateral approach (as may occur in rotational deformities), and degenerative spondylolisthesis ≥grade II where exiting nerve roots are more anterior and limit access (in patients with lumbarized sacra where L5–6 is a functional L4–5 segment, due to the likelihood of a more anterior lumbar plexus limiting lateral disc space access) [41]. The vascular and plexal anatomy may also present relative contraindications which often can be identified preoperatively through careful review of axial magnetic resonance imaging (MRI), noting the location of these structures relative to the lateral approach[41, 42].

Fig. 18.1 The MARS™ 3 V retractor system (**a**) and InterContinental® Plate-Spacer System (**b**), CALIBER®-L Expandable Spacer (**c**), and TransContinental® Spacer for lateral lumbar interbody fusion (LLIF) (**d**) (Globus Medical, Audubon, PA. Used with the permission of Globus Medical)

Surgical Procedure

Several platforms for mini-open lateral interbody fusion exist through different manufacturers. Several notable systems are direct lateral interbody fusion (DLIF®, Medtronic Sofamor Danek, Memphis, TN), lateral lumbar interbody fusion (LLIF®, Globus Medical, Inc. Audubon, PA) (Fig. 18.1), and extreme lateral interbody fusion (XLIF®, NuVasive, Inc. San Diego, CA) (Fig. 18.2). Several differences exist between the platforms, including the recommended approach location (more anterior or more posterior on the lateral disc space), the retractor design and functionality, the integration of neuromonitoring modalities into access and procedural instrumentation, as well as implant offerings and configurations. Of note, procedural recommendations for DLIF and XLIF include the use of monitoring (though different techniques for monitoring are recommended by each manufacturer), while the LLIF approach leaves that decision to the operating surgeon. Since the authors' personal experience is greatest with the XLIF alternative, we will confine our further discussion to that version of the procedure.

In a brief summary, the authors' preferred approach utilizes a mini-open (approximately 2.5–4 cm incision [23]) approach under direct visualization 90° lateral from midline for retroperitoneal access to the lateral border of the psoas muscle. At the psoas muscle, sequential dilation with integrated neuromonitoring is used to assess, in real time, the orientation and distance from the motor nerves using directional stimulation and discrete-threshold responses [28, 43]. Once the lateral disc space is exposed, standard surgical techniques are used for discectomy and interbody fusion, using a variety of specialized polyether ether ketone (PEEK) intervertebral implants (Fig. 18.3). Supplemental fixation can be used at the surgeon's discretion.

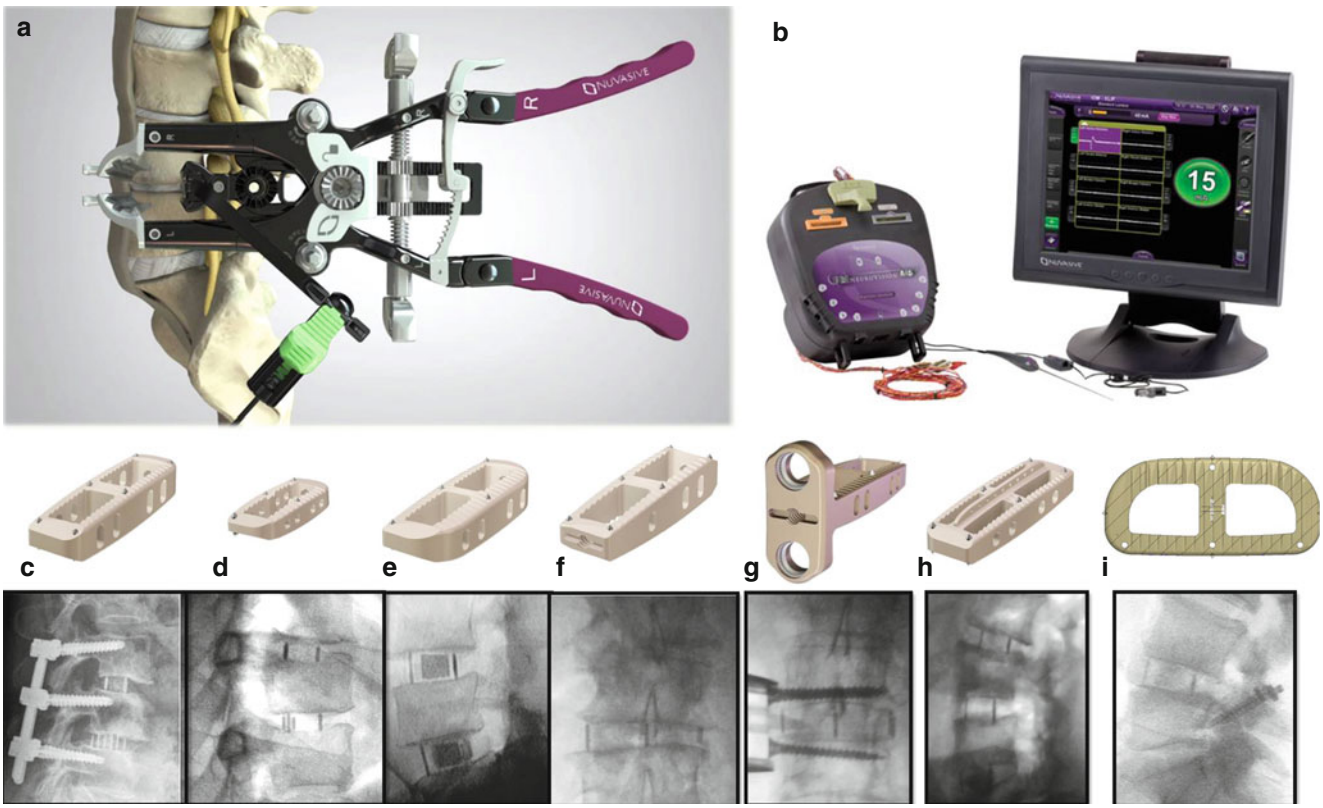

Fig. 18.2 MaXcess® IV retractor with posterior blade electromyography stimulating electrode (**a**), NV JJB™/M5® neuromonitoring platform (**b**), CoRoent® XL (standard 18 mm) (**c**), CoRoent XL-T (**d**), CoRoent XL-W (wide, 22 mm) (**e**), CoRoent XL-CT (coronally tapered) (**f**), CoRoent XL-F (tabbed) (**g**), CoRoent XL-K (keeled) (**h**), and CoRoent XL-XW (extra wide, 26 mm) (**i**) polyether ether ketone (PEEK) implants (NuVasive, Inc., San Diego, CA. Copyright NuVasive, Inc., used with permission)

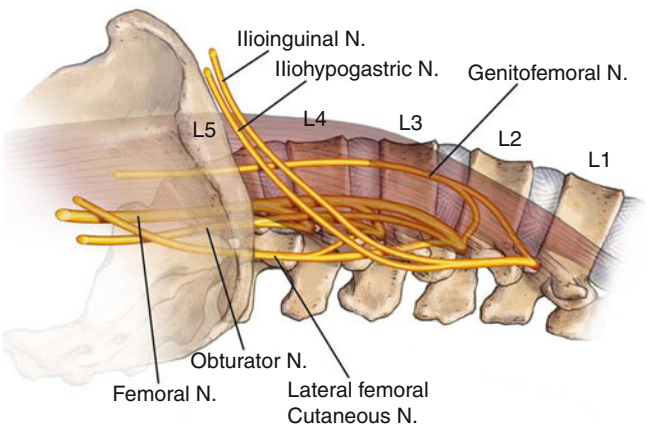

Fig. 18.3 Lateral illustration of the anatomy primarily related to the lateral transpsoas approach for lumbar interbody fusion (Copyright NuVasive, Inc., used with permission)

Anatomical Considerations

An understanding of the anatomy of this approach will help to guide the procedure as well as decreasing the likelihood of complications. While vascular and other soft-tissue structures that play a role in this approach will be discussed at their relevant point in the following surgical procedure, the two interconnected anatomic elements and that are essential to understand are the iliopsoas muscle and the nerves of the lumbar plexus. The iliopsoas muscle can be divided into the psoas major, psoas minor, and iliacus muscles. The lateral approach is primarily concerned with psoas major and psoas minor (subsequently referred to as the psoas muscle). The nerves of the lumbar plexus generally lie within and upon the psoas muscle, and nerve avoidance is the main rationale for the use of advanced neuromonitoring integrated into the procedure and instrumentation (Fig. 18.3) [43]. The origins of the psoas muscle are on the lateral borders of the vertebral bodies and transverse processes from approximately T12 to L5 with its insertion on the lesser trochanter of the femur. The psoas muscle increases in size (diameter) as it progresses caudally from L1 (Fig. 18.4) and is primarily responsible for hip flexion and rotation. The nerves of the lumbar plexus include the iliohypogastric (sensory/motor), ilioinguinal (sensory/motor), lateral femoral cutaneous (sensory) genitofemoral (sensory/motor), obturator (motor/sensory), femoral (motor/sensory), and direct muscular branches from T12–L4 which innervate the psoas

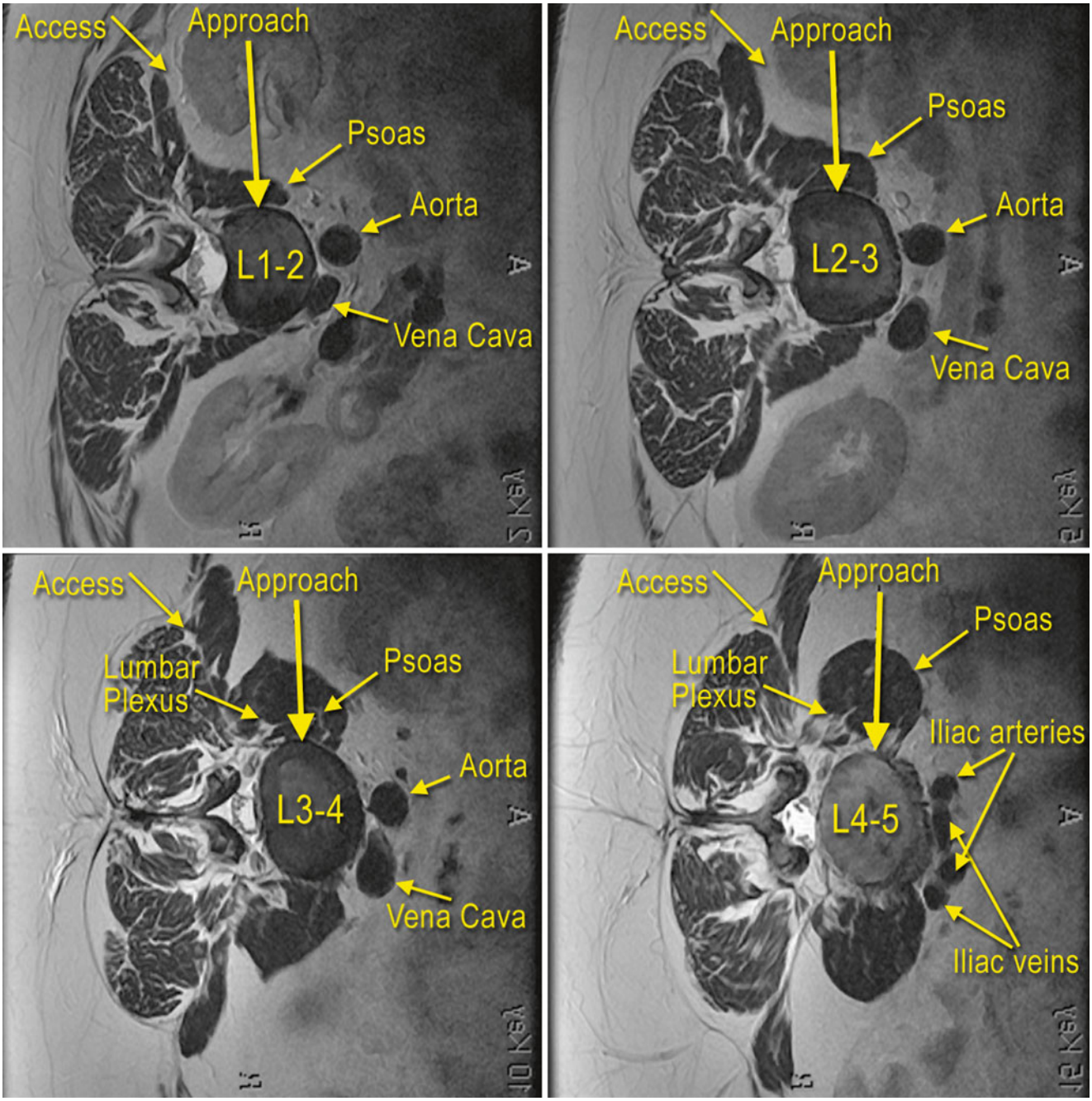

Fig. 18.4 Axial magnetic resonance imaging showing the anatomy relevant to the lateral approach thoracolumbar interbody fusion at the disc levels for L1–2 (*upper left*), L2–3 (*upper right*), L3–4 (*lower left*), and L4–5 (*lower right*)

major, quadratus lumborum, iliacus, and lumbar intertransverse muscles [43]. Several articles have attempted to define a "safe zone" through the psoas muscle to the lateral disc space during the lateral transpsoas approach [44–48], and despite some methodological and interpretation differences between the studies, the studies consistently show that the anterior ¾ of the disc space at L1–2, L2–3, and L3–4 and the anterior half of the disc space at L4–5 on a lateral approach are, in general, free of motor nerves [41]. Additionally, several studies have shown that the majority of the space dorsal to the lateral midline of the disc (third quadrant dorsal from the ventral border) is reproducibly free of motor nerves at L4–5 [46, 48]. It is due to the risk of injury to these sensitive neural structures that the authors prefer to use a real-time neuromonitoring platform, which will be described in more detail within the surgical technique.

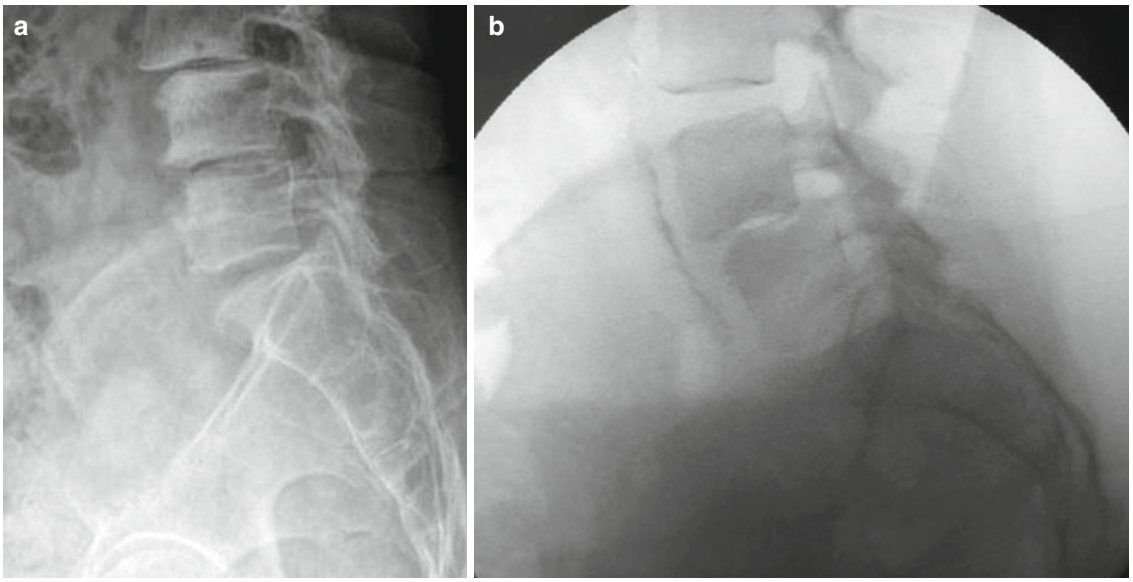

Fig. 18.5 Lateral radiography showing standard iliac crest position (**a**) and a high iliac crest (**b**) in patients with L4–5 disease (Images used with permission from William D. Smith, MD)

Preoperative Planning

Considerations in planning, as previously mentioned, must include a careful examination by the operating surgeon of the *expected* anatomy compared with the *individual* anatomy. If the patient is being treated at L4–5, lateral standing radiography should be used to evaluate the position of the iliac crest with respect to the lateral approach (Fig. 18.5). While a high crest does not necessarily contraindicate a lateral approach, care must be taken, when at the disc space, to work in a plane parallel to the endplates, which can be facilitated using specialized angled instrumentation. (On some occasions, a small lateral osteotomy of L4 may be necessary to remove osteophytes and facilitate access.) For all patients, axial MRI studies should be used to assess the anatomy at each level, including the position of the great vessels (as some, especially below the bifurcation, may migrate laterally) as well as the location and shape of the psoas muscle. In patients with lumbarized sacra (six lumbar vertebrae), the L5–6 segment often acts as a functional L4–5, though with the psoas shape and orientation more similar to L5–S1, being detached from the lateral border of the psoas and "tear-drop shaped" (Fig. 18.6). In these cases, it is likely that the lumbar plexus will have migrated anteriorly, as is common at the L5–S1 level, and the bifurcated great vessels will travel more posterolateral, toward the lateral disc space. Smith et al. in 2011 found a 2.8 % rate of lumbarized sacra in the authors' series of XLIFs at the functional L4–5 level (L5–6 in these rare patients) [41, 48]. Of those with transitional anatomy, 80 % were unapproachable at their L5–6 level based on the lack of approach corridor indicated by neuromonitoring feedback. The cases that were approachable were predictable by axial MRI, where the psoas muscle was "helmet shaped" and attached to the lateral disc space, resembling common L4–5 anatomy (Fig. 18.4). (In very rare cases where the iliac crest is quite low and the psoas is more dorsally located, L5–S1 can be approached. The authors maintain that such an approach should only be considered by experienced surgeons and that the operating physician should be prepared to abort the procedure if the working aperture is too small or too fraught with risk.)

Preoperative Treatment

As nerve and psoas muscle irritation is a potential side effect of the XLIF procedure, some surgeons choose to preoperatively administer Lyrica and/or gabapentin to prophylactically combat nerve irritation and/or 10 mg IV dexamethasone preoperatively to quell the inflammatory cascade in nervous or muscular tissue [49].

As intraoperative electromyography (EMG) is essential to this approach, anesthesia should be instructed to limit the use of muscle relaxants and, if required, to use those that are short acting, so as not to interfere with EMG results.

Considerations

Based on the authors' experience and consistent with other reports [23], there are five key steps to making the XLIF procedure efficient, safe, and reproducible [50]:

1. Careful patient positioning
2. Gentle retroperitoneal dissection

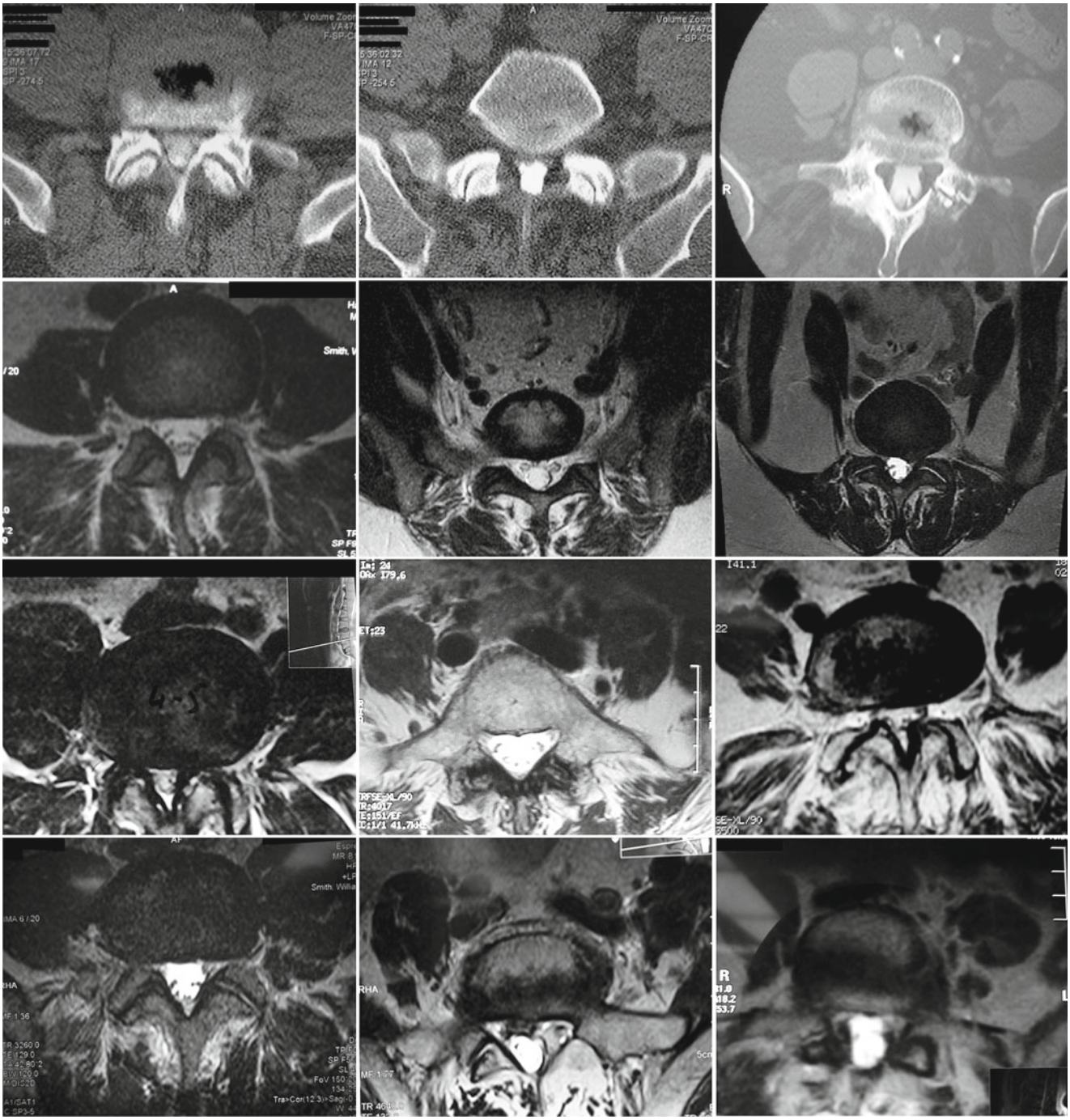

Fig. 18.6 Examples of magnetic resonance imaging and computed tomography showing psoas muscle orientation at normal L4–5 discs (*left*), normal L5–S1 discs (*center*), and at L5–6 (functional L4–5) discs (*right*). Note the helmeted, attached orientation of the psoas muscles at normal L4–5 levels, while the psoas muscle is laterally or anterolaterally detached with a tear-drop shape at L5–S1 and L5–6 levels (Images used with permission from William Smith, MD)

3. Meticulous psoas passage using an integrated neuromonitoring platform
4. Complete discectomy and fusion site preparation
5. Proper interbody implant sizing and placement

Operating Room Setup and Patient Positioning

The patient is placed on an unbroken, bendable, radiolucent surgical table in a true lateral decubitus position with the

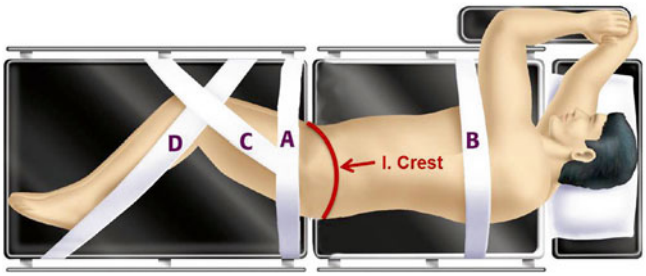

Fig. 18.7 Figure showing the patient in lateral decubitus position on a radiolucent table with the table break positioned at the greater trochanter with the iliac crest (i.e., *crest*, *red arrow*, and *line*) above the break. Tape is placed over the greater trochanter (*A*), over the thorax (*B*), from the greater trochanter to the knee (*C*), and from the table to the knee, past the ankle, then to the table (*D*) (Copyright NuVasive, Inc., used with permission)

knees slightly flexed (to relax the psoas muscle) with the greater trochanter at the table break. This will position the iliac crest above the table break. A true lateral decubitus position is essential to this procedure, as this position will allow for the abdominal contents to fall forward more easily during peritoneal release from the retroperitoneal space and lower the risk of injury to the peritoneum and its contents. This position also ensures, using intraoperative radiographic confirmation, that the surgical working plane is perpendicular to the sagittal plane of the disc space, which will encourage a safe trajectory away from sensitive contralateral anterior or posterior structures. Once in position, the patient is taped (Fig. 18.7) to hold the position when the table is broken and to ensure that the pelvis is tilted away from the spine allowing for access to the lower lumbar levels, especially L4–5, and that the ribs are extended away from the pelvis to allow for access at the upper lumbar levels (Fig. 18.8).

At this point, or at any point prior to the initial incision, the authors recommend performing an EMG twitch test to confirm muscle function and the absence of muscle relaxants. (The twitch test involves four sequential stimulations and readings, with the latter three responses reported as a percent response compared to the initial response. Accurately quantifiable EMG responses during the procedure require the fourth response in the twitch test to be 75 % or more of the initial response, confirming that muscle relaxants are not blocking EMG responses (Fig. 18.9).)

The operating room is set up to allow for the surgeon, anesthetist, and technicians to work in ideal positions with the C-arm placed across from the surgeon, straddling the table, with the neuromonitoring and fluoroscopy monitors placed on either side of the C-arm to allow for easy viewing of both by the surgeon (Fig. 18.10).

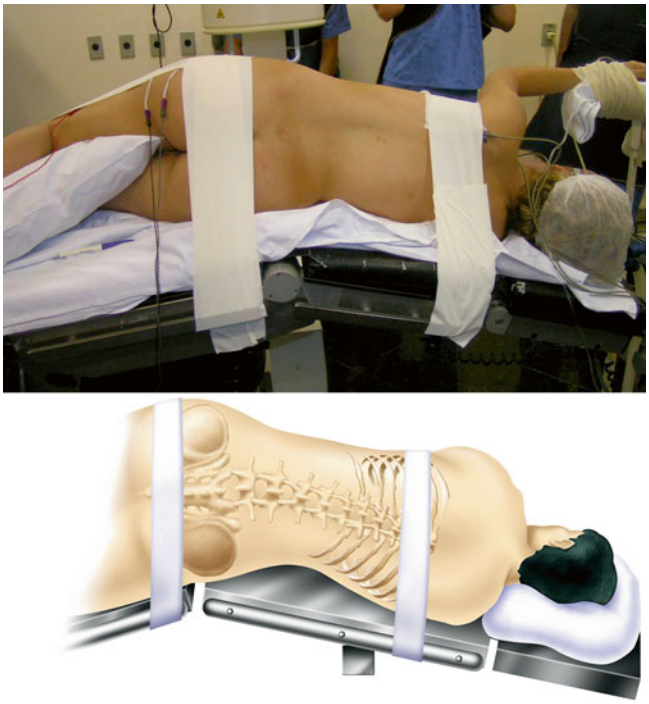

Fig. 18.8 Photograph (*top*) and illustration (*bottom*) of the table position and table break in the extreme lateral interbody fusion procedure (Copyright NuVasive, Inc., used with permission)

Fig. 18.9 NV JJB/M5 (NuVasive, Inc.) monitoring showing twitch test results. In order to confirm that muscle relaxants are not affecting muscle function, twitch tests 2–4 should be within 75 % of the baseline reading (1). In this case, the twitch test would have failed indicating that muscle relaxants were dampening muscle function (Copyright NuVasive, Inc., used with permission)

A true anteroposterior (AP) and lateral orientation should be determined at each level using fluoroscopy with the C-arm in a cross-table position (0°). This is achieved by first matching the position of the C-arm with the lordotic angle of the level

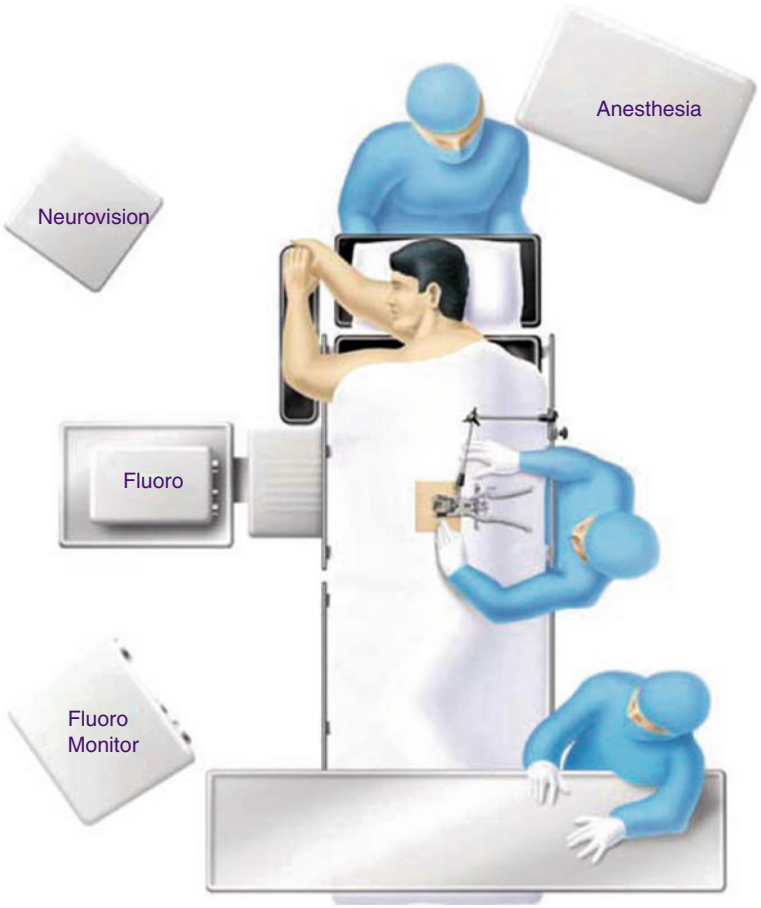

Fig. 18.10 Figure showing the configuration of the operating room for the extreme lateral interbody fusion procedure (Copyright NuVasive, Inc., used with permission)

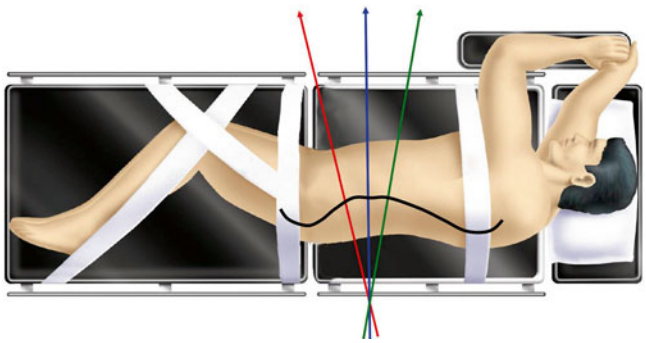

Fig. 18.11 *Arrows* indicate potential C-arm orientations to provide a true anteroposterior (AP) view on fluoroscopy (Copyright NuVasive, Inc., used with permission)

being treated to assist in providing a true AP orientation (Fig. 18.11). The table should be adjusted using the left/right tilt function rather than by adjusting the C-arm to get the proper view. Maintaining the C-arm in a cross-table configuration while adjusting the position of the patient will ensure that once a true AP and lateral position have been obtained, the correct working corridor orthogonal to the sagittal plane of the disc space will also be perpendicular to the floor. A true AP image will be obtained when the spinous processes are in the midline and the pedicles are symmetrical (Fig. 18.12a). To obtain a true lateral image, the C-arm can be rotated to be perpendicular to the floor (90°) adjusting the table in a horizontal plane. A true lateral image will be obtained when the pedicles at the level to be treated are superimposed on one another, the endplates are linear, and the posterior cortex is linear (Fig. 18.12b). Reestablishment of AP and lateral position should be obtained at each level treated. This is especially important in deformity cases where irregular or rotational anatomy may change substantially from level to level. It is imperative that the orientation of the patient change is necessary, not the orientation of the fluoroscope, allowing the surgeon to work in consistently orthogonal orientation and in line with gravity.

Anatomic and Level Identification

After standard aseptic surgical site preparation, the index level is identified on lateral fluoroscopy by crossing K-wires

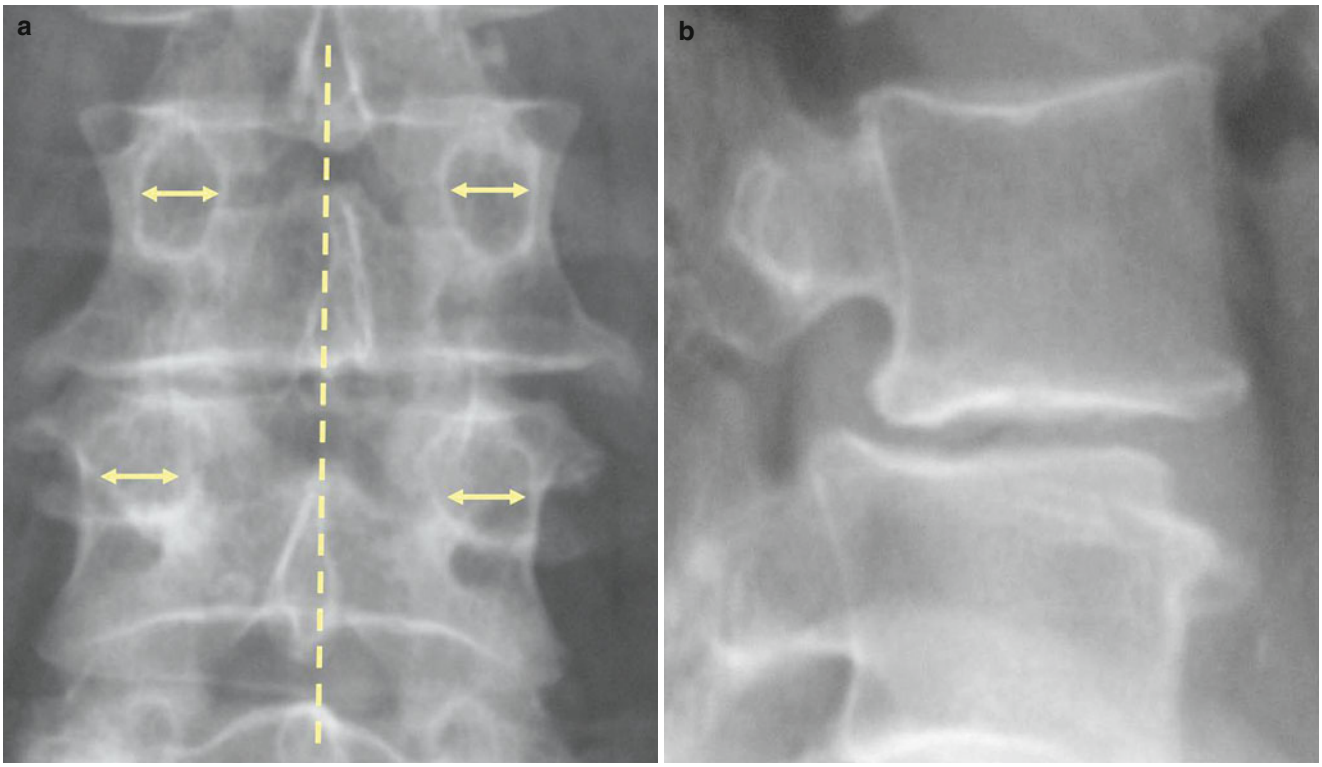

Fig. 18.12 Anteroposterior (AP) fluoroscopy (**a**) showing true AP orientation with midline spinous processes (*dotted line*) and symmetrical pedicles (*arrows*) and lateral fluoroscopy (**b**) showing true lateral orientations with parallel endplates, superimposed pedicles, and a linear posterior cortex

over the pathologic disc space, targeting the junction of the K-wires just posterior to the lateral midpoint (Fig. 18.13). Skin markings are used at the intersection of the K-wires to guide the location of the lateral incision. If a second incision were being made to access the retroperitoneal space and guide the initial approach instrumentation, it would be posterior to the lateral incision, at the lateral border of the erector spinae muscles (Fig. 18.14).

Retroperitoneal Access

Using the two-incision approach, the posterolateral skin incision is made, and then blunt scissor and finger dissection is used to carefully spread the fibers of the abdominal wall muscles. Use caution with the approach following the skin incision, especially when using electrocautery (use bipolar, if at all), to avoid injury to the subcostal nerve which innervates the abdominal wall muscles. Injury to the subcostal can may result in abdominal wall paresis postoperatively and present as a pseudohernia [51]. Careful finger advancement through the fibers of the abdominal wall muscles is generally met by a loss of resistance, indicating access into the retroperitoneal space (Fig. 18.15a, b). Once the retroperitoneal space has been accessed, a gentle sweeping motion should be used to more completely release the peritoneum, allowing the contents of the abdominal cavity to fall forward. This anterior migration of the peritoneum decreases the likelihood of a peritoneal encounter when delivering the dilators and access driver through the lateral incision. Once the peritoneum has been adequately mobilized anteriorly, palpation of the psoas muscle or the anterior tip of the transverse process should be performed for landmark identification for the approach (Fig. 18.15c).

Next, the finger within the posterolateral incision is swept superficial through the retroperitoneal space to underneath the lateral incision skin marking (Fig. 18.16a). This allows for passage from the lateral incision into the retroperitoneal space, avoiding the peritoneum. The lateral incision and blunt access through the muscles of the abdominal wall are made with similar care as the posterolateral incision (Fig. 18.16b). At this point it is often possible to palpate the sensory nerves (ilioinguinal, iliohypogastric). Once lateral exposure has been gained, the dilator is met by the finger through the posterolateral incision to be guided safely to the lateral border of the psoas muscle (Fig. 18.16c, d).

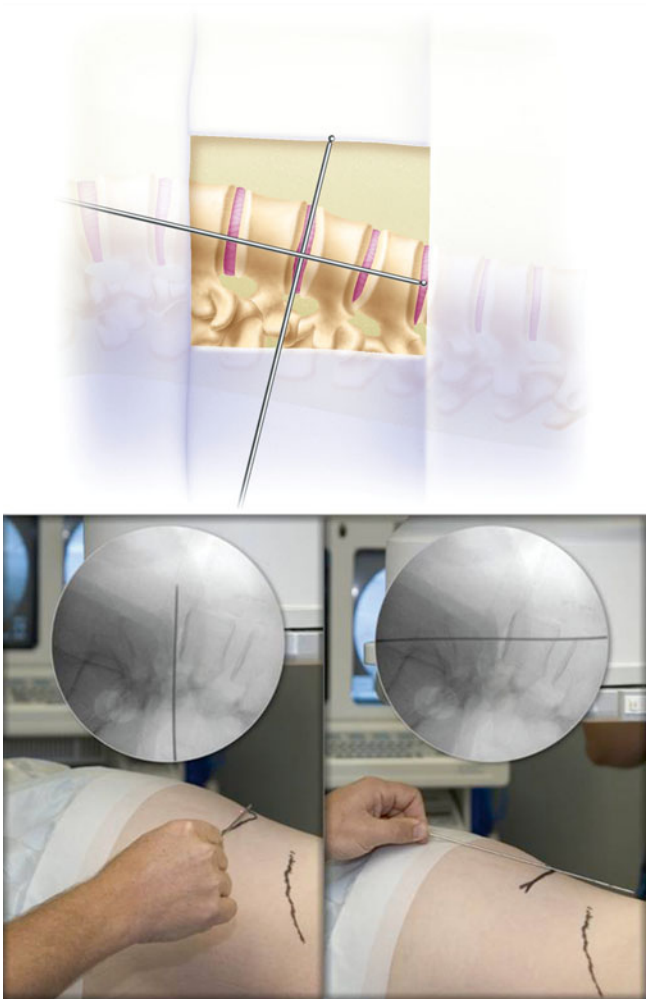

Fig. 18.13 Lateral illustration (*top*) and photograph and fluoroscopy (*bottom*) showing K-wire placement for level identification and localization for the extreme lateral interbody fusion procedure (Copyright NuVasive, Inc., used with permission)

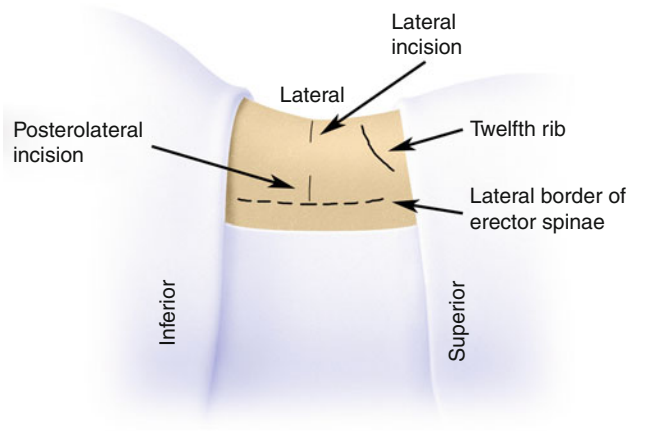

Fig. 18.14 Illustration showing the lateral and posterolateral incisions as well as the twelfth rib and lateral border of the erector spinae muscle (Copyright NuVasive, Inc., used with permission)

Transpsoas Approach

After the finger has guided the initial dilator to the surface of the psoas muscle, location should be verified using lateral fluoroscopy. The position of the initial dilator should generally be approximately between the center line and the anterior margin of the posterior third of the disc space (Fig. 18.17a, b). Once the dilator has been positioned, a second twitch test can be performed, with local stimulation at the site, to confirm muscle responsiveness to EMG stimulation during the approach (Fig. 18.9). Assuming muscle function is intact, as confirmed by the twitch test, prior to the insertion of the dilator into the psoas muscle, neuromonitoring should be established through the dilator. On the distal, leading end of the dilator is an EMG-stimulating surface, occupying a small triangular area, which allows for localized and directional stimulation. On the proximal end of the dilator is a surface for the EMG-stimulating clip to be placed and to transmit EMG signal to the distal end of the dilator, as well as an indicator of the direction of the stimulation (Fig. 18.18). Prior to dilation through the psoas muscle, activate stimulated EMG through the dilator and maintain stimulation throughout psoas dilation. To begin, use blunt dissection with the dilator through the fibers of the psoas muscle, slowly advancing the dilator toward the lateral disc and rotating throughout, paying attention to EMG responses and where the response was generated (direction) relative to the dilator. In addition to the directional stimulation of the EMG using the dilator, the authors' preferred method provides discrete-threshold responses, which indicate relative proximity to the dilator. The lower the threshold (in milliamps) required to evoke a response, the closer in proximity the motor nerve is to the stimulating field. Feedback is provided both visually and audibly, with thresholds below 5 mA indicating direct nerve contact [52], those between 5 and 10 mA reporting close proximity, and responses greater than 10 mA indicating a workable distance away from motor nerves (Fig. 18.19) [28, 43]. These features allow for proper placement of the approach instrumentation and retractor anterior to the lumbar plexus, where posteriorly oriented stimulation results in relatively low response thresholds and results of stimulation anteriorly result in high response thresholds (generally >20 mA). Since retraction will primarily be performed anteriorly and in cephalocaudal orientations, absence of nerves anteriorly and presence of nerves posteriorly are ideal for a safe exposure. During dilation, if response thresholds are found to be decreasing, indicating proximity to nerves, care should be taken to rotate the dilator

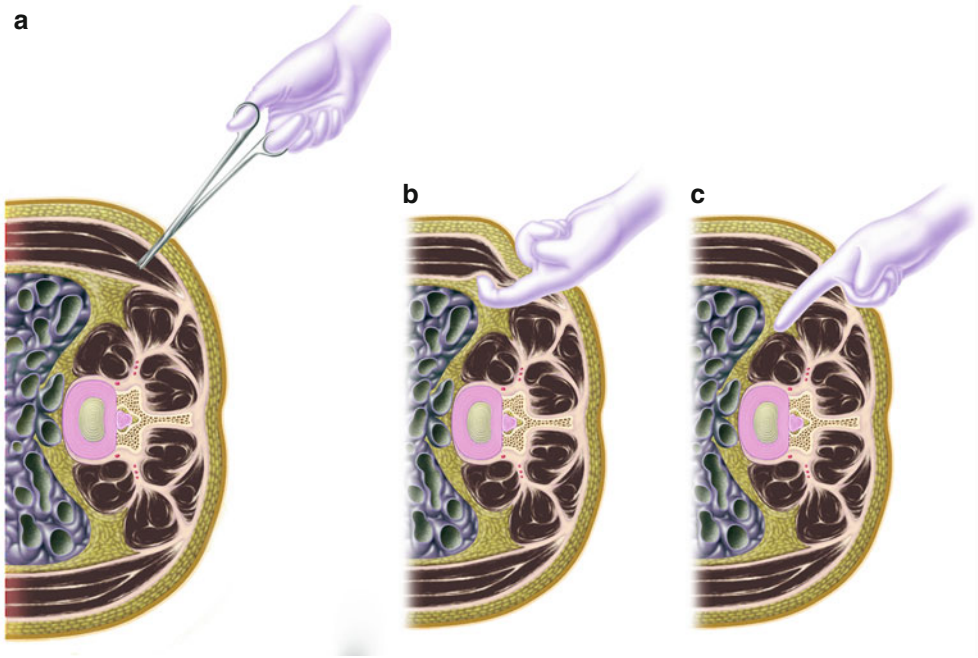

Fig. 18.15 Illustration showing initial blunt scissor dissection through the fibers of the abdominal wall muscles (**a**), access into retroperitoneal space (**b**), and palpation of the transverse process and lateral border of the psoas muscle (**c**), for orientation in the extreme lateral interbody fusion approach (Copyright NuVasive, Inc., used with permission)

360° to confirm the position of the nerve and monitor response thresholds to gain information on its relative distance. In the case where the initial approach trajectory is not supported by neuromonitoring feedback, the dilator(s) should be completely removed from the psoas muscle and the previous steps should be followed from a more anterior docking position.

Once the initial dilator is safely docked on the lateral disc space, lateral fluoroscopy is used to both determine its position on the lateral disc space and to confirm its trajectory. Any adjustments to the dilator position should be made under stimulated EMG conditions. (It should be noted that low "red" readings do not preclude safe surgery so long as they are located dorsal to the retractor.) Cross-table AP fluoroscopy should then be used to confirm that the dilator is in position and flush with the disc. Once the position and trajectory has been confirmed, a K-wire is introduced approximately midway into the disc to secure the position of the access instrumentation, with the dilator depth shown on the proximal surface (Fig. 18.20). Sequential dilation with EMG continues with two more dilators, followed by placement of the access driver (or retractor) over the third dilator. As with the previous dilators, the access driver is integrated with EMG stimulating capabilities and can stimulate posteriorly during its insertion (Fig. 18.21a, b). Fluoroscopic confirmation of the access driver should then be performed to confirm proper position and orientation (Fig. 18.22). Next, the retractor is stabilized using an articulating arm attached to the bed rail (Fig. 18.23a). The left and right blades of the access drivers accept two ends of a bifurcated light cable for direct, illuminated visualization of the lateral disc space. An EMG-stimulating ball-tipped probe should be used to confirm the absence of nerves within the field of the exposure, confirming nerve location posterior to the access driver blades. Once confirmed that nerves of the motor plexus are not within the exposure field and any other soft tissue has been moved out of the field, an intradiscal shim can be placed down the posterior blade to secure the retractor in the operative field and prevent retractor migration as well as posterior tissue creep (Fig. 18.24). The blades of the access driver can be opened independently in cephalocaudal and ventrodorsal orientations to allow for customized exposure based on individual anatomy and pathology (Figs. 18.23b, c and 18.25). Opening of the retractor blades should be performed slowly (and only as much as is necessary for exposure) to allow for relaxing of the surrounding psoas muscle and soft tissue to minimize trauma.

Disc Space Preparation

Disc preparation is performed in a conventional manner using standard instradiscal instruments. Disc preparation begins with an annulotomy sufficient in size to allow for placement of the intervertebral cage. The annulotomy should be performed by first making two cephalocaudal incisions on the dorsal and ventral margins of the annulotomy site. It is the authors' practice to make ventrodorsal annulotomy incisions so that the posterior border of the exposure is protected by the posterior blade shim of the access driver inserted into the disc. Dorsal to ventral annulotomy incisions

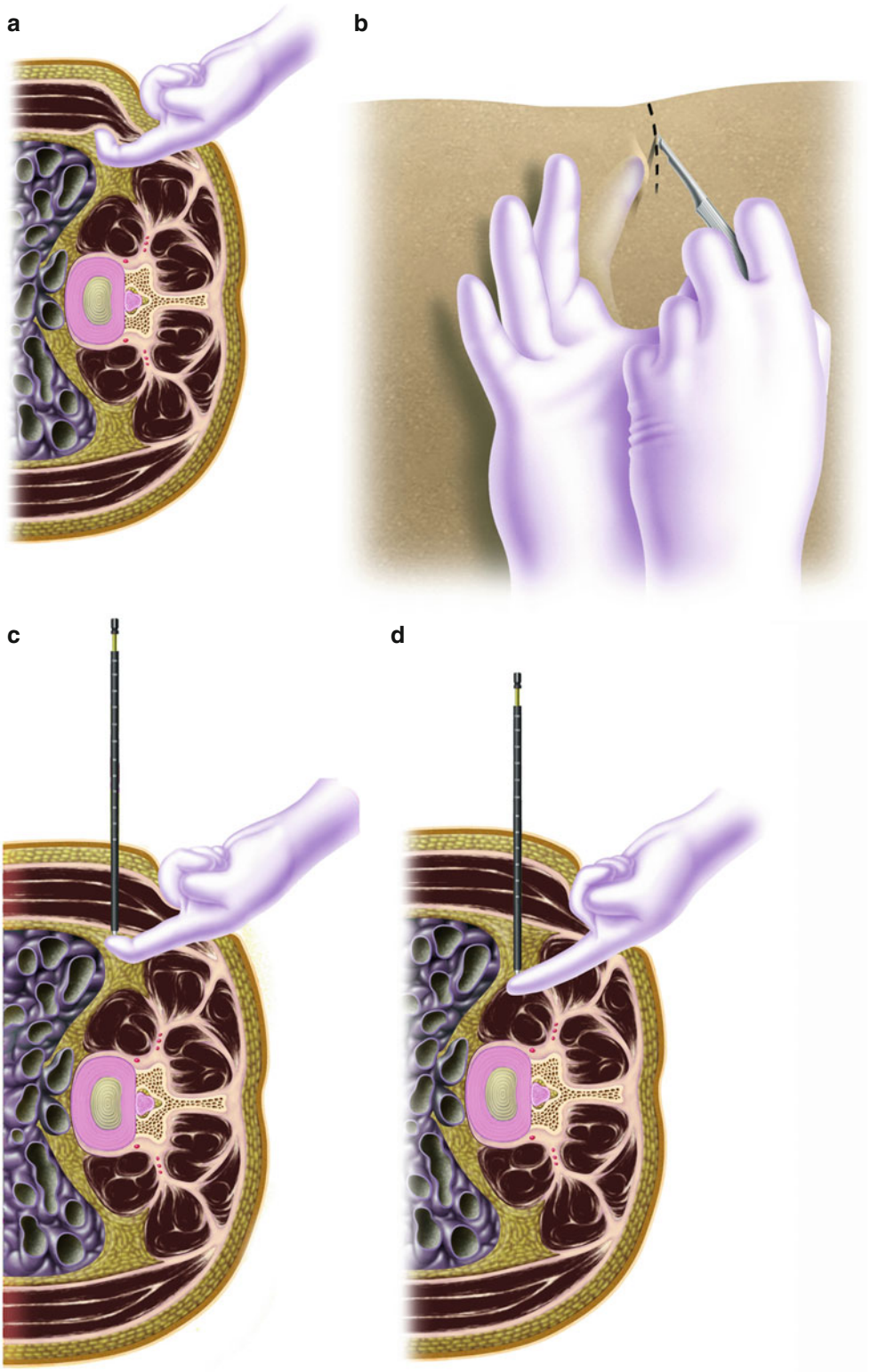

Fig. 18.16 Guided by a finger within the retroperitoneal space through a posterolateral incision, (**a**) the lateral incision is made (**b**) and initial dilators are safely guided through the retroperitoneal space (**c**) to the lateral surface of the psoas muscle (**d**) (Copyright NuVasive, Inc., used with permission)

may risk injury to ventral structures (vasculature). Once the ipsilateral annulotomy has been performed, disc space preparation can begin using a variety of instrumentation (Fig. 18.26a). The contralateral annulus should be adequately released to ensure parallel distraction of the disc space as well as symmetrical disc space preparation and the bilateral placement of the intervertebral implant on both lateral borders of the apophyseal ring (Fig. 18.26b).The disc space

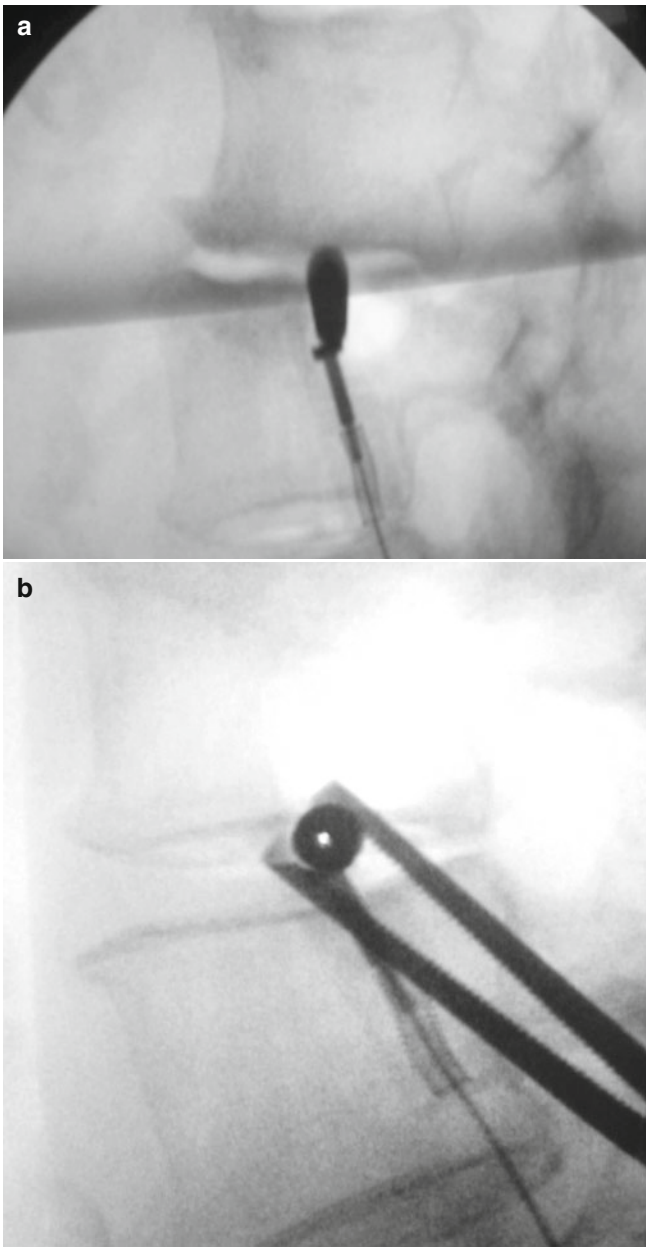

Fig. 18.17 Lateral intraoperative fluoroscopy showing approximate initial dilator approach position on the lateral disc space (**a**, **b**)

Fig. 18.18 Initial NV JJB®/M5® dilator with electromyography (*EMG*) stimulating field on the distal end and EMG clip site and directional stimulation marker on the proximal end (Copyright NuVasive, Inc., used with permission)

should be adequately evacuated of disc material and the endplates should be prepared in as careful a manner as possible, to avoid violation and increasing the risk of intervertebral implant subsidence. Violation of the endplate may be decreased by confirming a parallel working orientation to the endplates and perpendicular to the sagittal plane of the level and the floor. This helps decrease the likelihood of unintended endplate violation as well as anterior or posterior migration of instrumentation on the contralateral side [53]. It is the authors' preference to open the endplates in the center of the implant windows to facilitate fusion. In addition, if possible, the authors open the endplate in front of the cage and remove some cancellous bone to augment grafting and enhance fusion formation (sometimes producing at radiographic "sentinel sign"). In the authors' opinion, the endplate can be adequately prepared using only ring currettes with an extremely gentle technique—although rasps and currettes may be needed. Box cutters should be used only when there is assurance of the integrity and protection of the ALL to avoid any risk of unintentional ALL rupture or vascular injury.

Implantation

In implant sizing, considerations should be made as to the configuration of the implant used, to best correct defects in the local anatomy as well as to maximize contact with the apophyseal ring on the lateral borders to decrease the risk of subsidence (Fig. 18.3). Additionally, implant height should be determined to best restore the disc space to anatomic, not

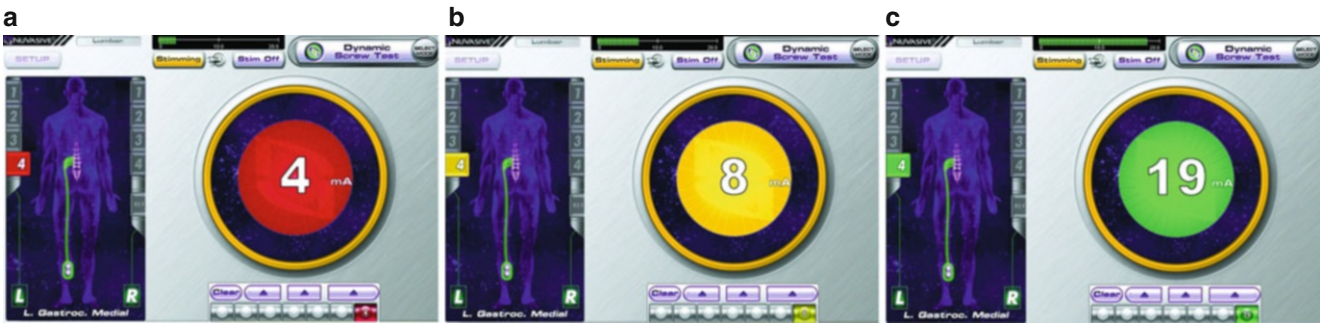

Fig. 18.19 Examples of discrete-threshold responses using NV JJB®/M5® with direct contact (**a**), close proximity (**b**), and more distant proximity to motor nerves (**c**) shown by the electromyographic threshold required to evoke a muscle response (Copyright NuVasive, Inc., used with permission)

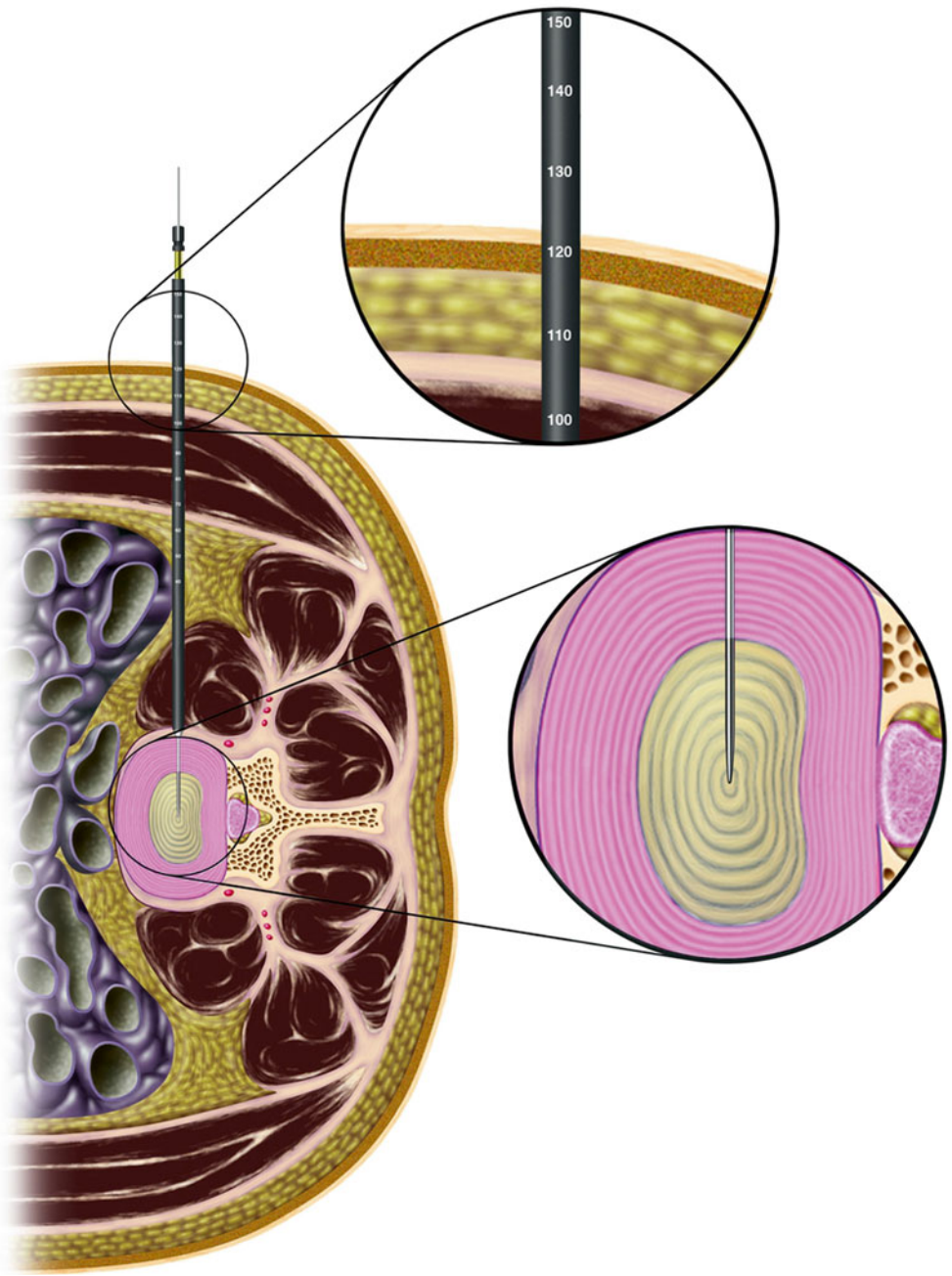

Fig. 18.20 Axial illustration showing K-wire placement into the disc space after the initial dilator has safely traversed the psoas muscle to the lateral disc space. Depth markings on the proximal end of the dilator indicate depth to the lateral disc space, allowing for proper sizing of the blades for the access driver (Copyright NuVasive, Inc., used with permission)

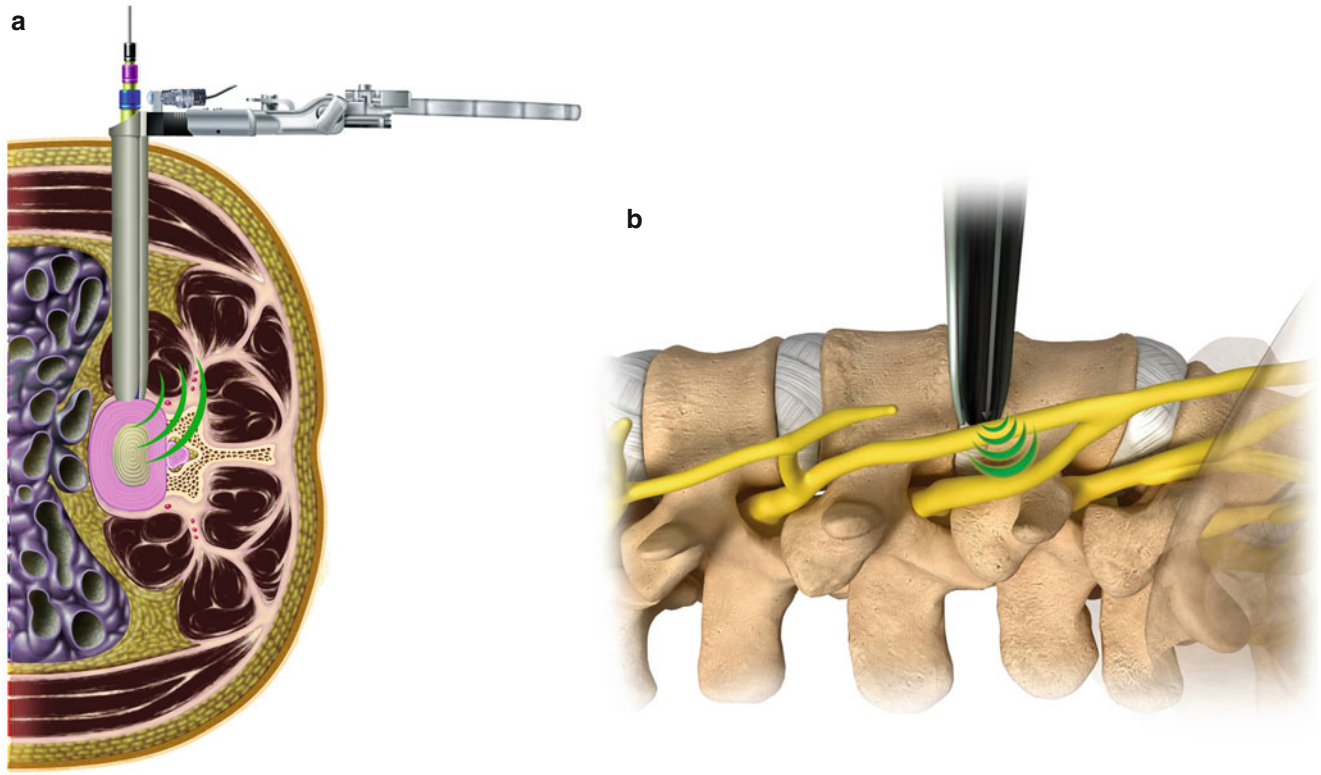

Fig. 18.21 Axial (**a**) and lateral (**b**) illustration showing electromyography stimulation through the access driver blades using stimulating electrodes integrated into the retractor system, allowing for continued monitoring of the lumbar plexus during the procedure (Copyright NuVasive, Inc., used with permission)

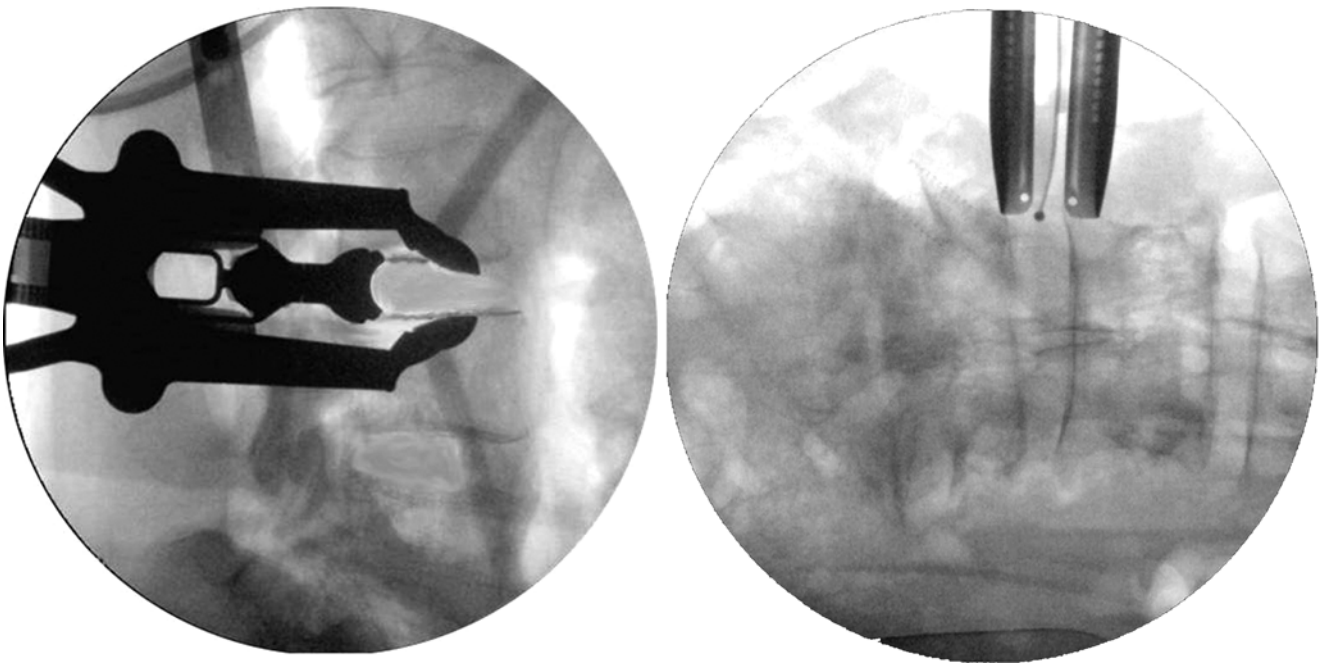

Fig. 18.22 Lateral and anterior fluoroscopy showing the access driver and blades docked on the lateral disc space

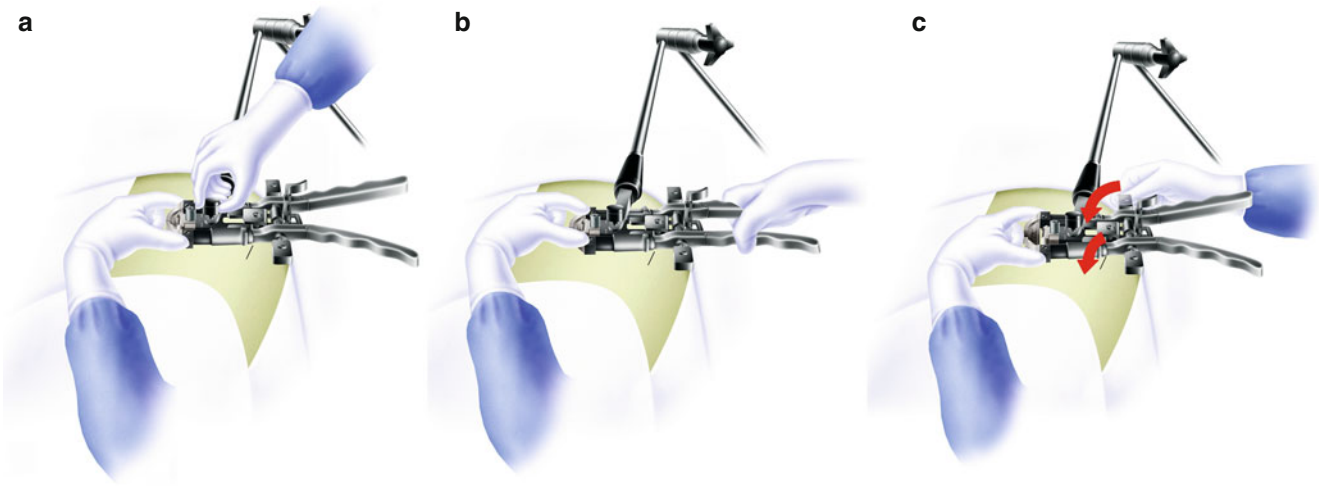

Fig. 18.23 Illustrations showing the retractor being secured to the articulating arm (**a**) and being opened independently in cephalocaudal (**b**) and ventrodorsal orientations (**c**) (Copyright NuVasive, Inc., used with permission)

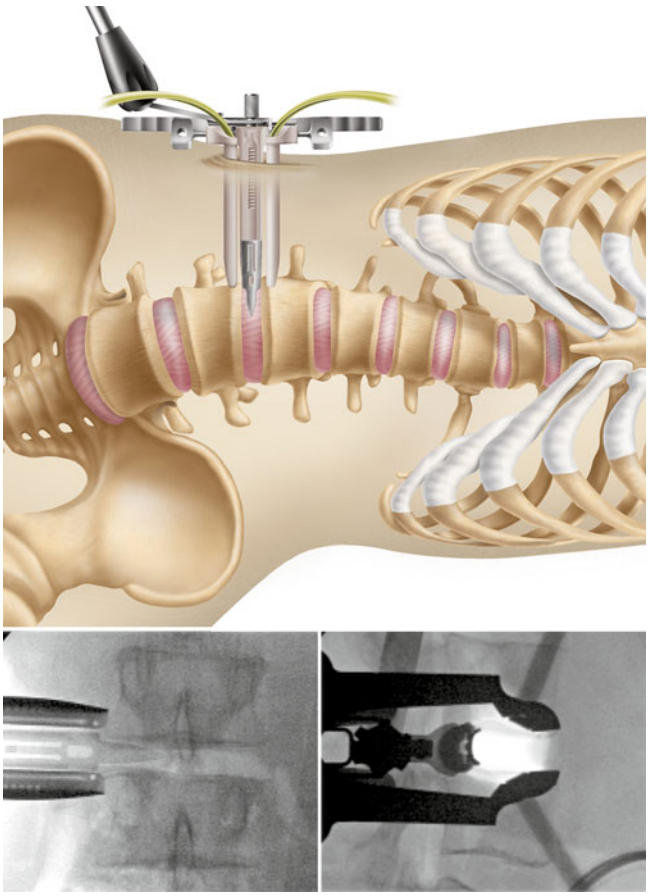

Fig. 18.24 Illustration (*top*) and anteroposterior (*bottom left*) (AP) and lateral (*bottom right*) fluoroscopy showing intradiscal shim placement, securing the posterior blade of the access driver to the disc space (Copyright NuVasive, Inc., used with permission)

superphysiological, levels. Over-tall implants may potentially strain the endplates and the ALL and PLL. The implant should be gently impacted (using the surgeon's hand or a mallet as necessary), and free-run EMG should be used to monitor nerve activity throughout. Proper anteroposterior positioning should be verified on lateral fluoroscopy and confirmation of positioning across the lateral borders, using AP fluoroscopy. Proper implant placement is individual and variable, depending on local anatomy and the goals of the procedure, though generally centered in the disc space from a medial/lateral perspective and approximately occupying the middle half in the anterior/posterior perspective (Fig. 18.27). Any implant position contained between the ALL and PLL ventrodorsally is acceptable, however. In the early literature, anterior cage placement was specified. Over time, with careful attention to the neuromonitor, more posterior cage placement has become routine, even preferred.

Anterolateral Plating

From the lateral approach, it is possible to place anterolateral plating for supplemental internal fixation, which results in a single-incision approach for discectomy, fusion, and fixation (Fig. 18.28).

Closure

Once the procedure is complete, the access driver should be removed slowly, examining the disc space and psoas

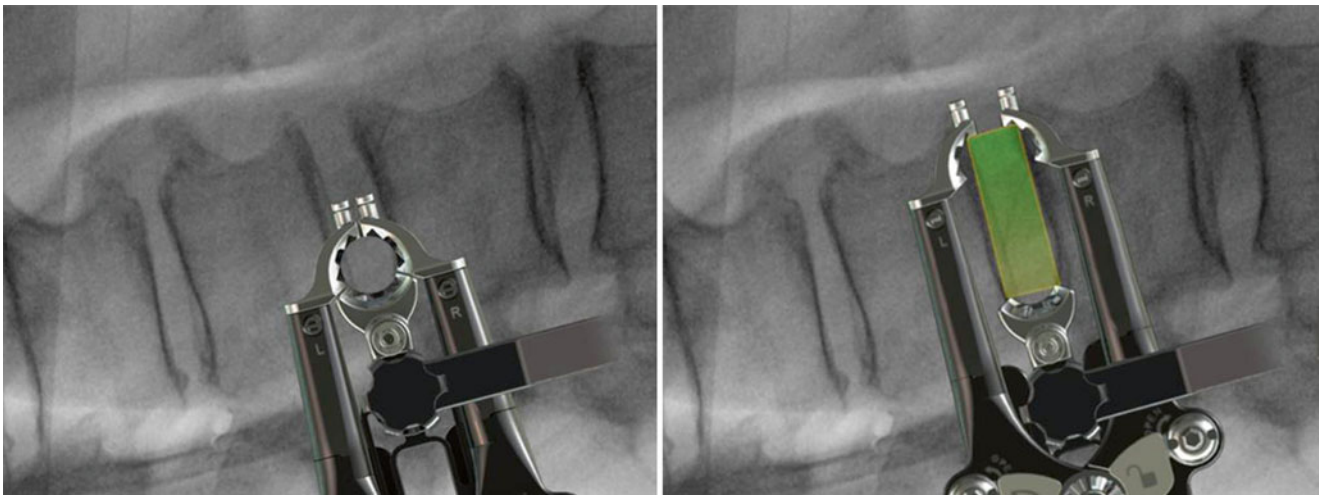

Fig. 18.25 Lateral fluoroscopy and superimposed illustration showing isolated ventrodorsal retraction. Independent retraction planes allow for customizable exposures to limit retraction in unnecessary orientations (Copyright NuVasive, Inc., used with permission)

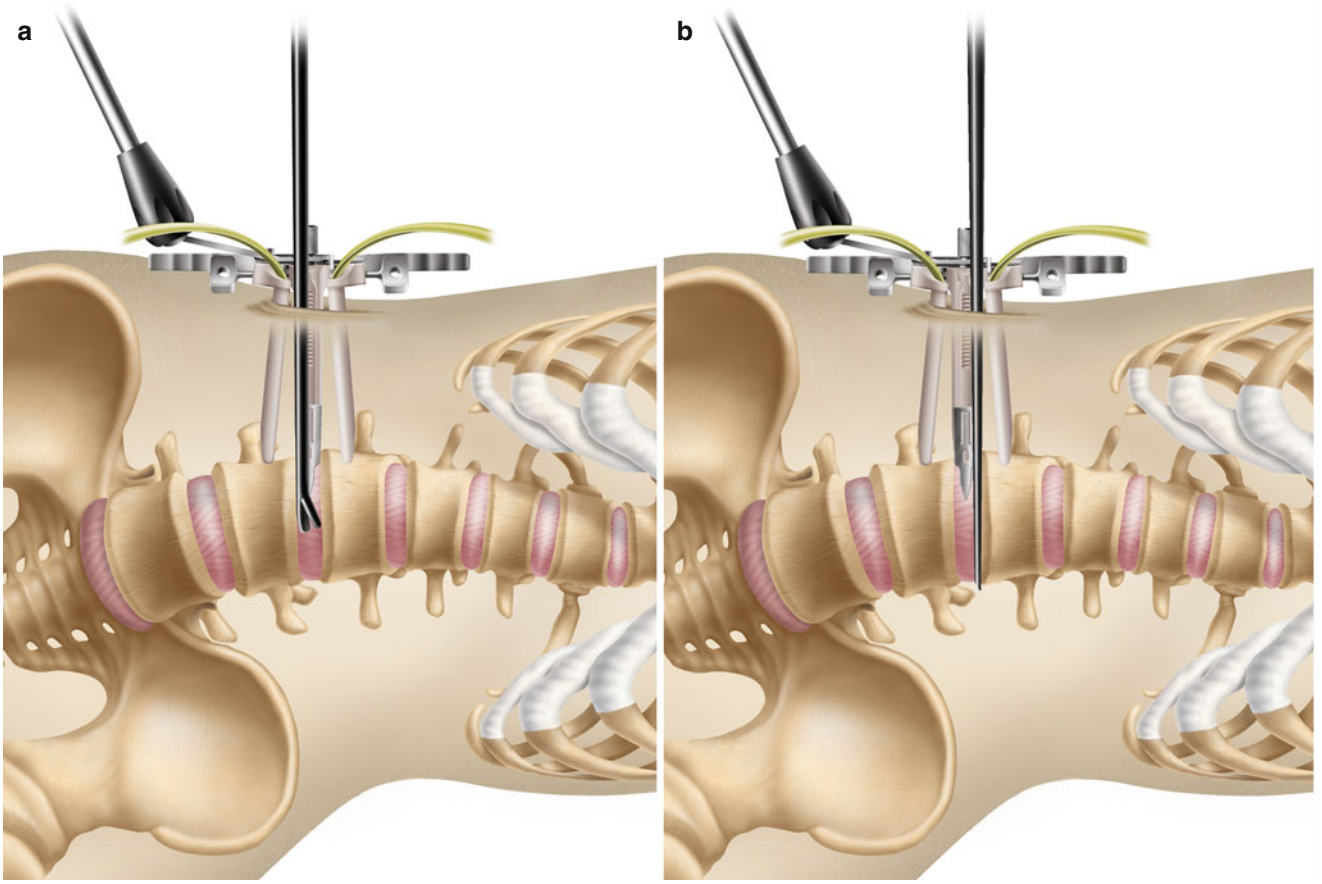

Fig. 18.26 Illustrations showing disc removal and preparation (**a**) and release of the contralateral annulus using a cobb elevator (**b**) (Copyright NuVasive, Inc., used with permission)

muscle for evidence of bleeding which may lead to hematomas. Topical analgesics and/or methylprednisolone may be administered topically onto the psoas muscle and surgical field to lessen any nerve or muscle irritation that may have occurred during surgery. The muscles of the abdominal walls are sutured to prevent incisional hernias, and the skin is closed using standard subcuticular suture.

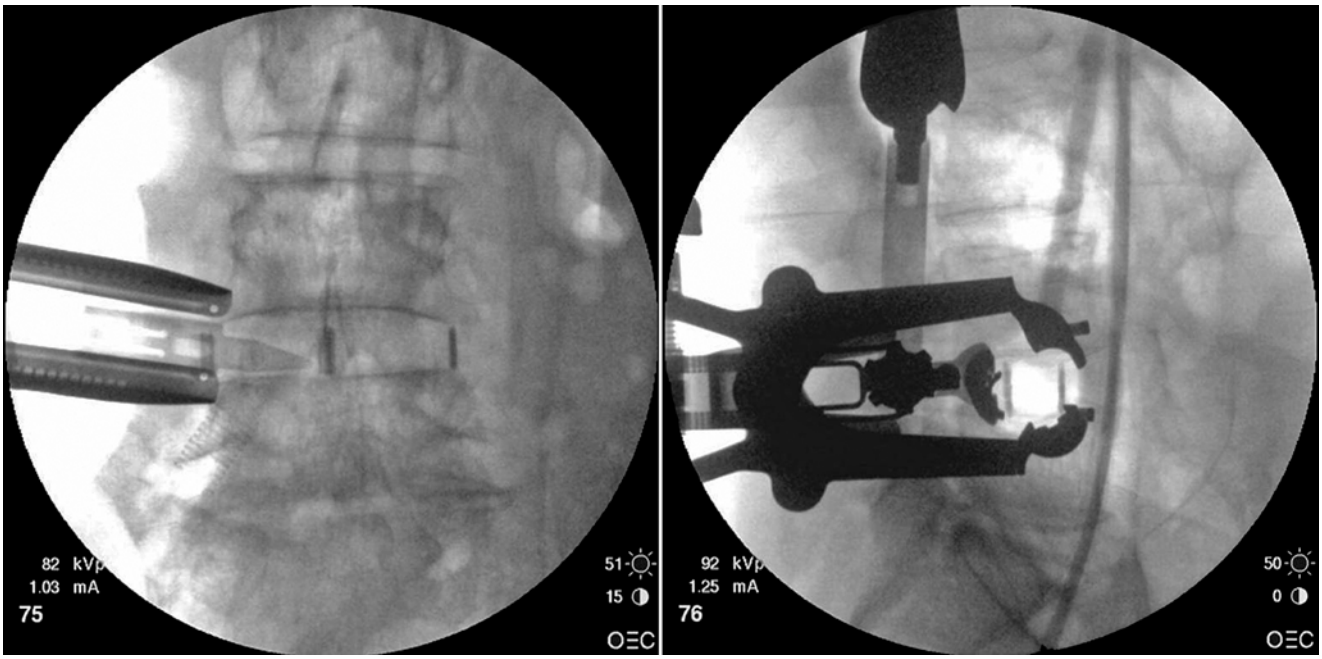

Fig. 18.27 Anteroposterior (AP) (*left*) and lateral (*right*) fluoroscopy showing CoRoent XL cage placement in the extreme lateral interbody fusion (XLIF) procedure

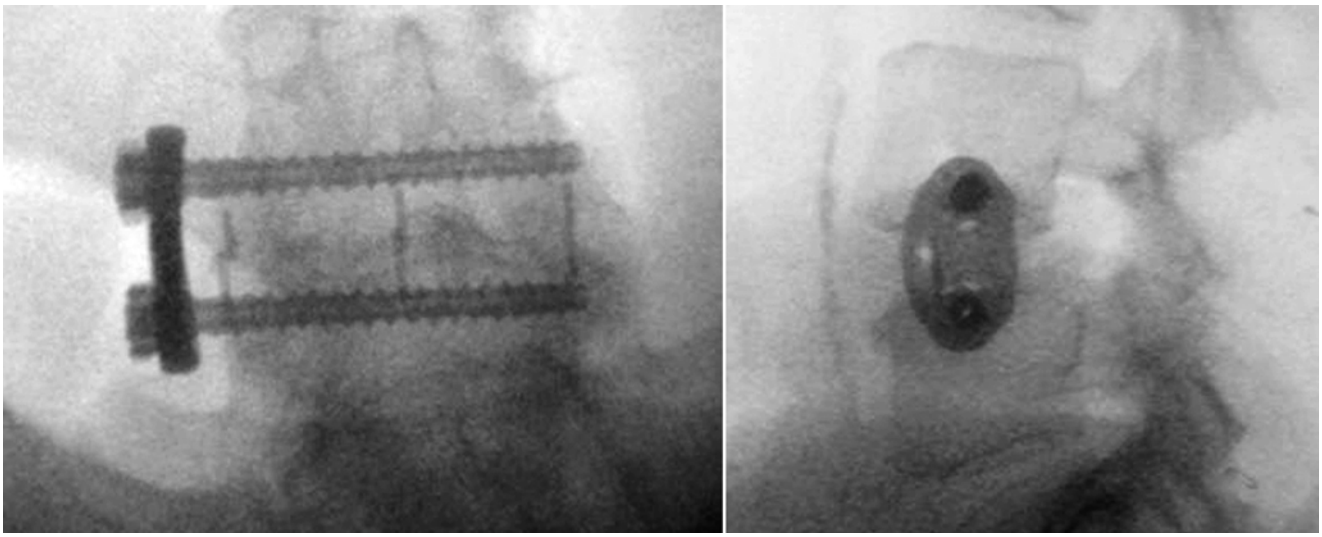

Fig. 18.28 Anteroposterior (AP) (*left*) and lateral (*right*) fluoroscopy showing anterolateral plating extreme lateral interbody fusion procedure, utilizing a single-incision approach for anterior lumbar interbody fusion and supplemental internal fixation

Supplemental Internal Fixation

Several supplemental internal fixation modalities can be placed from the lateral decubitus position, without repositioning. This includes anterolateral plating (as previously mentioned), unilateral pedicle screws and rod fixation (ipsilateral to the approach), uni- or bilateral facet screw fixation, and interspinous fixation. In the authors' experience, bilateral pedicle screws can be placed with the patient in the lateral position at one or two levels, but, in general, repositioning must occur if more than one level is to be thus fixated.

Postoperative Management

Early postoperative mobilization is a perceived benefit of most minimally invasive spinal procedures and should be encouraged as soon as is reasonable for each patient. Postoperative pain should be managed following standard

guidelines [49]. Side effects of the approach may include mild hip flexion (iliopsoas) weakness on the side ipsilateral to the approach and sensory changes in the anterior thigh/groin region. Hip flexion weakness is caused by passage through and irritation to the psoas muscle and generally resolves without intervention in the normal duration of muscle healing, typically within several weeks. Sensory disturbances are likely due to irritation to sensory nerves, namely, the genitofemoral nerve. Similarly, these tend to resolve during the postoperative period through normal recovery mechanisms [28, 54].

Surgical Considerations and Complication Avoidance Techniques

The unfortunate reality is that despite best efforts, complications will occur at some points over the course of one's experience, regardless of the approach or procedure used [55]. Based on the cumulative experience of many surgeons using lateral access approaches, several techniques and considerations have been either emphasized or developed to mitigate certain risks or pitfalls to the procedure. What follows are some of these considerations and complication avoidance techniques most commonly employed.

Positioning

The amount of table break used should be dependent upon the patient's individual anatomy. However, experience suggests that the extent of table break required to expose the surgical site adequately and perform the procedure is often overestimated, and therefore the least amount of table break necessary should be used. This will decrease tension on the soft-tissue structures (musculature, nerves) relevant to the approach.

The Lateral Retroperitoneal Exposure

Injury to the subcostal nerves during the initial abdominal wall exposure can occur and result in denervation of the abdominal wall muscles. Electrocautery should be used sparingly and the bipolar setting is preferred to avoid thermal injuries to the nerves.

The two-incision approach may be preferable during early adoption of the technique or due to surgeon preference. When using the single-incision approach, you must confirm by feel that the retroperitoneum has been accessed and that the peritoneum has mobilized anteriorly prior to insertion of the initial dilator. When confirmed in the retroperitoneal space, care should also be taken to avoid injury to the iliohypogastric and ilioinguinal nerves. These structures, if present, can be palpated, generally as cord-like structures, and once identified they should be protected and avoided during instrumentation. The kidney and ureter may also be palpated during the retroperitoneal exploration (the ureter tends to be larger than the superficial sensory nerves) and should be similarly protected and avoided.

Transpsoas Approach

Directionally stimulated neuromonitoring (with discrete-threshold responses) is designed to provide information on the location of nerves relative to the approach or procedural instrumentation. During the initial dilation this should be used to map the space for motor nerves, rather than to simply avoid high threshold readings, indicating increased distance from nerves. Instead, having lower threshold readings while carefully traversing the psoas gives geographic information, and with retraction gently applied in anterior and cephalocaudal orientations following initial docking, confirmation of the posterior position of the nerves allows a safe anterior working space along the posterior part of the lateral annulus (Fig. 18.25). So long as the retractor is not subsequently moved more posterior, this limits the potential for compressive or ischemic injury to the nerves. Any motor nerve ventral to the dilator and instrumentation should, in general, be managed by completely removing the dilator from the psoas muscle and redirecting the approach. During the dilation, real-time neuromonitoring should be used and adhered throughout to identify and avoid any potential nerve injuries.

High Iliac Crest at L4–5

With a high iliac crest, it may not be possible to approach the lateral disc space with a trajectory orthogonal to the sagittal plane of the disc space, therefore making a thorough disc space preparation and implantation difficult without excessively violating the inferior endplate (Fig. 18.29). Approach trajectory can be roughly determined using standing lateral and anterior plain films to determine crest position relative to the L4–5 lateral disc space (Fig. 18.5). In general, women tend to have an anterior superior iliac spine (ASIS) that falls off diagonally, making high-crest issues less prevalent in women than men, whose posterior superior iliac spine (PSIS) and ASIS tend to be plateau shaped. In the case of L4–5 disease and a high iliac crest, specialized angled instrumentation has been developed to release the contralateral annulus, adequately prepare the disc space, trial implant sizes, and deliver implants without violation of the endplates (Figs. 18.30, 18.31, and 18.32).

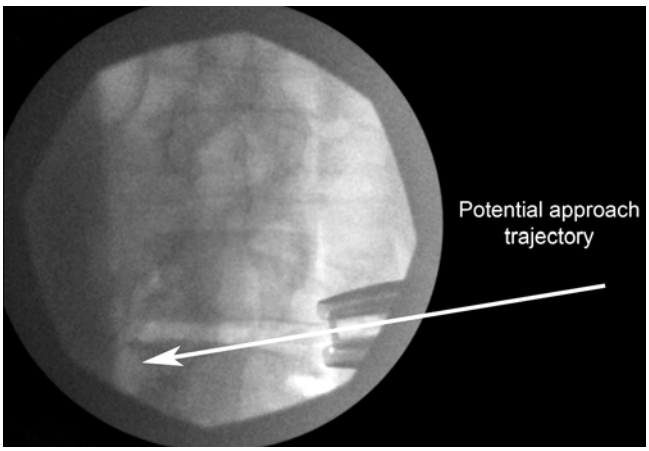

Fig. 18.29 Anteroposterior fluoroscopy showing L4–5 approach trajectory in a patient with a high iliac crest

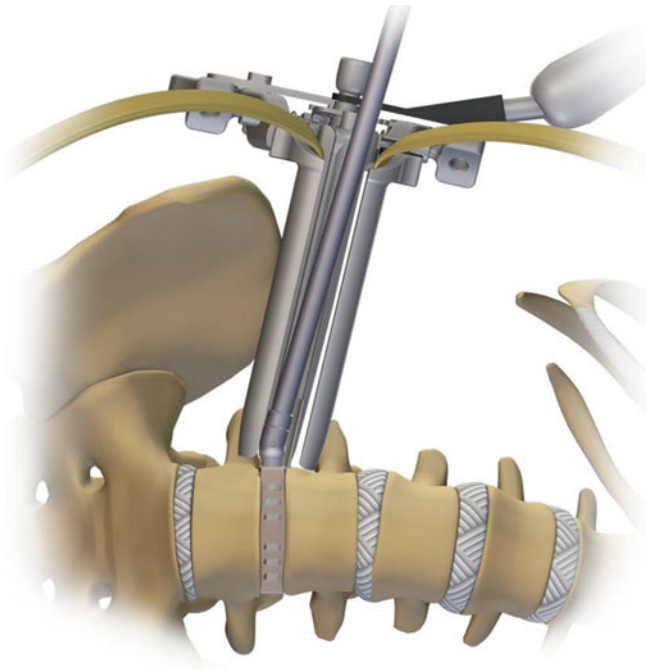

Fig. 18.30 Illustration showing L4–5 extreme lateral interbody fusion in a patient with a high iliac crest, necessitating the use of angle instrumentations to preserve the endplates during discectomy, preparation, trialing, and implantation (Copyright NuVasive, Inc., used with permission)

Avoidance of Subsidence

The disc height restoration and resultant indirect decompression afforded by this technique can be lessened or lost through subsidence of the implant into the vertebral endplates. As previously stated, proper technique in endplate preparation, ensuring that violations do not occur, is the primary defense against subsidence. However, wider implants with greater surface area tend to resist subsidence, in a manner similar to a snowshoe, and should be used if the local anatomy and exposure, confirmed by neuromonitoring, allow for placement of wider cages. In the case of a known intraoperative significant endplate violation, it is the authors' opinion that supplemental posterior fixation should be strongly considered.

Avoidance of Nerve Injury

In addition to all of the previous nerve mapping and avoidance techniques described earlier, there are other special options in retraction that may be used to decrease the risk of neural injury. In the authors' experience, periodic stimulation of the field posterior to the retractor (through the posterior blade) and comparison of the discrete-threshold responses thus obtained to the thresholds observed at the insertion of the retractor may reveal increasing thresholds over the course of the procedure. This may indicate that the nerve is experiencing ischemia or compression. This reinforces, in the authors' minds, both the essential nature of proactive neuromonitoring during the approach and throughout the case and the rationale for a complete but expeditious surgical procedure. The less time the psoas is under retraction, the less risk of compressive or ischemic injury to it or its related structures. In the case where extended 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.

Literature Results

In large-series studies, lateral access procedures have been shown to have favorable complication rates and treatment variables (estimated blood loss (EBL), operative time (ORT), and length of stay (LOS)) compared to conventional approaches, as previously mentioned. In one such series by Rodgers et al., 600 consecutive procedures were examined to determine rate of perioperative complication and treatment outcome [27]. In total, 741 levels were treated in 600 patients, with 99.2 % receiving supplemental internal fixation. Hemoglobin change from pre- to postoperative averaged 1.38 g and average LOS was 1.21 days. An overall complication rate of 6.2 % was observed, with 1.5 and 2.8 % being in-hospital surgical and medical complications, respectively. Post-discharge surgery-related complications occurred in 1.0 % of patients, and post-discharge medical complications occurred in 0.8 % of patients. Motor deficits (other than transient hip flexor weakness) were observed in 0.7 % of cases and nearly completely resolved in the postoperative period [27]. These complication results are favorable to the previously mentioned treatment and complication rates of

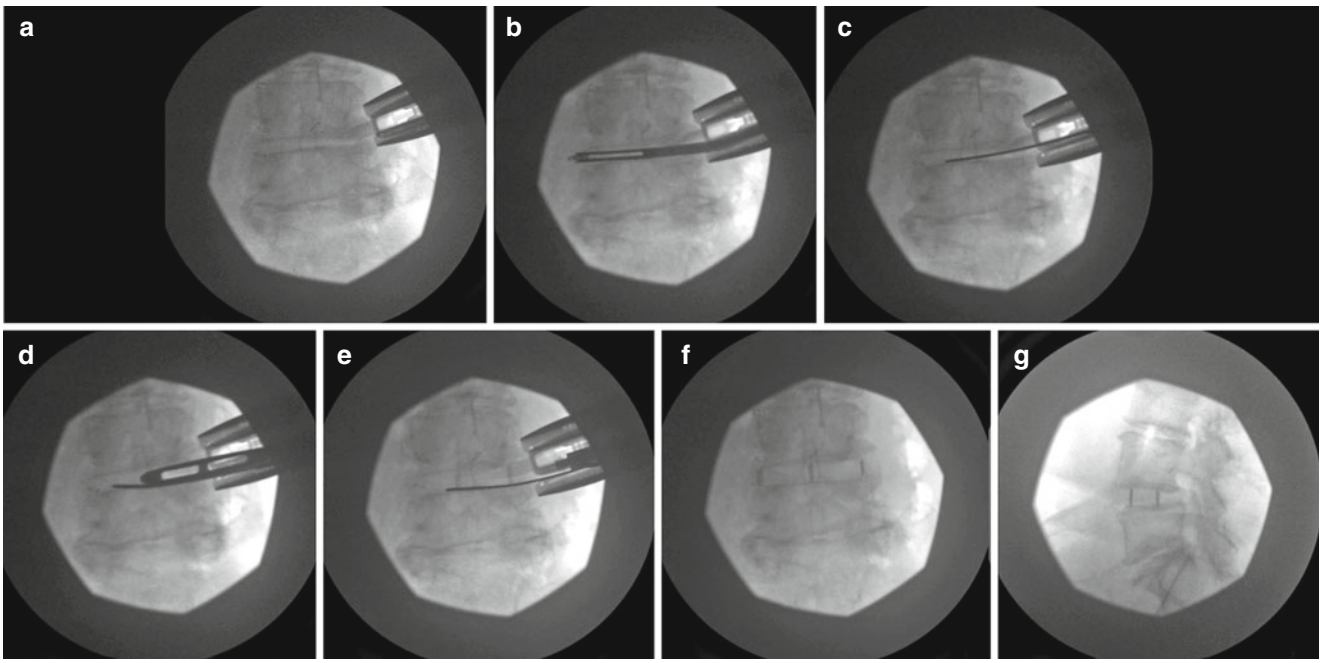

Fig. 18.31 Intraoperative fluoroscopy showing access to the L4–5 disc space in a patient with a high iliac crest (**a**), disc space preparation using angled box cutters to protect the endplates (**b**), introduction of inferior bendable slide (**c**) to protect the inferior endplate during implant trialing (**d**), implantation of intervertebral cage with the inferior slide in place (**e**), and postimplantation anteroposterior (**f**) and lateral (**g**) fluoroscopy showing L4–5 implantation in a patient with a high iliac crest without endplate violation

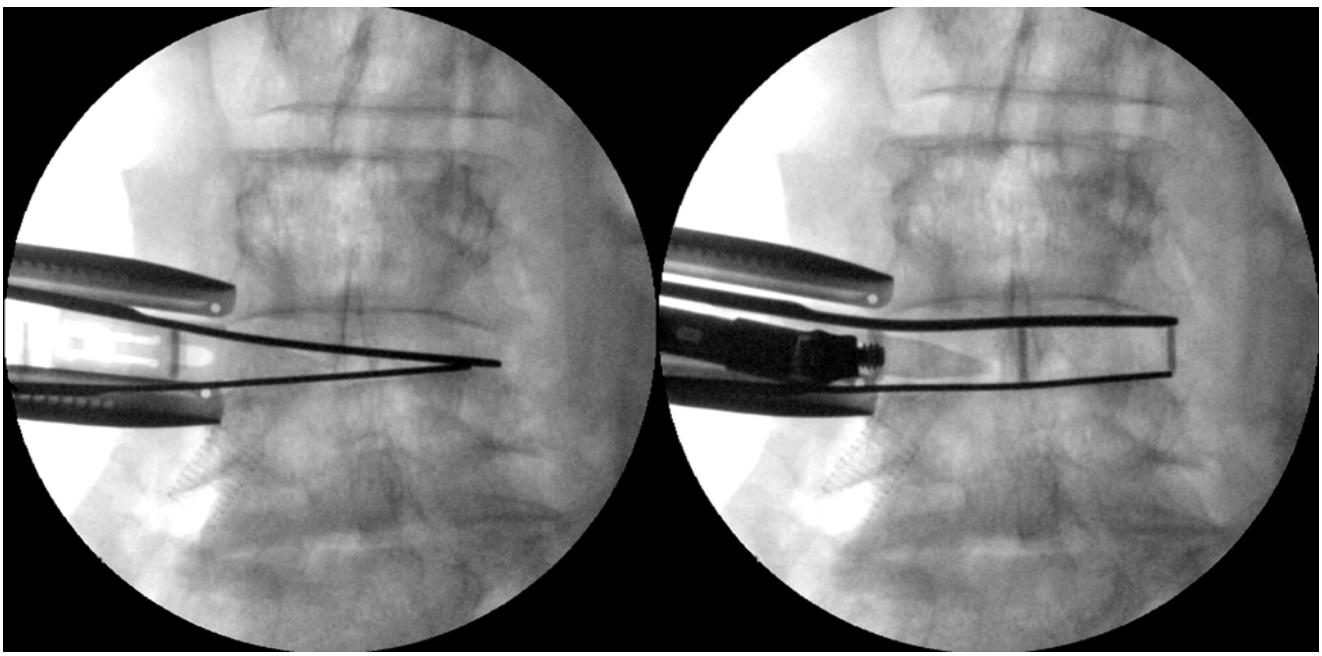

Fig. 18.32 Anteroposterior fluoroscopy showing CoRoent implantation at L4–5 in a patient with a high iliac crest using both superior and inferior bendable slides to protect both endplates

conventional surgical approaches. Similar results were observed as part of a prospective multicenter study examining the role of neuromonitoring and postoperative side effects and new neural deficits in XLIF [28]. In this study of 102 patients undergoing lateral fusion at either L3–4 and/or L4–5, Tohmeh et al. reported a new distal motor deficit rate of 2.9 %, all resolving in the postoperative period. Mild, transient iliopsoas/hip flexion weakness was observed in

27.5 % and new postoperative medial thigh sensory changes in 17.6 % of patients.

Long-term outcomes have been shown in several studies to be similar or favorable to those reported in conventional approaches [29, 32, 33]. Smith et al. in 2012 compared economics and outcomes of lateral access fusion to conventional ALIF and found lower complication rates and treatment variables with similar long-term outcomes. Additionally, costs, measured by hospital charges, were 10 and 13.6 % lower for one- and two-level lateral procedures, respectively, largely due to lower hospital stays and the resultant resource utilization [32]. In a review of 14 studies on the mini-open lateral approach for lumbar interbody fusion for degenerative and deformity indications, Youssef et al. [33] found ranges of mean improvement for pain from 32.4 to 80 % and Oswestry Disability Index from 39 to 82.1 % with patient satisfaction at 89.4 % and patients reporting that they would have chosen to undergo the procedure had their outcome been known in advance in between 71 and 89.4 % of cases.

Conclusion

The transpsoas procedure for anterior lumbar interbody fusion is a powerful approach with many inherent benefits, though with several risks which must be mitigated by diligent adherence to neuromonitoring and surgical technique.

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Presacral Approaches for Minimally Invasive Spinal Fusion

19

Neel Anand and Eli M. Baron

The presacral approach is a minimally invasive novel approach for performing discectomy and interbody fusion at L5–S1. Considerable experience exists with this approach. The advantages to this approach include preservation of the integrity of the surrounding musculature, ligaments, and annulus and also short operative time associated with this approach. This approach also carries considerably less risk than that associated historically with either posterior or traditional anterior approaches for lumbosacral fusion [1]. This chapter will review the anatomic considerations for this approach and technical aspects of this approach.

Anatomical Considerations

The sacrum is separated from the rectum by a layer known as the mesorectum. This is composed of lymphatics, blood vessels, and adipose tissue. The mesorectum is covered by visceral fascia. The ventral surface of the sacrum and coccyx is covered by parietal fascia. Between the visceral and parietal fascia lies an area known as the presacral space. This is largely comprised of loose connective tissue. Blood vessels, however, do course through this space. This includes the midline sacral artery, which has a variable course in relationship to L5–S1. Yuan et al., studied the anatomy [2] of the presacral space for the purposes of using this corridor for fusion. They studied cadavers and noted a safe zone that is in terms of the distance between the right and left internal iliac vessels at the S1–S2 level of 6.9 cm on MRI and 6.0 cm on CT, respectively. Additionally, they noted a distance of the anterior sacral margin to the rectum at the S3–S4 level being approximately 1.2 cm on MRI and 1.3 cm on CT. They concluded that this zone may be useful for performing a percutaneous approach. They also concluded that the sacrum and its overlying parietal fascia provided a relatively safe posterior border along which a blunt trocar could be advanced to avoid structures anterior to the presacral space.

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Clinical Background

This presacral corridor was first described by Cragg et al. where this passage route was used for successful lumbosacral biopsy in three cases [3]. This was eventually developed into a minimally invasive technique where discectomy and fusion could be performed [4]. Additionally, considerable experience exists using strut grafting in the setting of high-grade spondylolisthesis in a transvertebral manner; this also influenced the development of a minimally invasive transsacral approach [5–7].

Advantages of This Approach

As mentioned above, this methodology is advantageous in terms of achieving interbody fusion at L5–S1 as the ligamentous structures and connective tissue structures surrounding the spine are kept intact. Open anterior approaches have been associated with vascular injury *rates* ranging from 0.5 to 15.6 % [8, 9], a bowel injury rate of 1.6 % [10], and a prolonged ileus rate of 0.6 % [11]. By comparison, in a review of 5,300 cases of paracoccygeal transsacral L5/S1 fusions using an axial rod, being performed in the United States from January 2005 to January 2009, per the US FDA medical device reporting data, the complication rate in terms of bowel injury was noted at 0.47 %. An overall complication rate was noted of 0.7 % [1]. Fusion rates of AxiaLIF have been reported ranging from 91 to 96 % using varied radiographic assessment techniques [12–15]. This is comparable to fusion rates seen with ALIF where fusion rates using femoral ring

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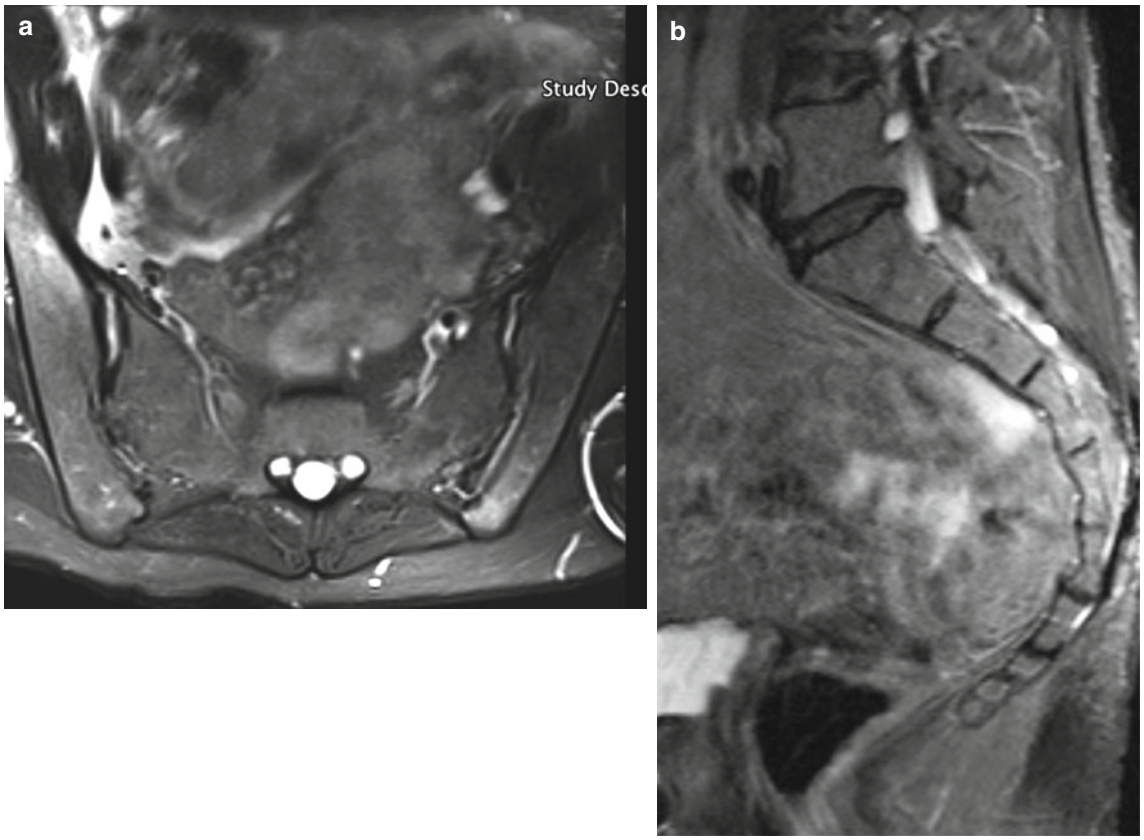

Fig. 19.1 (**a**, **b**) Axial and Sagittal pelvic MRI images demonstrating normal venous anatomy at the S1–S2 junction. Notice that there is no aberrant midline vasculature

allografts or iliac crest bone grafts (with supplemental pedicle screw fixation) have been reported to range from 77 to 91 % [16] and where fusions using cages or allograft with INFUSE (rhBMP-2/ACS) have been reported to have fusion rates ranging from 98 to 100 % (Medtronic Sofamor Danek, Memphis, TN) [17, 18].

Suggested indications for L5–S1 AxiaLIF include grade 1 degenerative spondylolisthesis, anterior column support in the setting of spinal deformity surgery, degenerative disc disease where fusion would be a consideration, and interbody fusion in the setting of pseudarthrosis of a previous posterolateral fusion at L5–S1. Contraindications of this approach would include previous surgery involving the presacral region, history of prior colostomies or pathology in the region of the rectum such as fistulas, and high-grade spondylolisthesis. Also, aberrant blood vessels anterior to the sacrum at the midline (especially at S1–S2) are a contraindication. In the preoperative work-up, it is recommended that a pelvic MRI be performed to rule out any existing aberrant midline vasculature structures and that there is an adequate corridor at the region of S1–S2 prior to performing this procedure as outlined below.

Work-Up

All patients who are to undergo paracoccygeal transsacral L5/S1 fusion require preoperative plain radiographs that include the entire scrum and coccyx. Anatomical variations of the sacrum such as a hook-shaped sacrum or a very flat sacrum may make the appropriate trajectory for placement of the AxiaLIF screw very difficult to near impossible. This mandates appropriate preoperative templating and planning flexion/extension views of the lumbar spine may assist in surgical work-up. Additionally, MRI of the lumbar spine and MRI of the pelvis are performed. Once again, it is critical to rule out any aberrant blood vessels in the region of S1–S2 (Fig. 19.1). We also make sure there is an adequate fat pad in the presacral space. Adhesions in this region would be a contraindication to this procedure. Any patient with a strong

history for possible abdominal adhesions (e.g., inflammatory bowel disease, pelvic inflammatory disease) should undergo pelvic CT with rectal contrast to evaluate for adhesions or altered rectal-sacral anatomy that would necessitate a different approach [19].

Device

The TranS1 Axial 3D screw is the commercially available device for transsacral fixation using the presacral approach (Trans1, Wilmington, NC). Initially, this device was a single screw that was screwed into a drilled channel through the sacrum, disc space, and L5 vertebral body over a guide wire. Distraction could be achieved if needed using the differential thread pitch in the proximal and distal part of the screw. Recent redesign however, has the device having four components. This allows for selective internal distraction if necessary by having a distraction rod internally rotating within the device within the S1 anchor and pushing on the shoulder within the L5 anchor to create distraction within the disc space. The biomechanics of the transsacral screw have been studied, and in the setting of supplemental posterior spinal fusion with pedicle screws, a rigid construct is achieved [20]. Ledet et al. studied the biomechanics of AxiaLIF fixation using bovine lumbar spines [21]. They compared the intact bovine lumbar spine to that post AxiaLIF (with either tapered or nontapered rods) where specimens were subject to axial compression, lateral bending, sagittal bending, and torsion. Further, they compared their data to that of numerous other devices historically used for interbody grafting ALIF and PLIF (including numerous cage designs, bone dowels, and femoral ring allograft). For the nontapered rod, they noted a mean increase in stiffness for flexion 169 %, lateral bending 562 %, torsion 134 %, and axial compression 144 % when compared with the intact model. For the tapered rod, they noted a mean increase in stiffness for flexion 131 %, lateral bending 288 %, torsion 116 %, and axial compression 132 % when compared with the intact model. The authors concluded that the AxiaLIF fixation rod compares favorably to other interbody devices and may be suitable to reduce pathologic motion at the L5–S1 motion segment, facilitating boney fusion. They stress that the minimal access without annulotomy avoids compromise of the biomechanics of intact ligamentous structures, contributing to more rigid fixation.

Fleischer et al. noted in biomechanical study of sacral screw strain long posterior fixation constructs that AxiaLIF, with pedicle screws, was similar in stability to placement of iliac screws, with a significant reduction in range of motion in flexion-extension, lateral bending, and axial torsion when compared with pedicle screws alone and with ALIF with pedicle screws [22]. A comparable reduction in S1 screw bending moments were seen with all these maneuvers, with the AxiaLIF pedicle screw construct having significantly reduced S1 screw bending moments when compared with pedicle screws alone and with ALIF with pedicle screws.

Surgical Technique

After induction under general anesthesia, the patient is positioned prone on a Jackson table. We often also use a Wilson frame. The advantage of the Wilson frame is that it allows easy access to the coccygeal and paracoccygeal region. Nevertheless, a Jackson table is quite useful as long as care is taken that the thighs are separated to provide access to the paracoccygeal region. It is very important that a retaining strap is not placed across a patient's thighs, as this will limit excursion of the surgeon's arm when using instruments to access the sacrum via this approach. Biplanar fluoroscopy is used. It is critical to have a clear image of the sacrum on both anteroposterior and lateral views.

The rectal area is then prepped and isolated. Some have recommended bowel prep prior to surgery but this is optional. A Betadine-soaked sponge is placed at the opening of the anus and a double plastic drape that is used to further secure to the patient with Mastisol (Ferndale Laboratories, Ferndale, MI) to isolate the rectal area. A one-inch incision is then planned over the sacrococcygeal region at the midline.

This can also be done slightly off midline, especially where hygiene is concerned such as in obese diabetic patients. A number 10 blade is used to incise the skin. A blunt guide pin introducer/stylet assembly (blunt dissecting tool) is used to pierce the paracoccygeal fascia and ligament adjacent to the sacrococcygeal notch. Care is taken to just pierce the ligament with the blunt probe, and an X-ray is taken immediately prior to any advancement of the probe (Fig. 19.2). The blunt dissecting tool is then marched up the ventral aspect of the sacrum. Great care is taken not to deviate laterally and enter the sacral ventral neuroforamina. Frequent spot-checks on lateral and anteroposterior fluoroscopic images are performed to ensure that the appropriate trajectory is being maintained. After one has experience doing this procedure, one develops a sense of the smooth feeling of passing the assembly along the parietal fascia of the ventral sacrum. If there is any doubt in terms of tactile feel, the procedure should be started from the beginning or be abandoned.

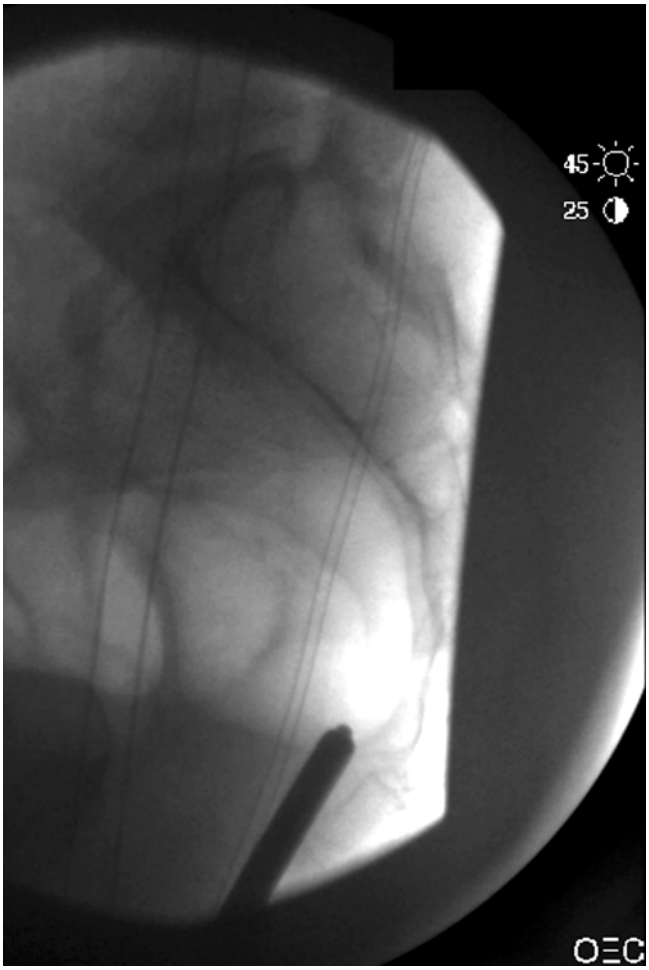

Fig. 19.2 Lateral fluoroscopic image showing blunt stylet after introduction through the paracoccygeal fascia

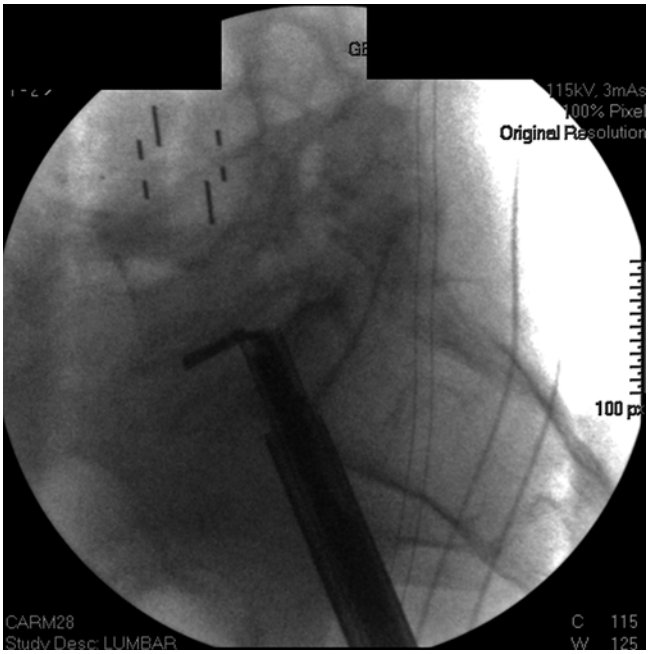

Fig. 19.3 A Nitinol cutter is used through the 10 mm dilator sheath and is used in the discectomy. Also seen in the lateral fluoroscopic image is an interbody spacer placed at L4–L5 via the transpsoas approach

Once the introducer/stylet assembly reaches S1–S2 junction, fine adjustments are made to the trajectory, and the blunt guide introducer is removed from the assembly, and a sharp guide pin is impacted into the sacrum. After the blunt introducer assembly is removed, a guide pin extension is secured to the guide pin. A 6 mm followed by an 8 mm cannulated dilator are used, which are slid over the guide pin and impacted into the sacrum. This is followed by a 10 mm dilator that has a thin-walled dilator sheath, which is slid over the dilator body. This is anchored into the sacrum using a cannulated slap hammer. The dilators and guide pin are then removed while the sheath is left in place.

Afterwards, a 9 mm drill is placed over the guide wire and used to drill through the sacrum up to the level of L5–S1 disc space. The drill is removed while twisting it in a clockwise manner; this way local bone is saved as autograft. A discectomy is then performed. This entails using a series of Nitinol cutters, rasps, and brush devices to remove disc material (Fig. 19.3). We take great care to perform a thorough discectomy. Removal of disc material posteriorly is avoided, especially in the setting of prior microdiscectomy, as this could result in graft material migrating towards the spinal canal.

Afterwards, the disc space is irrigated out with antibiotic-containing solution. The interspace is then packed with graft material including local reamings and graft extenders as required. The authors typically use local bone autograft, Grafton Putty demineralized bone matrix, and 2.1 mg of rhBMP-2/ACS [23].

Afterwards, the guide pin/extension assembly is placed back into the disc space through the 10 mm sheath. The 10 mm sheath is then removed. A 12 mm dilator is then assembled with a 12 mm dilator sheath. This is inserted over the beveled guide pin and is malleted into position with a slap hammer where the outer diameter of the sheath is completely within the bony sacrum. The dilator is removed and the dilator sheath is left behind as a working channel.

Subsequently, a 10.5 mm cannulated twist drill is used to drill over the guide pin through the sacrum just past the S1 endplate. The drill is removed while drilling in a counterclockwise manner to ensure the bone graft is left in place.

A 12 mm dilator tamp is placed over the wire. The 12 mm sheath and tamp are advanced with a slap hammer to the inferior end plate of L5 as verified on lateral fluoroscopy. The tamp is then removed and the sheath is left behind. The 10.5 mm drill is then inserted over the wire and used to drill to just below the level of the pedicle under lateral fluoroscopic guidance.

A dilator trial is then used (through the 12 mm sheath) with lateral fluoroscopy to assist in determining the length of the L5 and S1 components being used (Fig. 19.4). The screw

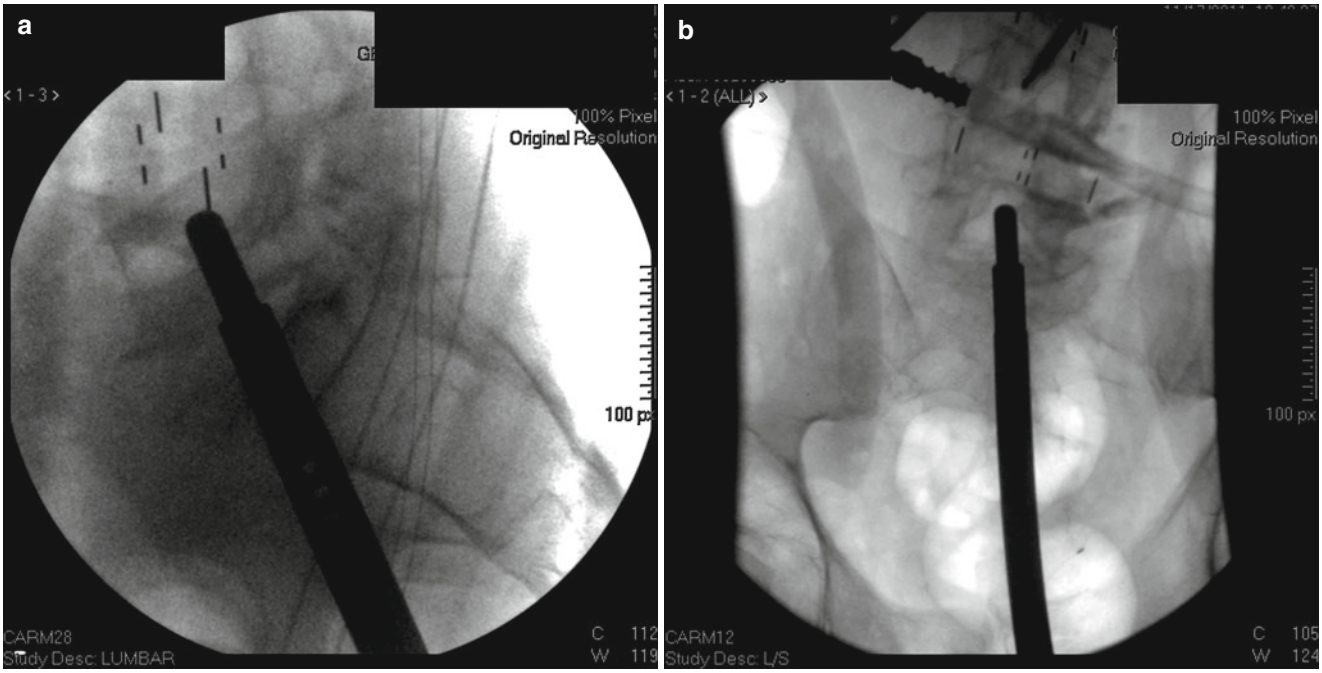

Fig. 19.4 (**a**) Dilator trial being used with lateral fluoroscopy to assist in determining the length of the implant used. (**b**) Anteroposterior fluoroscopy confirms appropriate trajectory in the coronal plane

is then assembled and kept ready by the scrub assistant on a ratcheting screwdriver.

The beveled guide pin is then put back into place. A 10 mm dilator is placed over the wire, and the dilator and dilator sheath are removed while keeping the guide pin in place. An exchange system is then chosen where its angle (30°, 45°, or 60°) approximates the face of the sacrum on lateral view. An exchange bushing is placed over the guide wire and advanced with its longer side dorsal until it contacts the sacral face. It is then rotated 180° so the angled surface of the bushing matches the sacrum. This is done again with its corresponding tubular retractor (Fig. 19.5). The retractor is then anchored to the sacral face using two fixation wires. Constant forward pressure is then maintained on the final tubular retractor for the duration of the procedure.

The titanium axial 3D screw assembly is then inserted along the guide wire and screwed across the sacrum, across the L5–S1 disc space, into the L5 vertebral body. The L5 anchor is fully engaged in the L5 vertebral and the S1 anchor is left with one or two threads proud to the sacral face (Fig. 19.6). The driver is then removed. Distraction can then be performed across the L5–S1 disc space if needed. A fixation rod is then placed through the tube and engaged into the L5 anchor portion using fluoroscopic confirmation. The tubular retractor is irrigated, the fixation wires are removed, and the retractor is removed.

The wound is irrigated and a three-layer closure is performed. We prefer to use cyanoacrylate on the skin in addition to placing a watertight dressing on the skin.

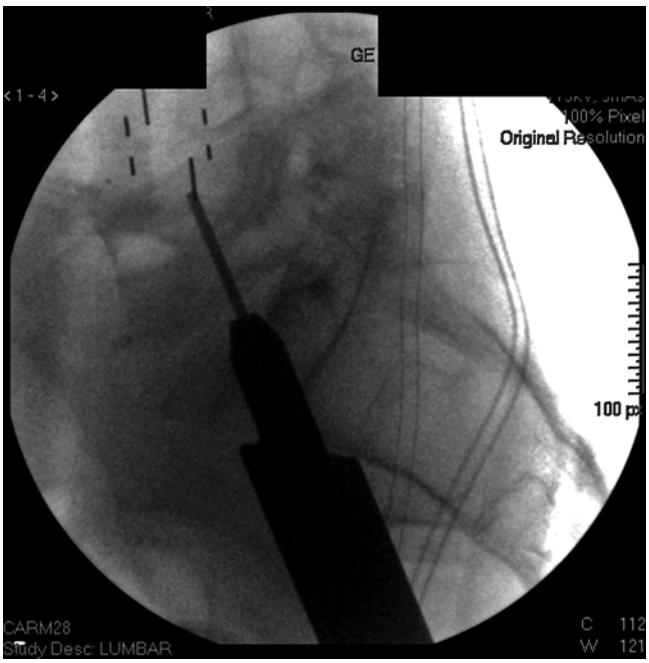

Fig. 19.5 Exchange bushing and corresponding tubular retractor placed over guide wire. The retractor matches the face of the sacrum

Tips and Pearls

As mentioned above, operating room belts and straps should not be placed along the patient's thighs as these may limit excursion of the surgeon's hands.

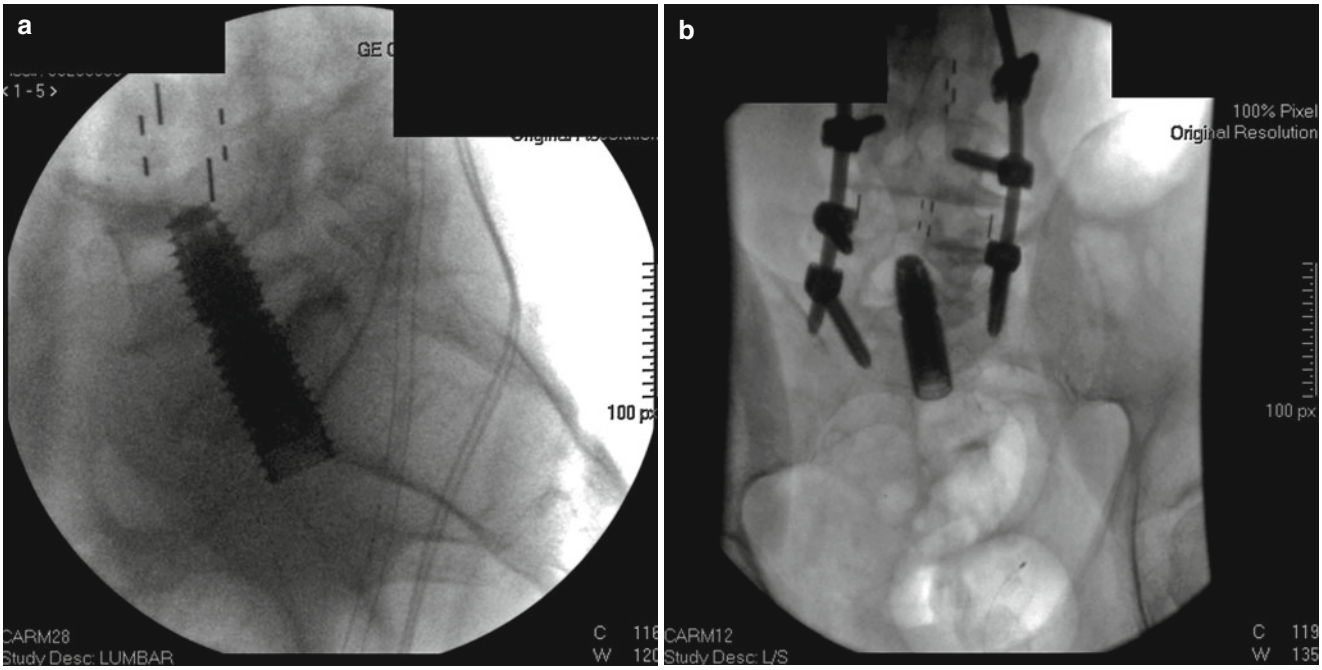

Fig. 19.6 (**a**, **b**) Lateral and anteroposterior fluoroscopic images post-axial 3D screw placement. Note that on the lateral image several threads remain proud to the sacral face; thus, bicortical fixation is achieved. The anteroposterior image is also post percutaneous pedicle screw and rod placement

It is critical that the working cannula remains in place, where it is always held by the surgeon along the ventral surface of the sacrum. If for any reason this moves, the procedure should start once again from the beginning. Simply replacing it along the sacrum is potentially dangerous as this may result is visceral injury.

Beveled dilators should be placed facing ventrally to maximize the chance of bowel being pushed anteriorly and away from the sacrum. Once, however, the dilators are up against the ventral surface of the sacrum, they are rotated into position matching the inclination of the sacrum [4].

It is important that the axial screw not be placed into the end plate at L5 as some subsidence may occur. This may result in penetration of the L4–L5 disc space. We rarely place the screw any further than the inferior margin of the L5 pedicle.

Postoperative Care

A dressing is kept on the incision for at least 5–7 days post-op. We routinely change the initial dressing on post-op day 2 or 3. The area is kept clean. Fecal contamination in general has not been an issue.

Outcomes

Anand et al. reported outcomes on 97 patients undergoing AxiaLIF L5–S1 fusion at the end of long-segment constructs, primarily in the setting of deformity [24]. Of these patients, only 14 patients had supplemental iliac screw fixation. Mean follow-up was 24 months. There were no intraoperative complications. There were two pseudarthrosis at L5–S1. There was one late infection with nonunion, and one had a sacral pedicle screw loosening. There were no sacral insufficiency fractures noted. At 1 year, fusion was noted in 67 of 71 patients by plane radiograph and confirmed in 56 of the 67 by CT scan. AxiaLIF was concluded to being a viable alternative for providing anterior column support for long-segment fusion [24]. Aryan et al. reported initial clinical and radiographic experience in 35 patients undergoing L5–S1 percutaneous AxiaLIF fusion [12]. Indications included lumbar degenerative disc disease, disc degenerative lumbar scoliosis, and lytic spondylolisthesis. Two patients additionally underwent transpsoas lateral lumbar interbody fusion at L4–L5. Ten patients had stand-alone AxiaLIF, while 24 patients underwent supplemental pedicle screw fixation, and 2 patients had AxiaLIF as part of a larger construct. In 20 patients INFUSE was used; in 16 patients OP-1 (rhBMP-7) was used (Stryker Spine, Allendale, NJ). The authors assessed fusion with lumbar flexion and extension radiographs and with CT scan in 31 patients at 1 year. They noted a 91 % fusion rate at last follow-up. Mean follow-up was 17.5 months. They concluded that L5–S1 discectomy and fusion through a presacral approach could be performed safely and that this corridor may provide an alternative route of access to the L5–S1 interspace and those patients who have unfavorable anatomy or contraindications to a traditional open anterior approach.

Tender et al. recently reported three cases of patients who underwent AxiaLIF fusion in the treatment of grade 2 spondylolisthesis at L5–S1 and back pain [25]. All patients underwent spondylolisthesis reduction with a percutaneous pedicle screw system followed by AxiaLIF fusion. At 1 year, all patients were noted to have solid fusions.

Recently Tobler et al. reported results of 156 patients from four clinical sites that underwent L5–S1 interbody fusion via the presacral approach [14]. In all cases, fusion surgery was performed in patients with refractory axial low back pain with failure of nonoperative management for at least 6 months duration. Diagnoses included 61 % of patients having degenerative disc disease, 21 % having spondylolisthesis, 7.7 % with spinal stenosis, and 8.3 % with herniated nucleus pulposus. Of these 156, 123 patients also underwent percutaneous placement of pedicle or facet screws. Two-year outcomes were reported. Mean pain scores improved from 7.7 preoperatively to 2.7 postoperatively. There were also substantial improvements in Oswestry Disability Indices. Mean scores improved from 36.6 preoperatively to 19.0 at 24 months. Of the patients, 86 % realized a clinically significant improvement in pain severity and functional improvement. The overall radiographic fusion rate at 2 years was approximately 94 %. In terms of evaluation of fusion and fusion mass, standard anteroposterior and lateral radiographs as well as dynamic flexion-extension films were used in 89 patients, and thin-cut CT scans were used in 66 patients. There were no vascular, neural, urologic, or bowel injuries reported in this group. The authors conclude that the presacral approach remains promising as a methodology for achieving L5–S1 fusion but additional corroboration is required in patient groups.

In terms of fusion rates, Gerszten et al. recently reported outcomes of a retrospective case-matched chart review where a matched cohort of 99 patients underwent fusion performed by two surgeons at two institutions (2005–2007): 45 patients at one hospital received rhBMP-2 and 54 patients at the other did not receive rhBMP-2 [13]. In the rhBMP2 group a medium kit of INFUSE was used in combination with beta tricalcium phosphate (Vitoss granules; Orthovita, Malvern, PA, USA) or silicate-substituted calcium phosphate (Actifuse; Apatech, Hertfordshire, UK). In the non-rhBMP-2 group, a combination of 6 cm^3 of bone marrow aspirate obtained from iliac crest was used with 10 cm^3 of silicate-substituted calcium phosphate. Fusion was assessed by CT scanning. They noted fusion rates were 96 % with rhBMP-2 and 93 % without rhBMP-2. They concluded that clinical outcomes were similar for patients who underwent an AxiaLIF L5–S1 interbody fusion with or without rhBMP-2 and saw little effect of rh BMP-2 on fusion rates.

Tobler et al. reported a 2-year outcome in 26 patients undergoing AxiaLIF [15]. The fusion was at L5–S1 in 17 patients and at L4–L5 and L5–S1 in 9 (where the L4–L5 fusion was performed using TLIF technique. All patients had symptomatic degenerative disc disease at L5–S1. rhBMP-2 and Vitoss (Orthovita, Malvern, PA) were used as grafting material. Fusion was assessed by CT scanning and flexion-extension radiographs, where CT was performed at 6- and 12-month follow-up and flexion-extension films at 6, 12, and 24 months follow-up. The authors noted a 92 % fusion rate at 1 year and a 96 % fusion rate at 2 years. No major complications were noted. These included foraminal stenosis, pain related to a pedicle screw, and a painful incision.

Complications

The biggest hesitation for surgeons to perform this procedure is the possibility of bowel injury. We noted a bowel injury rate of 0.47 % in a review of 5,300 cases of Trans1AxiaLIF being performed in the United Sates from January 2005 to 2009 per the US FDA medical device reporting data [1]. It is certainly possible that this complication may be underreported. Nevertheless, Lindley et al. recently reported complications in a retrospective review of charts of 68 patients who underwent AxiaLIF over a 4-year period [26]. They noted a relatively high complication rate of 26.5 %. They noted a rectal perforation rate of 2.9 % and superficial wound infection rate of 5.9 %.

If a bowel injury is suspected intraoperatively, rigid proctosigmoidoscopy or flexible sigmoidoscopy may be performed early on to identify the injury. Other alternatives include a Gastrografin enema. If the patient presents postoperatively with potential bowel injuries, CT of the abdomen and pelvis with rectal Gastrografin should be performed. Typically, injury to the sigmoid colon and intra-abdominal rectum presents with signs and symptoms of an acute abdomen. Injuries to the extraperitoneal rectum may present less obviously with a possibility of a localized abscess. If either of these is suspected, consultation with a colorectal surgeon is highly recommended [27].

If a vascular injury is suspected, venous bleeding typically will tamponade in the retroperitoneal space. This should be suspected if there is sacral pain or unusual pain or bloody drainage in the wound area. Additionally, patients with venous injury may present with a decrease in hemoglobin and hematocrit or other symptoms related to compression of the bladder, rectum, or uterus. Arterial bleeding is highly unusual and should be identified at the time of the surgery. CT scan of the pelvis may identify any collection. If a presacral collection exists and the patient is stable, drainage is not recommended as this may lead to massive bleeding or infection. Any situation where there is expanding pelvic hematoma or hemodynamic instability may require some emergency resuscitation and angiography with possibly embolization [27]. Wound dehiscence may also occur in obese and diabetic patients. This may require a return to the operating room for irrigation, debridement, and reclosure. We have made our incisions off midline for patients who are very obese with diabetes.

Other complications reported included superficial wound infection, sacral fracture, pelvic hematoma, and transient nerve root irritation [26].

Conclusions

The presacral corridor allows for minimally invasive L5–S1. It is a novel approach to the lumbosacral spine and is a useful alternative to other, more common, methodologies for performing interbody fusion.

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Mini-open Lateral Thoracic Fusion

20

Elias Dakwar and Juan S. Uribe

Surgical Indications

The surgical indications for thoracic disc herniation being treated with a mini-open lateral approach include thoracic pathology requiring fusion including thoracic disc herniations [1–4] manifested by myelopathy, progressive neurologic deficit, and refractory radicular pain (Table 20.1) [5–20]. Indications for thoracic fusion (and/or corpectomy) also include tumor [21], fracture [22], or infections causing myelopathy, progressive neurologic deficit, refractory radicular pain, instability, or progressive deformity of the spine. The thoracic lateral mini-open approach can be employed from approximately T4 (limited by the position of the scapula/axilla) through T12.

Relative contraindications to the thoracic mini-open lateral approach include patients presenting with primarily posterior thoracic involvement (compressive or pathologic), patients with severe cardiopulmonary disease, and patients having undergone contralateral pneumonectomy.

Detailed Surgical Technique

The operative technique for the mini-open lateral approach for thoracic discectomy/corpectomy and fusion has previously been described [1, 2, 4, 21, 22].

The preoperative evaluation and planning includes proper imaging such as magnetic resonance imaging (MRI) or computed tomography (CT) myelogram to evaluate the location and characterization of the pathology. The exact vertebral level, number of ribs, and number of non-ribbed lumbar vertebrae must also be verified and followed preoperatively and

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Table 20.1 Examples of symptoms and signs of thoracic disc herniation reported in the literature

Myelopathy	Pain	Miscellaneous
Sensory disturbances	Band-like chest pain	Multiple sclerosis symptoms
↑ or ↓ skin sensitivity	Axial thoracic back pain	Spinal neoplasm/ tumor symptoms
Hyposthesia	Axial lumbar pain	Psychiatric disorder symptoms
Paresthesia	Periodic lumbago	Demyelinating disease symptoms
Anesthesia	spinal pain	Ovarian disorder symptoms
Complete sensory deficit	"Labor-like" pain	Reproductive disorder symptoms
Genital anesthesia	Radiculopathy	Cardiac disorder symptoms
Dysesthesia	Pain accentuated by cough	Symptom intermittency
Motor disturbances	Point tenderness	Severe headaches
Abdominal reflex loss	Pure axial back pain (absent other symptoms)	Spontaneous intracranial hypotension
Hyperreflexivity	Pure radicular pain (absent other symptoms)	Accompanying scoliosis
Abnormal reflexes	Abdominal pain	Accompanying kyphosis
Diffuse weakness	Intercostal neuralgia	Resultant from trauma
Monoparesis/ paraparesis	Radiculomyelopathy	Paraspinal muscle rigidity
Monoplegia/paraplegia	Angina pectoris	Sphincteric changes
Brown-Séguard syndrome	Groin pain	Bladder dysfunction
Rapid-onset paraplegia	No pain	Bladder urgency
Progressive paraplegia		Bowel dysfunction
Spastic, ataxic gait		Potency disturbances
Lumbar neurologic symptoms		Trophic disturbances
		Gallbladder disease
		Gastritis
		Renal calculi

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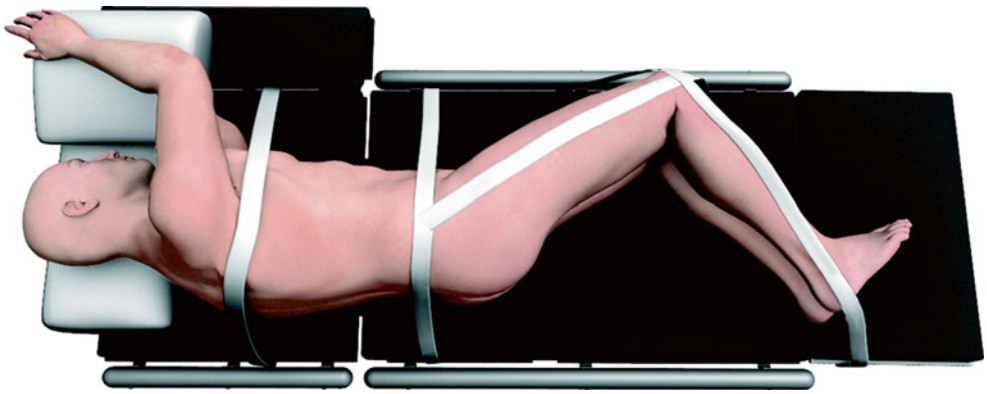

Fig. 20.1 Aerial illustration showing patient positioning for a mini-open lateral approach (extreme lateral interbody fusion (XLIF®, NuVasive, Inc.), for thoracic fusion. Copyright NuVasive, Inc.; used with permission)

in surgical preparation to ensure accurate intraoperative localization in avoidance of wrong-level surgery. If the pathology is predominantly on one side of the spine, an ipsilateral approach is used. When the pathology is centrally located, then the approach is from the right side for the upper levels (T4–T8) and from the left side on the lower levels (T9–T12) to avoid the great vessels. The location of the great vessels should also be noted preoperatively on axial MRI at each level being treated for any aberrancy.

After general endotracheal intubation, an arterial line, venous access, Foley catheter, and neurophysiological monitoring electrodes are placed. The patient is then positioned in the true lateral decubitus position with the operative side up and overlying the flex point of the operative table. An axillary roll and sequential compression devices are placed. The knees are flexed with a pillow between them and all pressure points are padded. The arm on the operative side is placed on a table-mounted armrest (Fig. 20.1). The patient is secured to the table with wide tape both over the hip and just below the axilla (Fig. 20.1). Intraoperative fluoroscopy is used to ensure that the patient is placed and secured in a true lateral orientation, with the working corridor to the disc space orthogonal to the floor (true 90° lateral trajectory). Preoperative antibiotics and steroids (if indicated) may be given. The patient is then prepped and draped in the usual sterile fashion.

Intraoperative fluoroscopy is used to identify and mark the appropriate disc level (in the case of a thoracic disc herniation) or vertebrae (in the case of a corpectomy) (Fig. 20.2). The two approaches most commonly used for the mini-open thoracic fusion are transthoracic and retropleural.

Intraoperative neurophysiologic monitoring should be used in all thoracic fusion cases, including motor-evoked potentials (MEPs) and somatosensory-evoked potential (SSEPs) modalities, as applicable.

For the transthoracic approach (Fig. 20.3) [1, 2], a 3–5 cm oblique incision is made directly over the targeted level 90° off midline between the ribs following the angle of the ribs (Fig. 20.4). Monopolar cautery is used to dissect through the subcutaneous tissue, latissimus dorsi, and intercostal muscles.

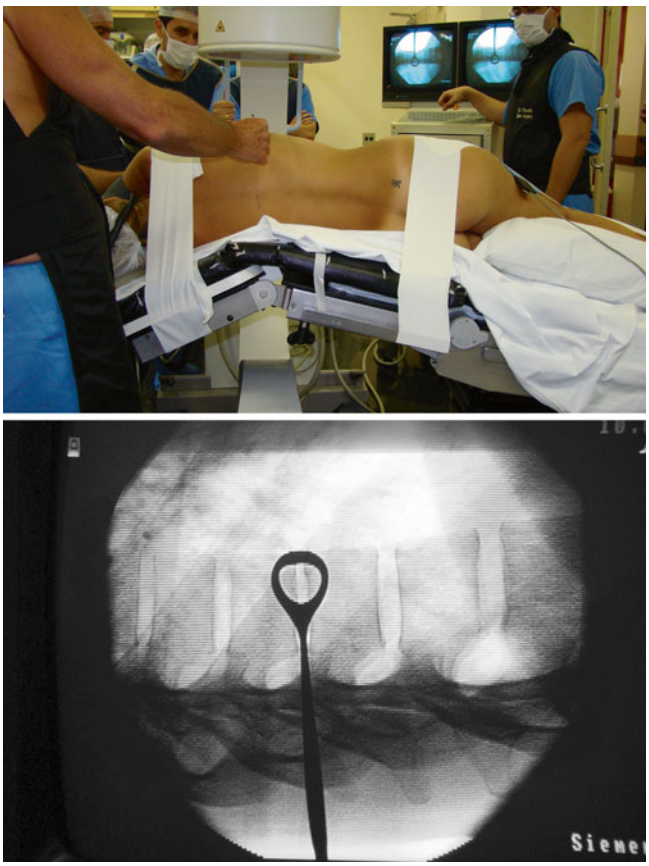

Fig. 20.2 Posterior photograph (*top*) and lateral fluoroscopy (*bottom*) showing level localization using a mini-open lateral approach for thoracic fusion

The endothoracic fascia and parietal pleura are then sharply divided to enter the thoracic cavity. The lung is then deflected anteriorly with the surgeon's finger as sequential dilators are placed under fluoroscopy over the targeted level (Fig. 20.5). Then a table-mounted retractor is placed over the dilators and proper placement is confirmed with fluoroscopy (Fig. 20.6).

For the retropleural approach (Fig. 20.7) [3, 4, 23], a 5–6 cm oblique incision is made directly over the rib that is

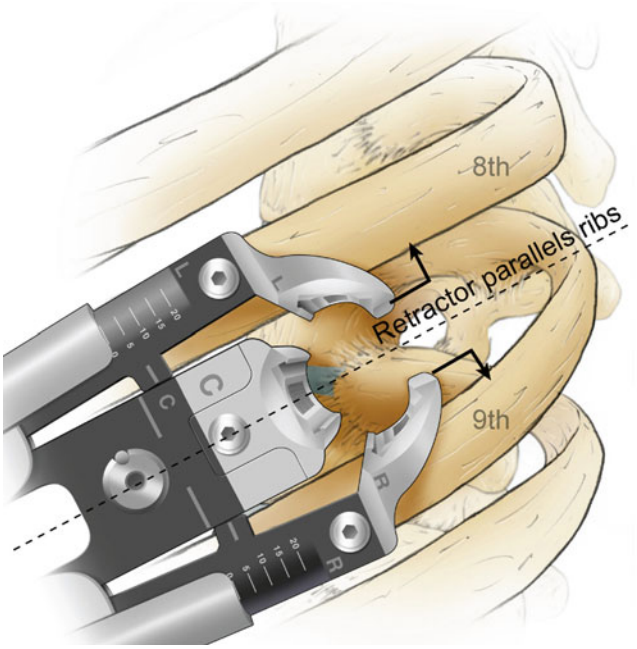

Fig. 20.3 Lateral illustration showing MaXcess® (NuVasive, Inc.) retractor placement between the ribs for a transthoracic mini-open lateral approach (Copyright NuVasive, Inc.; used with permission)

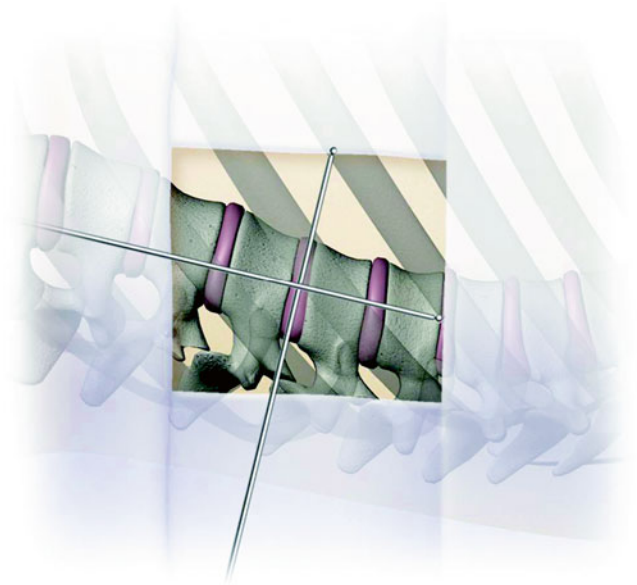

Fig. 20.4 Lateral illustration of level targeting in a mini-open lateral approach for thoracic fusion (Copyright NuVasive, Inc.; used with permission)

overlying the targeted pathology on lateral fluoroscopy. Monopolar cautery is used to dissect through the subcutaneous tissue, latissimus dorsi, and intercostal muscles. The periosteum of the rib is incised with the monopolar cautery along its exposed length. Using Alexander and Doyen periosteal elevators, the periosteum is elevated circumferentially off the rib. Special care is taken as to not injure the neurovascular bundle at the inferior edge of the rib or parietal pleura deep to the rib. A rib cutter is then used to excise approximately 6 cm of rib (Fig. 20.8). The cut edges are then waxed for hemostasis. Immediately underlying the rib, the endothoracic fascia, which fuses with the periosteum, is identified and sharply cut exposing the parietal pleura. The plane between the parietal pleura and endothoracic fascia is developed using the surgeon's finger, Kittner sponges, and sponge sticks (Fig. 20.9). The pleura is swept free in the cranial and caudal direction as well as anteriorly until the lateral surface of the vertebral bodies and disc spaces are visualized (Fig. 20.10). If the pleura is violated, primary repair with suture can be done. Then a table-mounted retractor is placed over the targeted level to maintain exposure (Fig. 20.7). Accurate placement is confirmed with intraoperative fluoroscopy.

Once accurate placement of the retractor has been confirmed and adequate exposure is achieved, the goals of surgery are accomplished in the traditional methods. For thoracic disc herniations, the head of the rib is then removed with either a rongeur or high-speed drill to expose the posterolateral portion of the disc (Fig. 20.11). One must then incise the disc space and perform a discectomy using a combination of curettes and pituitary rongeurs, being sure to remain anterior to the spinal canal. Working in a true 90° orientation to the disc space, perpendicular to the floor, will discourage posterior migration of procedural instrumentation. A discectomy is performed using standard techniques (Fig. 20.12). Next, using a high-speed drill, the posterior corners of the vertebral bodies adjacent to the disc and the superior portion of the lower pedicle are removed (wedge osteotomy) creating a small cavity directly in front of the thoracic herniation (Fig. 20.13). This maneuver will expose the spinal canal. The remainder of the disc in now removed away from the spinal cord and into the cavity created with down-pushing curettes and rongeurs (Fig. 20.14). The posterior longitudinal ligament must also be taken to ensure complete decompression of the spinal canal. The end plates of the adjacent vertebral bodies are prepared in the usual fashion, and an interbody cage with bone graft material of the surgeon's choosing is placed laterally along the width of the vertebral body (Fig. 20.15). Lateral plate or screw-rod fixation can be used for stabilization.

Thoracic corpectomies and fusions secondary to fractures, infections, and tumors can also be performed through this approach, though almost always requiring taking a small portion of rib at the incision site and using a slightly larger incision to allow for adequate working space for decompression and reconstruction with vertebral body replacement devices. Once accurate placement of the retrac-

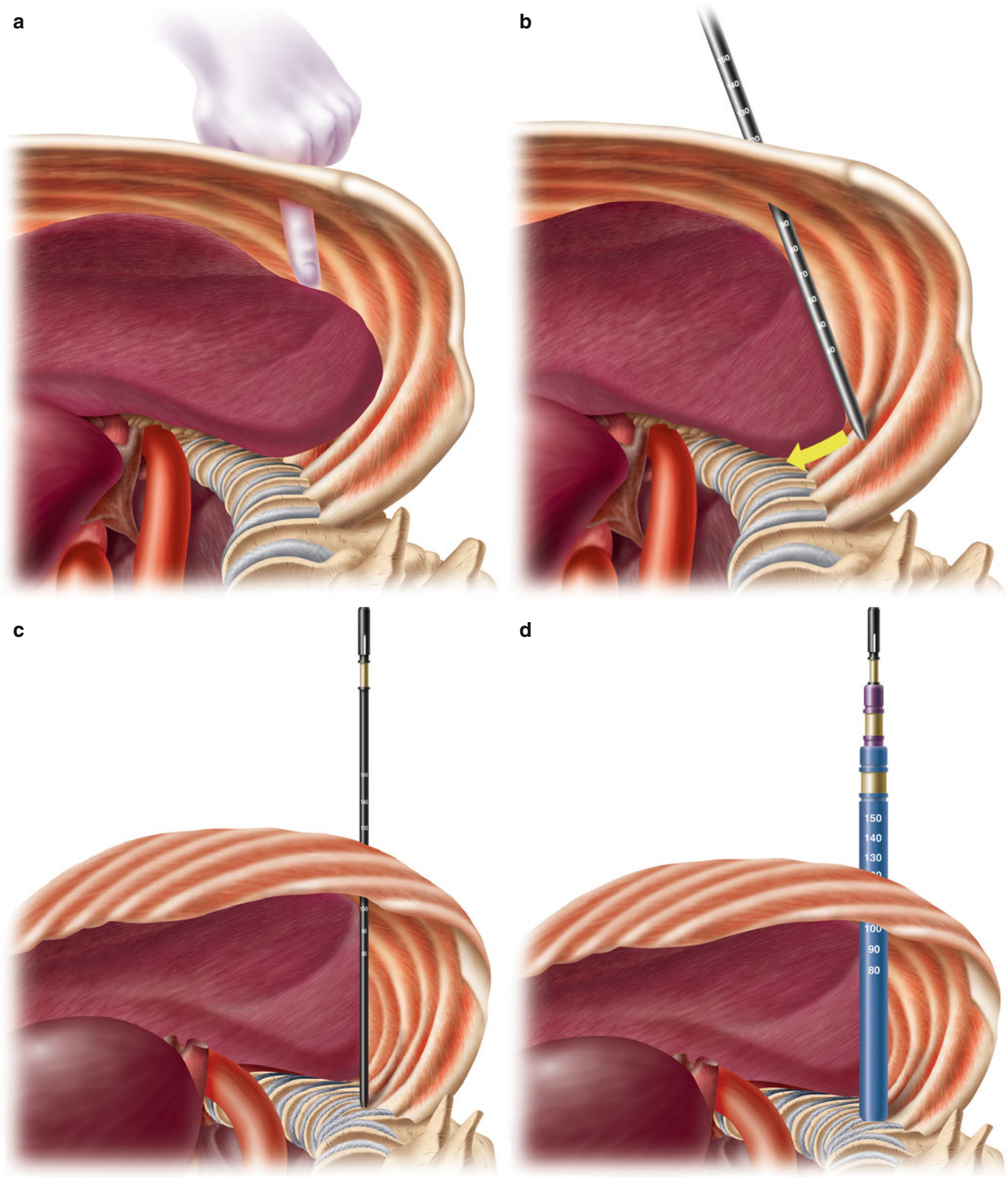

Fig. 20.5 Inferior illustrations showing digital approach (**a**) and lung deflection (**b**–**d**) using the approach instrumentation (dilators) in a mini-open lateral approach for thoracic fusion (Copyright NuVasive, Inc.; used with permission)

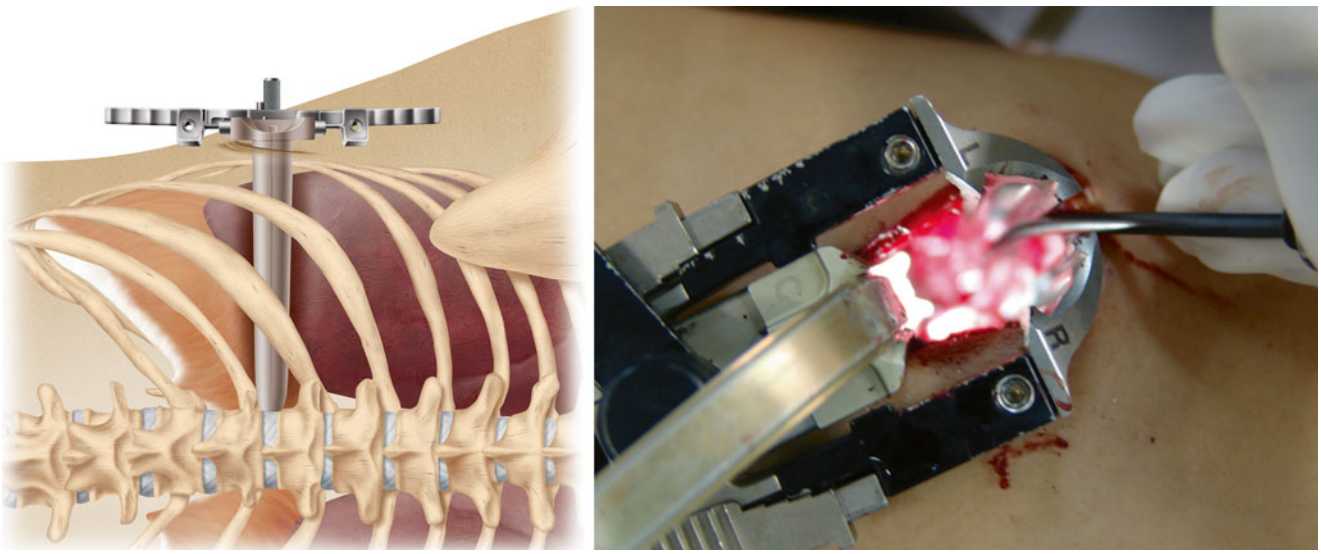

Fig. 20.6 Posterior illustration (*left*) and lateral intraoperative photograph (*right*) showing a docked MaXcess retractor in a mini-open lateral approach for thoracic fusion (Copyright NuVasive, Inc.; used with permission)

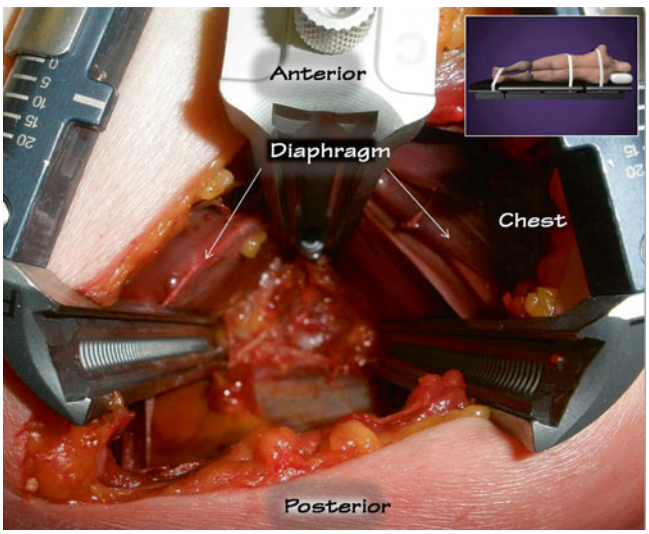

Fig. 20.7 Lateral photography showing MaXcess retractor placed in a retropleural approach

tor has been confirmed and adequate exposure is achieved (Fig. 20.16), the goals of surgery are accomplished in the traditional methods. For corpectomies, the segmental vessels that are crossing the index level must be coagulated and divided (Fig. 20.17). The disc spaces above and below the targeted vertebral body are incised and discectomies are performed using curettes and rongeurs. Then under fluoroscopic guidance, an osteotome is used to make an anterior and posterior cut line in the vertebral body creating a large defect.

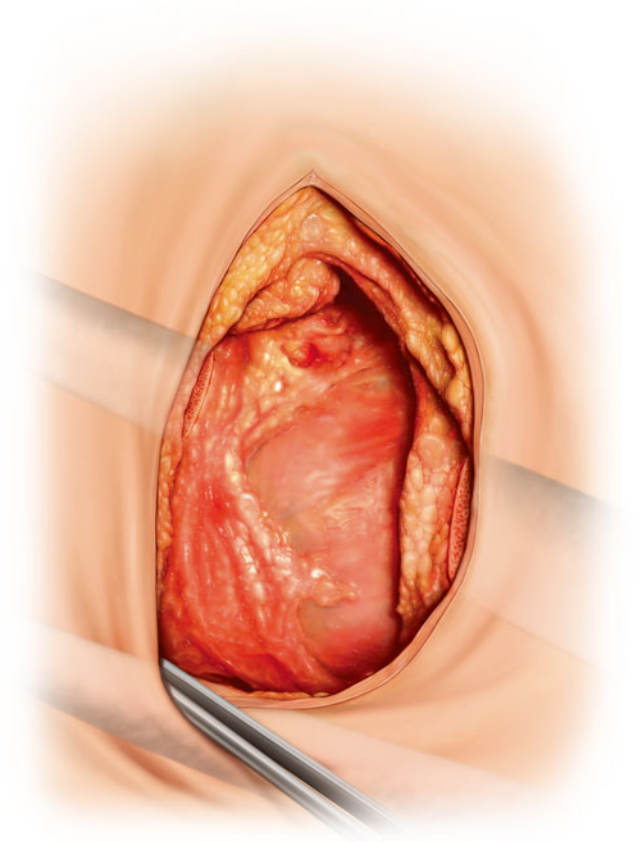

Fig. 20.8 Lateral illustration showing partial rib resectioning for retropleural approach in a mini-open lateral approach for thoracic fusion (Copyright NuVasive, Inc.; used with permission)

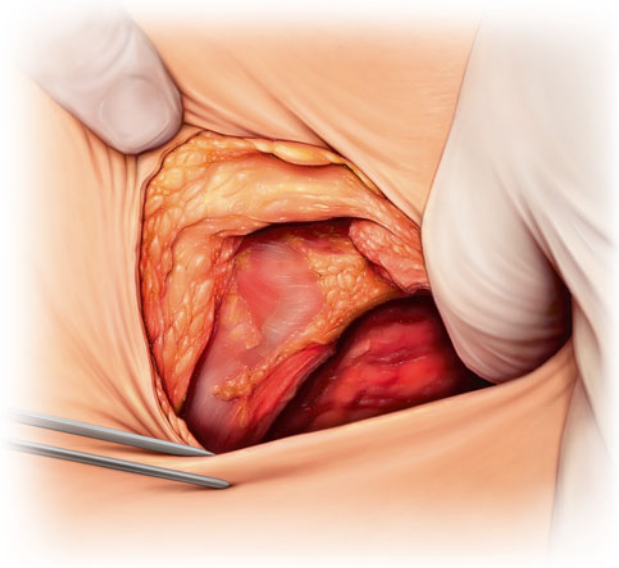

Fig. 20.9 Lateral illustration showing digital pleural deflection for a retropleural approach in a mini-open lateral approach for thoracic fusion (Copyright NuVasive, Inc.; used with permission)

Then using a high-speed drill and down-pushing curettes, the remaining posterior portion of the vertebral body is pushed into the created defect and away from the spinal cord. The posterior longitudinal ligament must also be resected to ensure complete decompression of the spinal canal. Once complete decompression is achieved, the end plates are prepared and a wide footprint cage is placed (Fig. 20.18). Anterior instrumentation can be placed through the retractor (Fig. 20.18).

If during these approaches the visceral pleura was violated or an air leak was identified, then a chest tube must be placed. If the approach was completely retropleural, then no chest tube is placed. If the parietal pleura was violated but no air leak was identified, then one may use the red rubber catheter Valsalva technique to expel all excess air out of the thoracic cavity. A red rubber catheter is placed in the thoracic cavity with a purse string suture placed around its exit hole and the exterior end of the tube submerged in water. A Valsalva is then performed and held until all air is expelled, noted with the discontinuation of bubbles. The red rubber catheter is then quickly removed and the purse string suture secured.

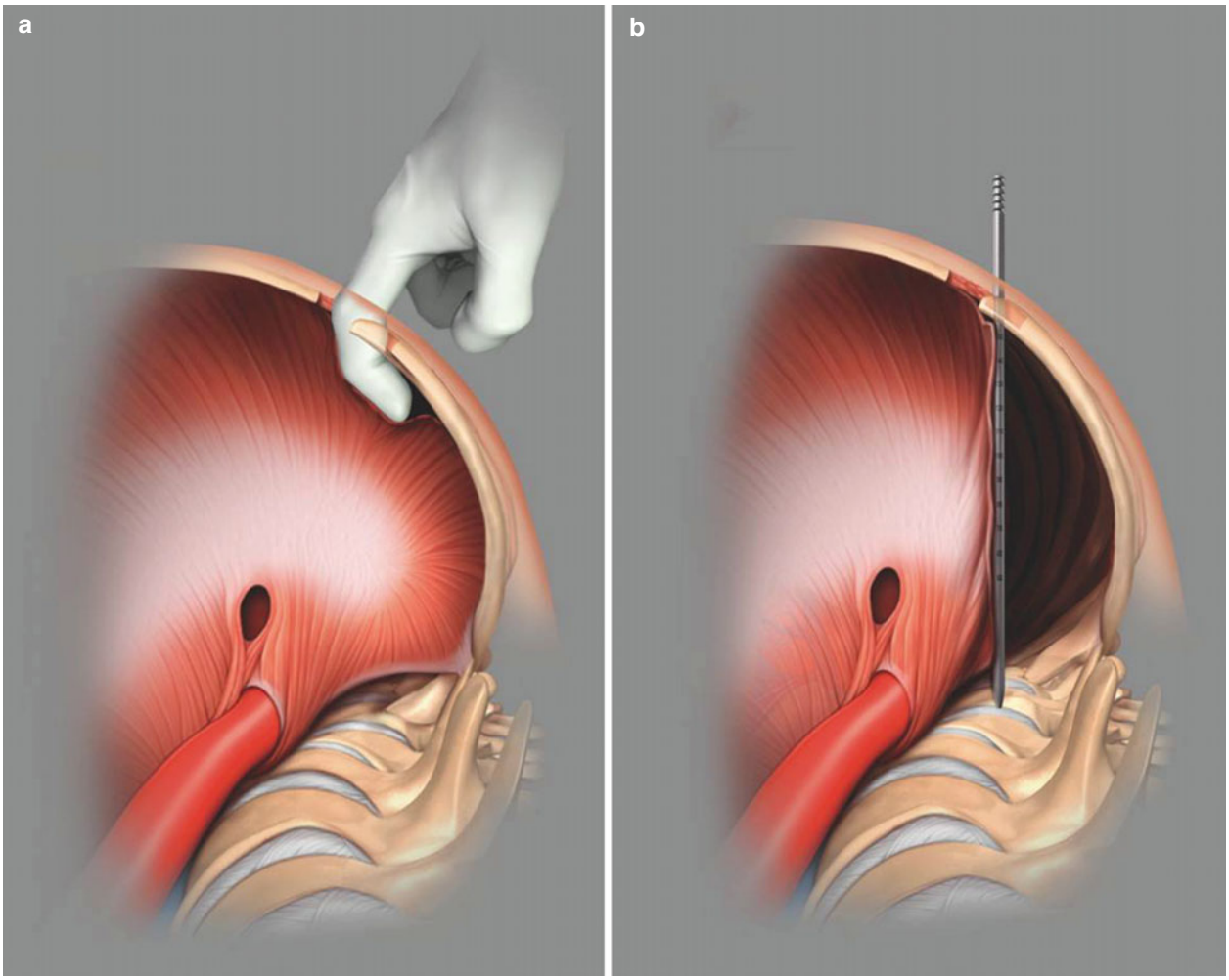

Fig. 20.10 Inferior illustration showing a retropleural digital approach (**a**) and with approach instrumentation (**b**) (Copyright NuVasive, Inc.; used with permission)

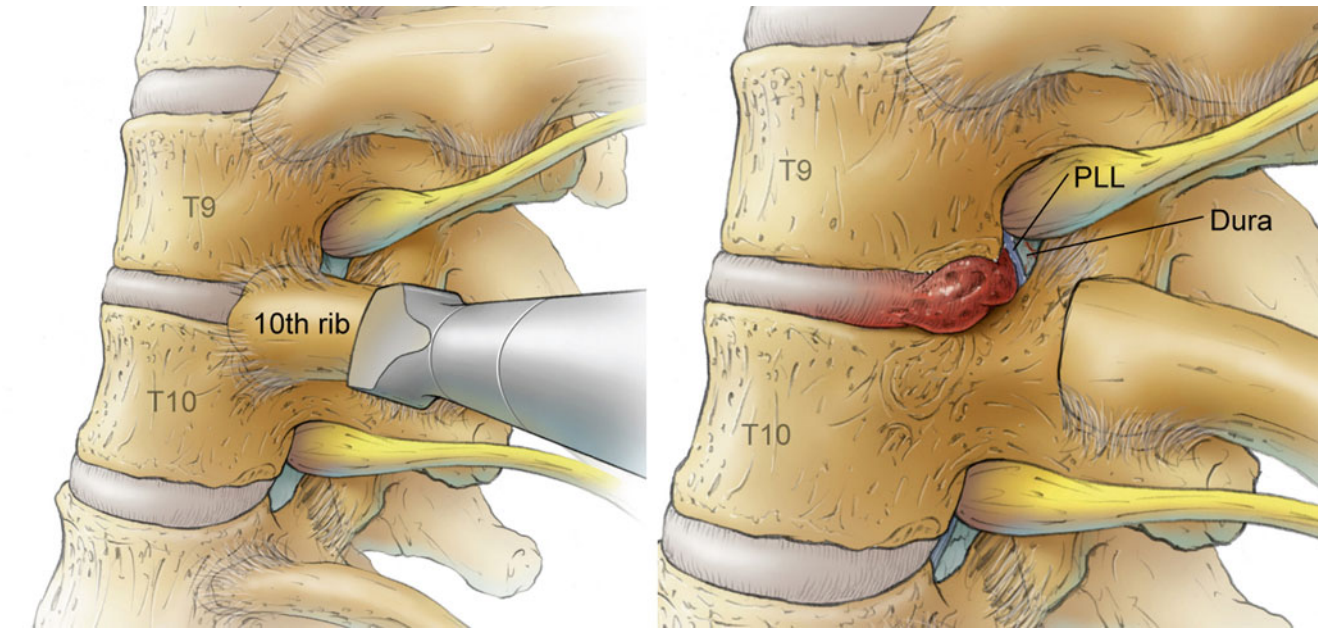

Fig. 20.11 Lateral illustration showing lateral exposure of the anterior spine (*left*) and rib head resectioning (*right*) in a mini-open lateral approach for thoracic fusion. *PLL* posterior longitudinal ligament (Copyright NuVasive, Inc.; used with permission)

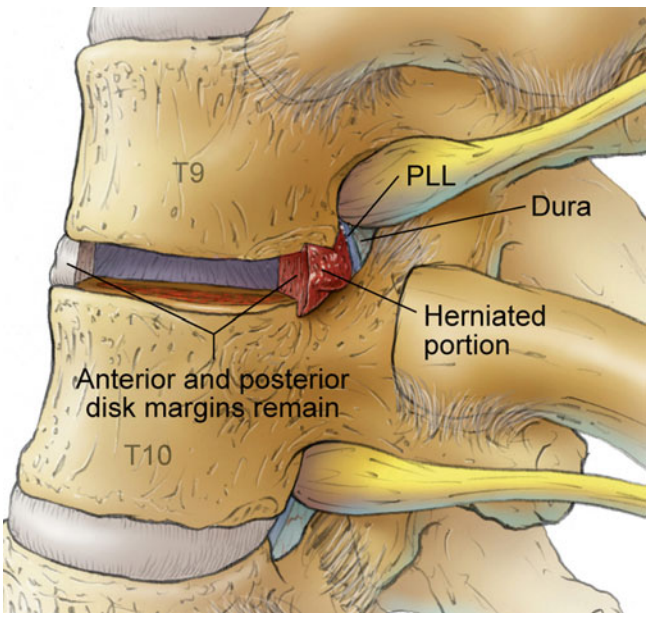

Fig. 20.12 Lateral illustration showing thoracic discectomy and thoracic herniated disc exposure in a mini-open lateral approach for thoracic fusion. *PLL* posterior longitudinal ligament (Copyright NuVasive, Inc.; used with permission)

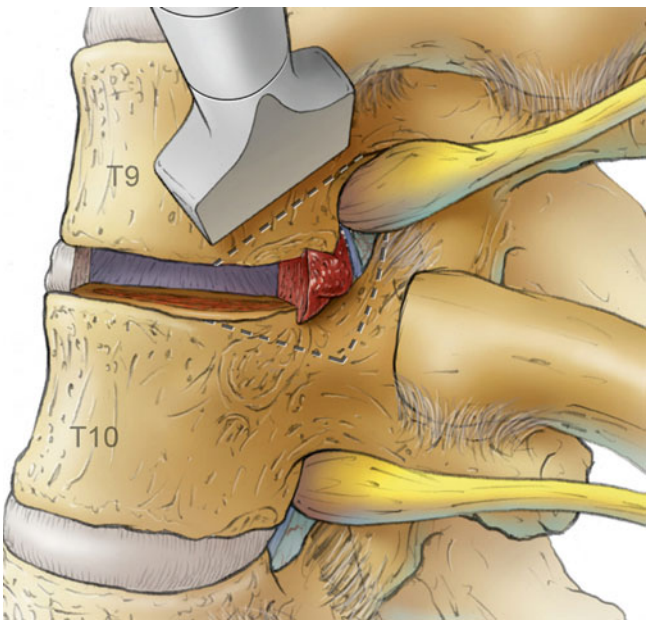

Fig. 20.13 Lateral illustration showing an example area for wedge osteotomy to fully expose a thoracic herniated disc in a mini-open lateral approach for thoracic fusion (Copyright NuVasive, Inc.; used with permission)

Pearls and Pitfalls

- Avoid wrong-level surgery by using intraoperative fluoroscopy and knowing the exact number of ribbed vertebrae and non-ribbed lumbar vertebrae. We recommend that localization be performed by counting caudally from C2 as well as cranially from the sacrum.
- Avoid neurologic injury when operating on a thoracic disc herniation or corpectomy by creating a small cavity for which to push the compressive elements into and away from the spinal cord.
- Throughout the procedure, confirm that the patient has remained in a true lateral position and has not rotated

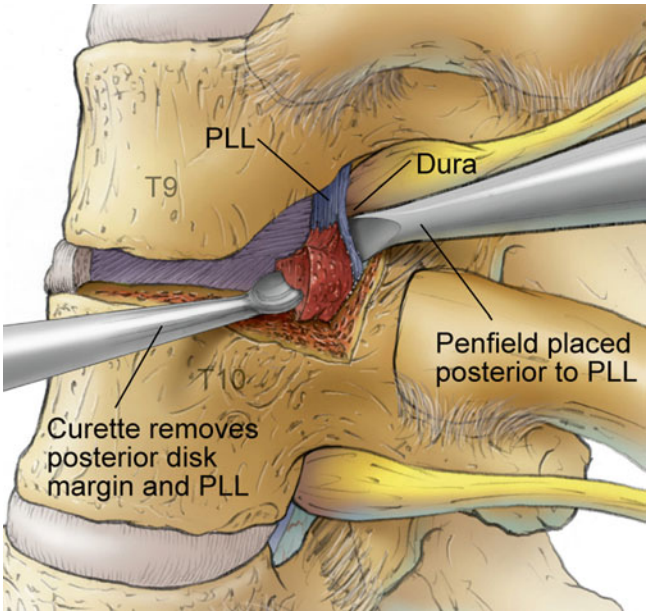

Fig. 20.14 Lateral illustration showing complete thoracic disc herniation following wedge osteotomy in a mini-open lateral approach for thoracic fusion. *PLL* posterior longitudinal ligament (Copyright NuVasive, Inc.; used with permission)

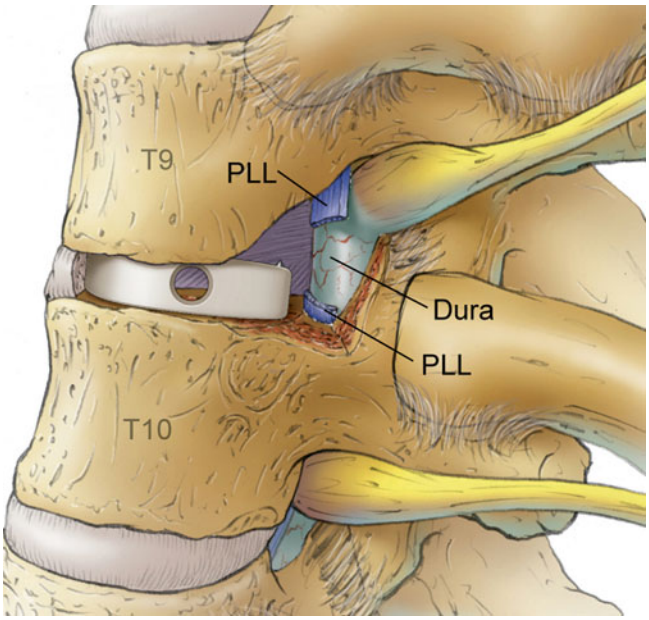

Fig. 20.15 Lateral illustration showing final thoracic herniated disc removal and spinal cord decompression with placement of a polyether ether ketone (PEEK) intervertebral cage in a mini-open lateral approach for thoracic fusion. *PLL* posterior longitudinal ligament (Copyright NuVasive, Inc.; used with permission)

anteriorly or posteriorly. This will avoid inadvertently migrating more anterior (to avoid vasculature) or posterior (to avoid the spinal cord) than intended.

- The posterior longitudinal ligament must be resected to ensure complete decompression of the neural elements.

Literature Review

Given that the 90° lateral approach to the lumbar spine was first introduced in the literature in only 2006 [24], reports of more advanced applications have only very recently been published. Despite the relatively brief published history of the transthoracic and retropleural mini-open lateral approaches to the thoracic spine, early reports show generally favorable complication and outcome results when compared both with conventional open approaches as well as alternative less-invasive approaches.

Deverin et al. [2] reported a series of 12 single-level thoracic disc herniations treated with a transthoracic mini-open lateral approach with 28-month follow-up. In this, OR time averaged 210 min with EBL of 440 mL per case. Only one patient was admitted to the intensive care unit (ICU) postoperatively, whereas all others were transferred directly to the surgical floor. Average hospital stay (LOS) was 5 days. Two complications occurred: one pleural effusion and one instance of intercostal neuralgia. Preoperative pain (visual analog scale, VAS) improved 67 % from preoperative to last follow-up, from an average of 9–3. Quality of life (QOL; SF-36 physical and mental component scores (PCS & MCS, respectively) was measured, and PCS improved from 26.7 to 33.7 from pre- to last follow-up with MCS improving from 37.1 to 47.8 over the same visits. Of the eight patients that presented with progressive myelopathy (leg weakness, gait disturbance, sphincter dysfunction), all had improvement postoperatively. Of the ten patients who completed a postoperative satisfaction questionnaire, 80 % were satisfied with their outcome [2].

Karikari et al. in 2011 [25] published a series of 22 patients treated with a mini-open lateral approach for isolated thoracolumbar spinal disease. Of the 22 patients studied, 3 (14 %) were treated for thoracic disc herniations. In these cases, EBL, ICU length of stay, and LOS were 67 mL, 0.3 days, and 3.7 days, respectively. No patients experienced any peri- or postoperative complication, and through an average of 17 months follow-up, all patients demonstrated solid radiographic fusion [25]. Back pain (VAS) improved 46 %, from an average of 8.3 preoperative improving to 4.5 at last follow-up, with similar improvements observed in disability (Oswestry disability index, ODI), from an average of 54 preoperative to 31.3 at last follow-up (42 % improvement). All thoracic disc patients met the criteria for substantial clinical benefit (SCB) [26] on either VAS or ODI.

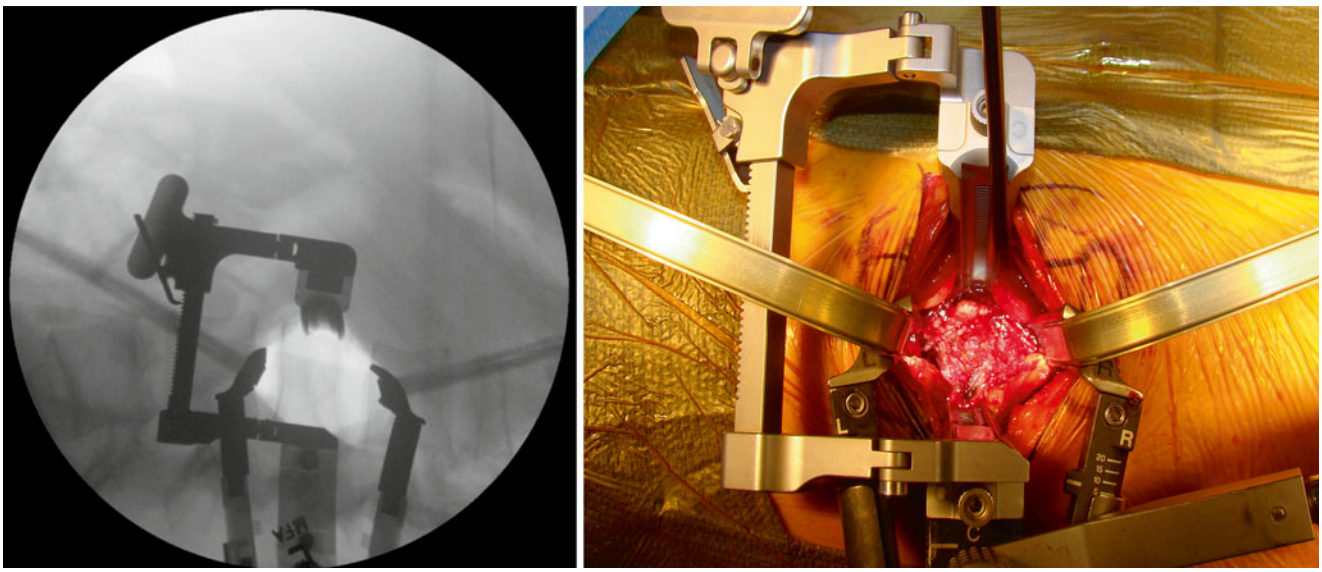

Fig. 20.16 Lateral fluoroscopy (*left*) and intraoperative photograph (*right*) showing placement of the MaXcess retractor with optional anterior retractor blade, exposing for corpectomy in a mini-open lateral approach

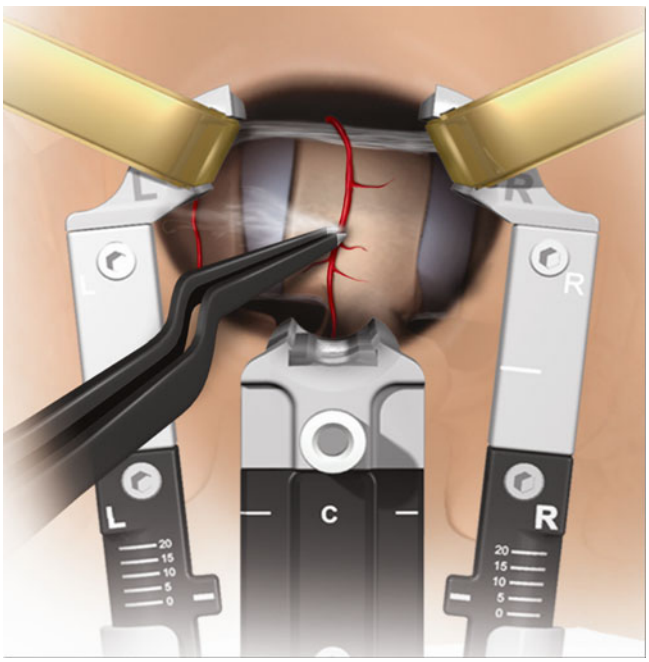

Fig. 20.17 Lateral illustration showing ligation of segmental vessel in corpectomy using a mini-open lateral approach (Copyright NuVasive, Inc.; used with permission)

In a report from a multicenter study, Uribe et al. [4] described outcomes following XLIF for thoracic disc herniation in 60 consecutive patients treated at one of five international institutions with an average follow-up of 11 months. Myelopathy was present in 70 %, radiculopathy in 52 %, axial back pain in 77 %, and bowel and/or bladder dysfunction in 27 % of cases. All but 6 (10 %) cases were treated with an interbody spacer. Supplemental internal fixation included anterolateral plating (33 %), pedicle screws (10 %) with no supplemental fixation used in 57 %. Transpleural approaches were used in 75 % and retropleural approaches in 25 % of cases. Median OR time, EBL, and LOS were 182 min, 290 mL, and 5 days, respectively. Chest tubes were avoided in 13 patients (retropleural approaches). Four (6.7 %) major complications occurred in total: one patient experienced pneumonia, one patient required postoperative chest tube placement for retropleural free air, one patient experienced new lower extremity weakness, and one wound infection occurred in a posterior incision. Three (5 %) reoperations occurred, one for posterior wound infection, one for removal of symptomatic residual disc, and one for posterior re-exploration. Pain (VAS) improved 60 % from preoperative to last follow-up (7.8–3.1); an excellent or good overall outcome was achieved in 80 % of cases, with fair or unchanged outcome in 15 % and a poor outcome in 5 % of cases. Myelopathy was improved in 83 %, radiculopathy in 87 %, back pain in 91 %, and bladder and/or bowel dysfunction in 88 % of cases. In a review of the literature, the authors found the approach to have similar or superior outcomes to historical controls, even when comparing the approach against other modern minimally disruptive approaches for treating thoracic disc herniations [4].

Multiple reports have described the mini-open lateral approach in the treatment of thoracic trauma and tumor [21, 22, 27, 28]. These reports have shown, similar to the thoracic disc literature, generally favorable results with attenuated

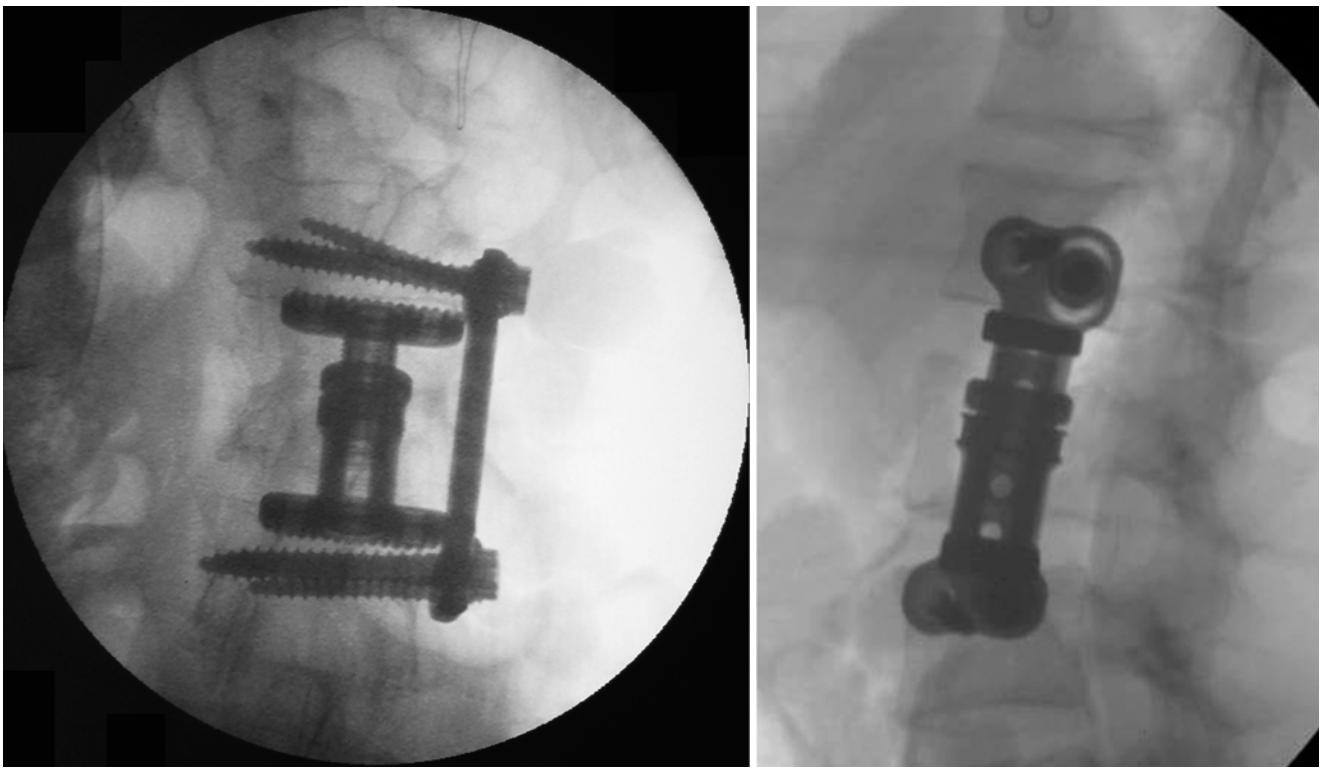

Fig. 20.18 Anterior (*left*) and lateral (*right*) postoperative fluoroscopy showing placement of a wide footprint expandable vertebral body replacement device (XCore®, NuVasive, Inc.) for corpectomy using a mini-open lateral approach

treatment variables (ORT, EBL, LOS) with low complication profile and similar or improved long-term outcomes compared to conventional open surgical approaches and the majority of minimally invasive approaches for this challenging pathology.

Avoiding and Treating Surgical Complications

Knowledge of the local anatomy, careful surgical technique, magnification, and adequate lighting will avoid most surgical complications. Working perpendicular to the floor with the patient in a true lateral position will ensure avoiding the great vessels anteriorly and the spinal canal posteriorly. If a segmental vessel is injured, it should be coagulated and divided. If the great vessels are injured, although exceedingly rare, they need to be primarily repaired. If a cerebrospinal fluid leak is encountered, primary repair is difficult. In these instances, the authors recommend placement of a fat graft with synthetic fibrin glue and a lumbar drain. If a chest tube is also required, it must be removed prior to the lumbar drain. In the event that a postoperative pneumothorax is identified, then a chest tube is placed.

Postoperative Care

Perioperative antibiotics are used until all drains/tubes are removed. Intercostal nerve blocks are used for improved postoperative pain control and decreasing the chances for respiratory splinting. Patients are mobilized as soon as possible to prevent thromboembolic complications. Chest radiographs are taken immediately after surgery and on postoperative day 1 to ensure no pneumothorax.

Conclusions

The treatment of thoracic pathology with a mini-open lateral approach is a viable alternative to both conventional open approaches for the surgical treatment of thoracic pathology but also represents a middle ground between those conventional approaches and thoracoscopy. Early results are promising and should be considered during the course of clinical decision-making for these challenging pathologies.

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Thoracoscopic Fusion

21

Peter Grunert and Roger Härtl

Introduction

The first thoracoscopic procedures were introduced by Jacobeus in the 1920s to perform intrapleural pneumolysis for the treatment of pulmonary tuberculosis [1, 2]. The evolution of modern thoracoscopic spinal procedures began in the 1990s after video-assisted endoscope systems were introduced [3]. Since then, operative and visualization instruments have constantly improved and helped to expand our surgical possibilities.

Anterior approaches to the thoracic spine have the advantage of direct access and visualization of anterior vertebral lesion. Vertebral body reconstruction is more feasible as the spinal cord can be avoided for the implantation of interbody construct. An anterior approach with stabilization may replace posterior surgery or may allow for the use of shorter segment fixation from the back.

Open transthoracic procedures are still more widely performed then thoracoscopic operations despite significant morbidity including intercostal neuralgia and postthoracotomy syndrome [4]. This is likely due to the technical challenges and the significant learning curve associated with thoracoscopic procedures. Several conditions such as extensive pleural adhesions or other intraoperative complications may require conversion to an open approach. Therefore, the surgeon must master both techniques.

As an alternative to pure open or pure thoracoscopic procedures, a tubular "mini-open" approach has recently been described for thoracic disc herniations and other pathologies [5] and will be described in detail in another chapter. Some authors have combined tubular and thoracoscopic access strategies to improve orientation and visualization during surgery in the thoracic cavity [6].

While the purely thoracoscopic approach is associated with a significant learning curve, we believe that it presents a truly minimally invasive option for achieving certain surgical goals, especially when it comes to the implant delivery and fusion.

Indications and Contraindications

The indications for thoracoscopic fusion procedures include:

- Anterior column fractures of the thoracic spine with and without spinal cord compression
- Posttraumatic deformity of healed fractures with or without instability
- Infections of the anterior column
- Primary or metastatic anterior column tumor
- Thoracic disc herniation
- Scoliosis correction

Contraindications to an anterior transthoracic approach include:

- Significant preoperative cardiopulmonary disease prohibiting single-lung ventilation
- Significant homeostatic disorder
- Extensive pleural adhesions
- Acute posttraumatic lung failure
- Previous chest surgery

Instruments and Implants

High-resolution rigid endoscopes are used with a wide diameter for a broad field of view. Endoscope tips should have a 0º angle if placed directly over the target lesion or a 30º angle if placed caudal or cranial to the target. The latter is generally preferred as it causes less interference with the working tools.

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Fig. 21.1 MACS-TL© plating system. The blue polyaxial screw is connected to a clamping element through which the yellow stabilization screw is inserted. A plate connects both clamping elements (Copyright Aesculap Implant Systems, LLC; used with permission)

The thoracic cavity is accessed through flexible portals, which facilitate the insertion of the endoscope and operative tools. Flexible portals have the advantage of minimizing the pressure on intercostal nerves, thus lowering the incidence of intercostal neuralgia. A trocar can help to tunnel the portal through the chest wall [3]. Soft tissue dissection tools such as a pleural dissector, lung forceps, or a fan retractor are necessary to mobilize the lung for the transthoracic approach [3]. Instruments for spinal dissection are very similar to the ones used in open procedures with an adapted length to overcome the long working channel of 14–30 cm. They include rib dissectors, Kerrison rongeurs, disc rongeurs, curettes osteotomes, bone graft impactors, Penfield instruments, and microsurgical spinal cord and dural dissection tools. High-speed drills are used for bone dissection [22]. We prefer the diamond tip in the thoracic spine to reduce the chance of vascular injury.

Several implants have been designed specifically for thoracoscopic procedures. They require a low profile for anterolateral placement and need to be insertable through a small approach. Cannulated screws are advantageous as they can be guided by K-wires into the vertebral bodies [7].

In the lower thoracic spine and the thoracolumbar junction, double-screw plating systems are predominately used for single- or two-level fusions after corpectomy or discectomy. Most are angle-stable, four-point fixation devices with two screws inserted into each vertebral body (Fig. 21.1). As the anteroposterior diameter of the vertebral bodies narrows caudocranially, two-screw fixation systems become less appropriate for cranial segments. Single-bolt plating systems [8] (Fig. 21.2) are thus more applicable for fusion procedures in middle or upper thoracic segments.

Fig. 21.2 Vantage© system. Bolt at *top* of the figure, plate and locking nuts at the *bottom* (Images provided by Medtronic, Inc.; used with permission)

Biomechanical studies showed that plate/bolt constructs are stiffer, in terms of flexion and axial rotation, than plate/screw or dual-rod constructs after two-level corpectomies [9]. In addition, single-bolt systems make two-level fusions more technically feasible when compared with double-screw constructs. The range of possible screw trajectories is limited by the relative positions of the insertion site on the vertebra and the portal on the skin. Thus, placing a single large bolt into the vertebral body is easier than placing two smaller screws at separate angles [9].

Several cages for anterior column reconstruction are available. Expandable titanium cages are feasible for thoracoscopic procedures as they can be inserted when collapsed to fit through a small skin opening. The possibility of expanding and collapsing the cage in situ makes optimal placement easier and eases kyphosis correction in fractures compared to non-expandable cages [10, 11].

For bone autograft, tricortical iliac crest is still widely used for reconstruction purposes despite donor site morbidity. In terms of fusion rates, subsidence, or implant failure, no consensus exists regarding the superiority of cages compared to bone autograft or allograft [12–14].

Anesthesia

All procedures are performed under general anesthesia. Patients have to be intubated with a double-lumen endotracheal tube in order to perform single-lung ventilation [11].

After blocking the airway on the approach side, the lung becomes atelectatic, which facilitates intraoperative mobilization and retraction.

Patient Positioning

The patient is placed in a lateral decubitus position with the hips taped to the operating table. In addition, there is four-point support at the scapula, symphysis, and sacrum. Securing the patient facilitates intraoperative tilting of the operating table, which increases surgical exposure by gravity, thus reducing the need to retract soft tissue mechanically [19].

A left-sided approach is generally recommended to avoid the liver as well as the inferior vena cava. The disadvantage of a left-sided approach is that it often requires further mobilization of the aorta depending on the procedure. Other factors related to the patient-specific anatomy or pathology may override these concerns; for example, if a calcified thoracic disc herniation presents towards one specific side, an ipsilateral may be safer and more efficient. Approaches to the upper thoracic spine (T1–T5) require abduction of the upper arm in order to place portals in the corresponding intercostal spaces [19].

After the patient is positioned, the operative level should be identified and marked using fluoroscopy. Correct identification of the lesion and projection of the disc interspace or vertebral body of interest onto the skin using skin markers is of the greatest importance and requires intraoperative fluoroscopy. We use a preoperative CT that should include the lower portion of the cervical spine and/or the first two lumbar levels in addition to the pathology. We then count either from the first rib down or from the lowest rib cranially.

Portal Positioning

Most thoracoscopic fusion procedures require three to four portals, each serving an individual function. Spinal dissection tools, drills, and instrumentation devices are inserted through the working portal (12.5 mm) and the endoscope through a viewing portal (10 mm). Additionally there is a suction/irrigation (5 mm) and retractor portal (10 mm) [10, 11, 15, 16].

Positioning of the portals is a critical operative step as it determines the trajectory of working tools and implantation devices. The most commonly used configuration places the working portal directly over the lesion with the endoscope positioned on the same axis two to three intercostal spaces away cranially (lower thoracic spine) or caudally (middle or upper thoracic spine). Suction/irrigation and retractor portals are positioned ventral to the working portal. This setup prevents interference of the endoscope with dissection tools and allows direct vision of the target. The disadvantage of this configuration lies in the fact that the working portal is not directly aligned coaxially to the trajectory of the fixation screws. Because of this perceived inadequacy, Dickmann described a configuration which places four portals over the intended screw trajectories [18].

As a general principle, to prevent brachial plexus and vessel injuries (Fig. 21.3), the portals should not be inserted through the axillary space in the upper thoracic spine (T1–T5). The first and second intercostal spaces should be spared as well to avoid the subclavian vessels.

In the lower thoracic spine (T9–L1), diaphragm incision may be necessary for spine exposure. Fusion procedures on T12–T1 require portal insertion in the retroperitoneal space [18].

The endoscopic portal is to be inserted first. An approximately 1.5 cm skin incision is placed parallel to the intended intercostal space. Blunt dissection follows through the intercostal muscles and the parietal pleura into the thoracic cavity. After the endoscopic portal is inserted, the remaining portals follow under endoscopic visualization.

Spinal Exposure

Mobilization and cautious retraction of the lung exposes the parietal pleura covering the vertebral bodies.

After verifying the correct level by fluoroscopy and internal rib count, the parietal pleura has to be incised. The primary incision should be placed over the rib heads in order to avoid the segmental vessels, which run along the midportion of the vertebral body. Thereafter, the pleura must be carefully mobilized over all vertebral bodies intended to be fused, as well as over the corresponding rib heads (Fig. 21.4). This follows ligation and transection of the segmental vessels. In cases when extended mobilization of the aorta is necessary, additional segmental vessels from adjacent segments have to be ligated and divided.

In order to expose the pedicle and the lateral surface of the vertebral body, the rib heads along with up to 2 cm of the proximal rib need to be resected. This is accomplished by disarticulating the costovertebral joint and transecting the rib with either a drill or an oscillating saw. Prior to resection, the neurovascular bundle has to be detached from the caudal rib margin.

The spinal canal is accessed by resection of the pedicle with a Kerrison rongeur from caudal to cranial. The pedicle can be thinned out with the drill first. This allows for visualization of the dura and the posterior edge of the vertebral body, which is crucial for avoiding spinal cord injury in endoscopic decompression and fusion procedures [20].

In order to approach the thoracolumbar junction, the diaphragm, which inserts at the first lumbar vertebra, has to be incised. The incision should be placed parallel to the

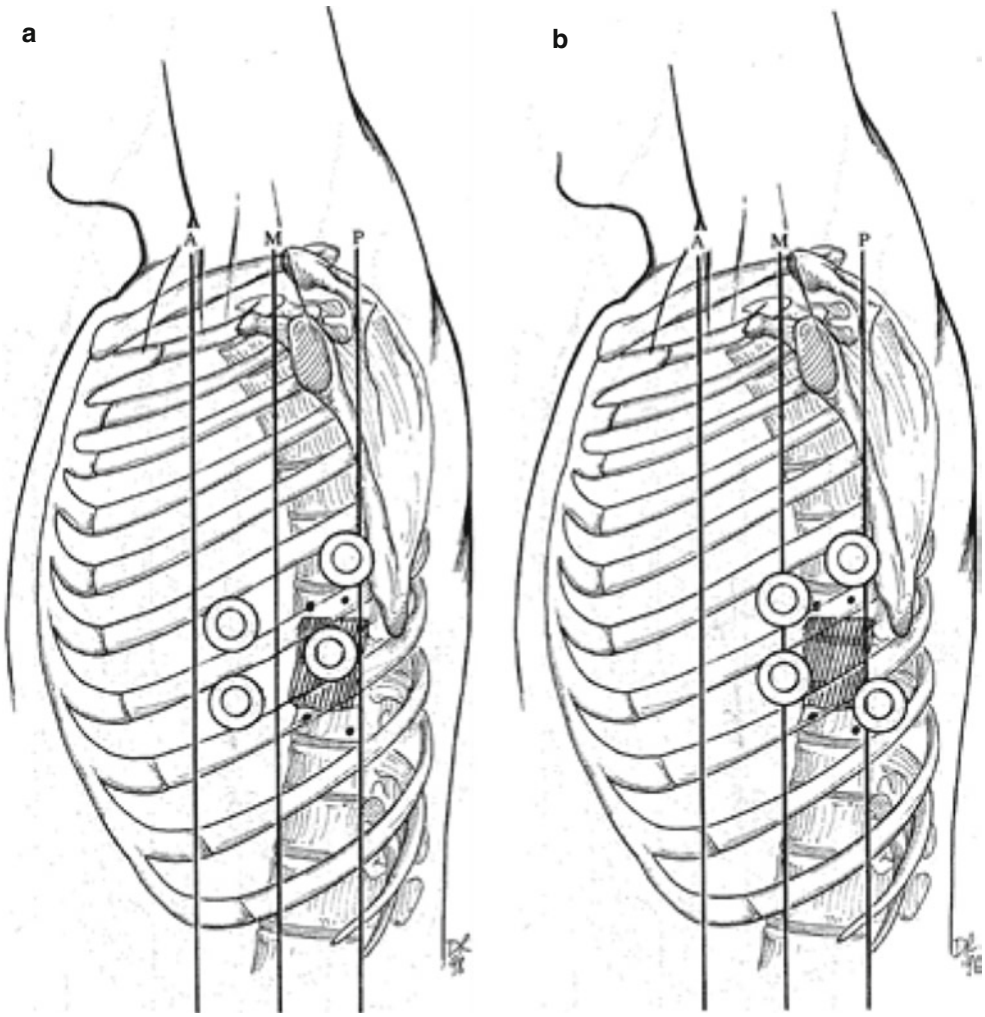

Fig. 21.3 (**a**) Displays the most widely used portal configuration with the working portal placed over the target area (hatched vertebra). The endoscope portal is placed proximally, the suction and irrigation portals ventrally (in between the anterior and medial axillary line) to the working portal. (**b**) Displays a portal configuration described by Dickman [18] with all portals aligned along the intended trajectory of the screws (*black dots* on vertebrae)

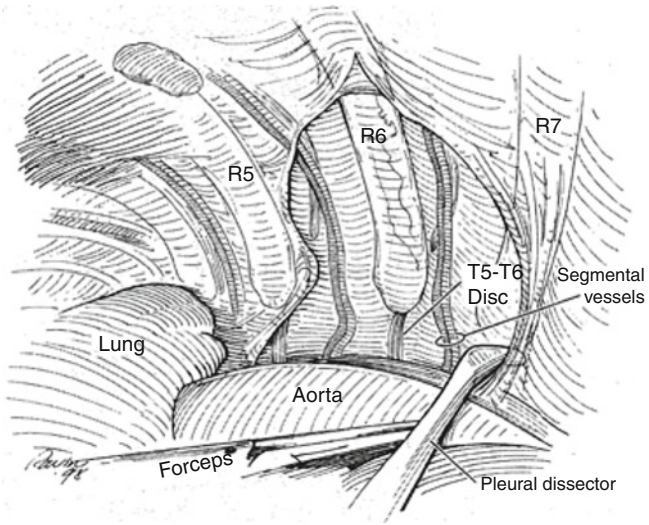

Fig. 21.4 Spinal exposure of the 6th and 7th thoracic segment. The parietal pleura is mobilized over both involved ribs. The segmental vessels have to be prepared

diaphragm attachment to spare muscle fibers, which prevents postoperative herniation. In the retroperitoneal space, the insertion of the psoas muscle has to be prepared and mobilized posteriorly to expose the lateral surface of the vertebral body.

Fusion Techniques

Discectomy and Fusion

To perform a discectomy the patient is placed in the aforementioned decubitus position, with the working portal inserted over the target segment. Thoracic discectomies down to T8 usually do not require instrumentation unless a large portion of the vertebral body is resected. Based on anecdotal evidence, below T8 we prefer to perform an interbody fusion with instrumentation. The thecal sac and the disc herniation are approached as described above. Prior to disc extraction the posterior polyaxial screws attached to the clamping element are implanted into the cranial and caudal vertebral body of the involved segment. They serve as a landmark throughout the procedure and facilitate distraction of the segment during discectomy or implantation of an

interbody construct. After the vertebral body and the spinal canal have been exposed, K-wires connected to an impactor are placed on both vertebral bodies approximately 10 mm ventral to the posterior edge and 10 mm from the distal end plate [16]. K-wires are then advanced into the vertebral body under fluoroscopic control. Strict parallel alignment to the posterior border of the vertebral body is mandatory to avoid perforation of the spinal canal. After decortication with a cannulated punch, the posterior polyaxial screw-clamp assembly is inserted, guided by K-wires under fluoroscopic control. The screws have to be aligned parallel to the end plate and the posterior border of the vertebral body. K-wires are removed after the screw has been engaged [16].

In the next step, the intervertebral disc is incised and disc material extracted with disc rongeurs. In many cases a partial corpectomy above and below the disc space may be necessary to avoid manipulation of the spinal cord during removal of disc fragments.

The proximal rib harvested during the approach is used as an interbody construct. The autograft has to be tailored to fit into the disc space, and a recess to anchor the cage needs to be drilled into both vertebral bodies to prevent migration [21]. Prior to implantation the segment can be slightly distracted to ease implantation and to facilitate graft compression.

After the distance has been measured between both screw heads, a matched size stabilization plate is inserted and fixed to the polyaxial heads with fixation nuts. Now the anterior stabilization screw is attached to the clamp and screwed into the vertebral body. The anterior screw should be 5 mm shorter than the posterior screw to prevent contact. Finally, the polyaxial mechanism is locked with locking screws, which are tightened with a torque wrench.

After dissection and instrumentation is completed, the operative field is irrigated with antibiotic solution and inspected. Loose bone or disc fragments have to be removed. Epidural hemostasis should be carried out with bipolar cauterization or topical hemostatic agents. Portals are removed and the incision sites are inspected for bleeding. In the next step, chest tubes are inserted through the portal incisions under endoscopic vision and secured to the chest with purse-string sutures. An apical chest tube is used to expand the lung by creating a pressure gradient. Inferior and posterior chest tubes are used to drain fluid from the thoracic cavity. Finally, the endoscope is removed, and the remaining portal incisions are closed with subcutaneous sutures [21].

Corpectomy and Fusion

As described above the patient is positioned in a true lateral decubitus position. The working portal is placed over the target vertebral body. If double-screw systems are used, placement of working portals aligned to the screw trajectory can also be considered.

This section will describe the application of a lateral plate for instrumentation along with an expandable cage for reconstruction.

Spinal exposure is performed as described above. At the corpectomy level, the rib head along with the proximal rib and the pedicle have to be resected. Rib bone is saved as grafting material; resection of the pedicle enables visualization of the spinal canal and lateral dura.

After removal of the proximal and distal IVD with disc rongeurs and preparation of the end plates, a large cavity is drilled into the center of the vertebral body. Subtotal resection follows, preserving the anterior and contralateral walls. The posterior cortex and posterior ligament are then resected into the cavity, which now enables removal of an epidural mass [22]. Alternatively, osteotomes can be used to start the corpectomy bone removal.

Prior to instrumentation, a rectangular graft bed has to be prepared by thoroughly removing all disc material and cartilaginous end plates. The bone surfaces must be flush and parallel to the surface of the cage.

Under fluoroscopic control, a K-wire is inserted in the intended bolt entry point of the proximal and distal vertebra. The ideal bolt position is the center of the lateral surface on the vertebral body, aligned parallel to the end plates and the anterior wall of the spinal canal. After decorticating the entry point with a cannulated punch, bolts are inserted over the K-wires and screwed into the vertebral bodies under fluoroscopic control until bicortical fixation is achieved. Length of the bolts should be calculated preoperatively on CT or MRI.

In the next step, the expandable cage has to be implanted. The height of the corpectomy site is measured using a parallel distractor. A scale on the handle of the distractor indicates the height of the implant in its neutral position. In addition, the proper cage end plate size and angulation, which depend on the level of implantation, have to be chosen.

The bone cups of the selected cage are now filled with bone graft. Thereafter, the cage is grasped with an implant holder, inserted into the defect, and positioned in the center of the vertebral end plate. The parallel distractor is now used to expand the cage until sufficient compression is achieved to prevent migration. If present, kyphotic deformity can be corrected by cage expansion under fluoroscopic control. The implant can always be collapsed to its neutral height for repositioning and explantation. In order to enhance the fusion process, bone graft is packed in and around the cage.

In the next step, a matched sized plate is inserted over the bolts; the curve of the plate should match the natural thoracic kyphotic curvature. The nuts are inserted with the smooth surface positioned against the plate. Finally, a limiting torque wrench driver is used for tightening.

Hemostasis, portal removal, chest tube insertion, and wound closure should be carried out as described in the discectomy section.

Complications

In general, the complication rate of thoracoscopic procedures is relatively low. Yet every step of the operation has potential risks.

Intraoperative pulmonary or anesthesia-related complication can derive from incorrect tube placement, potentially leading to insufficient gas transport. Single-lung ventilation generally induces a ventilation-perfusion mismatch, which can lead to arterial desaturation as well as to inefficient CO_2 clearance with subsequent acidemia. For this reason, detailed preoperative pulmonary examination is mandatory to rule out high-risk patients. Correct positioning of the tracheal tube has to be verified bronchoscopically [17]. Continuous blood gas analysis needs to be obtained to monitor oxidation and pH status during the procedure.

Pneumothorax and atelectasis are the most common postoperative pulmonary-related complications. Persistent pneumothorax can be due to an air leak caused by a lung defect. Continuous suction through chest tubes should be applied primarily for treatment. If ineffective, reoperation may be necessary to staple the lung defect. Atelectasis is caused by nonventilation of the ipsilateral lung with subsequent accumulation of secretions in the airway. Periodic intraoperative lung reinflation and postoperative intermittent positive air pressure ventilation minimize the risk [17].

Intraoperative vascular complications require immediate response as severe bleeding can quickly impair endoscopic visualization, making it difficult to maintain orientation in the surgical field. Bleeding of segmental vessels often occurs due to inadequate exposure during the approach and should be treated with coagulation or clipping.

Injuries of large intrathoracic vessels like the aorta, venae cavae, or azygos vein are potentially life-threatening complications and require conversion to an open approach to facilitate repair [16]. By confining the operative field using visual landmarks, laceration of the aforementioned vessels can be prevented. Preoperative endovascular embolization should be attempted in order to minimize bleeding during resection of highly vascularized tumors.

Insertion of instruments should always be carried out under visual control. Instruments are to be maneuvered strictly with two hands and should be additionally stabilized against the chest wall to avoid uncontrolled movements [16].

Puncturing of the dura leads to CSF leaks. Although technically challenging, it is recommended to suture the defect to be watertight even if this necessitates conversion to an open procedure. The negative intrathoracic pressure promotes persistent CSF leak. Lumbar drainage should be applied postoperatively and the patient kept flat for 72 h; the chest tubes should not be placed on suction, if possible.

Postoperative Care

Unless preoperative pulmonary conditions like COPD or cardiovascular diseases are present, the patient is extubated immediately after the procedure. Chest X-rays are recommended on the operative and first postoperative day. Further follow-ups depend on the occurrence of pulmonary complication and the ventilation capacity of the patient.

Under normal conditions without signs of after bleeding, the chest tubes are removed on the first postoperative day to facilitate early mobilization and ventilation training. Anteroposterior and lateral X-rays targeting the operative field are obtained on the second postoperative day to rule out operative complications such as implant failure or dislocation as well as signs of instability. We further perform follow-up X-rays and CT scans after 6 months and 1 year to evaluate the fusion process of the involved segments.

Conclusion

Thoracoscopic fusion procedures represent a minimally invasive alternative to open thoracotomy approaches. Constant advancement of implantation devices as well as endoscopic instruments helps to facilitate these challenging operations. The patients benefit from reduced tissue trauma, diminished blood loss, and lessened postoperative pain. However, the procedure has a steep learning curve, is technically demanding, and often requires longer operation time when compared to open procedures.

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The Painful Sacroiliac Iliac Joint

22

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Anatomy

Though the gross surgical anatomy of the SI joint appears straightforward, an understanding of the complex microanatomy is critical in understanding the complexity of making a diagnosis of SI joint dysfunction. In 1864, Von Luschka described the sacroiliac joint as a true diarthrodial joint [29]. It has many of the classic characteristics including a joint capsule consisting of an outer fibrous membrane and inner synovial membrane which defines the synovial portion of the joint, cartilage covering each of the bony surfaces, ligaments connecting the bones, and movement between the joint surfaces. Like most synovial joints, inflammatory disease of the SI joint may result in pannus tissue formation [18]. However, unlike the majority of synovial joints which contain hyaline articular cartilage on both bony surfaces, the sacroiliac joint only has the expected hyaline articular cartilage on the sacral surface and instead has a thin fibrocartilage on the iliac surface [4]. The mismatch between the two surfaces may contribute to degeneration of the SI joint [4].

The SI joint capsule is primarily located in the anterior third of the joint and has a distinct synovial membrane. There is a ligament overlying the capsule that is confluent with the iliolumbar ligament. Posteriorly, there is no obvious synovial membrane, but there is a functional capsule consisting of a strong tension band formed by the interosseous ligament and accessory structures including the posterior sacroiliac, sacrospinous, and sacrotuberous ligaments. Additional support is provided by the dynamic function of the gluteus maximus and medius, erector spinae, biceps femoris, psoas, and piriformis muscles, as well as the lumbodorsal fascia [8].

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By virtue of the small range of motion of the SI joint, roentgen stereophotometric analysis (RSA) is the preferred method for precise measurements. There are however, few studies available using RSA. In one group of 25 patients, aged 18–45, Sturesson and colleagues determined, using RSA analysis, that the physiologic motion of the SI joint has a mean rotation of 2.5° (range 0.8–3.9) and mean translation of 0.7 mm (range 0.1–1.6) [31]. No difference in the range of motion was noted between patients with symptomatic or asymptomatic SI joints.

The precise innervation of the SI joint has not been clearly identified. One of the earlier studies from adult cadaveric specimens suggested that the innervation of the SI joint was derived *exclusively* from dorsal rami of S1–S4 with no branches from the sacral plexus [17]. Another adult cadaveric study reported that the upper ventral portion of the joint was innervated primarily by the ventral ramus of L5, the lower ventral portion was innervated by S2 or branches from the sacral plexus, the upper dorsal portion of the joint had innervation from lateral branches of the dorsal ramus of L5, and that the lower dorsal portion was innervated by a mix of lateral branches of the dorsal rami of the sacral nerves. Using local anesthetic blocks to try to define the functional anatomy has also not been successful. In a prospective, double-blind, randomized clinical trial, asymptomatic study participants underwent L5 dorsal ramus blocks and S1–S4 lateral branch blocks and were then subjected to ligamentous probing and capsular distension [11]. All patients in the control group reported pain with ligamentous probing, but only 60 % who had lidocaine injections had discomfort with ligamentous probing. Eighty percent of patients in the control group felt SI joint capsular distension, while only 60 % in the lidocaine group could feel the capsular distension. This variability reflects both potential patient-to-patient anatomic variability, as well as the technical difficulty of precisely targeting (fluoroscopically) guided injections. In a cadaveric study assessing the latter point, only 36 % of S1 and S2 lateral branch injections with green dye showed staining on the actual nerve during dissection [11].

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Gender differences between SI joints have also been described. Increased levels of estrogen and relaxin are responsible for hormonally induced ligamentous laxity. This phenomenon, combined with weight gain during pregnancy and compensatory lordosis, is thought to place pregnant women at higher risk for SI joint dysfunction [1, 3]. Separately, men seem to have greater translational motion in comparison to women, with rotational motion as the greatest movement [5]. In that small study of four specimens, rotation was measured by placing K-wires with a triad of radiographic markers and then using computational photometry to calculate the helical axis of rotation as a 300 N force was applied to a bar fixed rigidly in the spinal canal of the sacrum to a fixed posterior superior iliac spine. The axis varied depending on the specimen. In the female specimens, the axis traveled parallel and close to the ischial tuberosities. One male specimen had an axis of rotation dorsocranial to the sacroiliac joints and the other male specimen had an axis of rotation centered on the joint under peak rotational moment.

The complex anatomy of the SI joint and patient-specific variability in innervation and biomechanics makes the diagnosis of SI joint dysfunction difficult and the diagnosis of SI joint dysfunction *responsive to surgical management* even more challenging. SI joint dysfunction can present as chronic low back pain. The chronicity of symptoms can be associated with depression, substance abuse, and anxiety disorders [22]. These problems can be difficult to diagnose as it is an area that is often clinically overlooked or ignored by clinicians.

There are no pathognomonic findings on physical exam. In one study, an international, 14 person multidisciplinary expert panel representing the fields of rheumatology, orthopedic surgery, clinical anatomy, prolotherapy, chiropractic care, manual therapy, physiatry/rehabilitation medicine, osteopathy, and radiology was asked to rank 20 different physical examination tests described in the literature for diagnosing SI joint dysfunction based upon reliability. The 12 physical exam tests ranked as being most likely to be reliable for diagnosing SI joint dysfunction were then studied in a group of 85 patients referred for SI joint injections with a diagnosis of SI joint dysfunction. No single examination finding or constellation of examination findings was able to predict a positive or negative response to SI joint block from local anesthetic [10]. Twenty percent of asymptomatic control patients reported false-positive findings on SI joint provocative testing [9]. Even radionuclide bone scanning, classically thought of as a potentially sensitive but nonspecific imaging modality, only has a sensitivity between 13 and 46 % [20, 26].

Despite the daunting diagnostic challenge, low back pain can be generated by the SI joint. In one small study with ten asymptomatic volunteers, provocative SI joint injections were performed. All ten patients developed pain symptoms. Six of the ten had pain localized to the ipsilateral medial buttock inferior to the posterior iliac spine. Two patients had additional extension of pain into the region of the greater trochanter, and the other two patients had sensory changes radiating into the thigh [12]. The authors then evaluated a separate group of 54 patients with chronic low back pain. Sixteen patients were identified as having a pain pattern similar to that generated by provocative tests. Fourteen of those patients had >50 % pain reduction after local anesthetic was placed into the SI joint. A subset of nine patients with SI joint dysfunction that responded to local anesthetic agreed to have an additional provocative discogram and an additional provocative lumbar facet joint injection. In these nine patients, none had a positive reaction to the provocative discogram or provocative lumbar facet injection.

The diagnosis of SI joint dysfunction must start with a high index of suspicion that the SI joint can be the source of pain. The history and physical examination must consider and exclude other sources of pain including referred pain from the hip and/or lumbar spine or other regional (tumor) or systemic causes. Patients with SI joint dysfunction rarely have symptoms in the midline or above the level of L5 [35]. The Fortin finger test is thought to be highly sensitive, but not very specific, and can be used to help rule out SI joint pathology. A positive Fortin finger test requires that the patient localize the pain with one finger to an area immediately inferomedial to and within one centimeter of the posterior superior iliac spine (PSIS) and then consistently point to the same area over at least two trials (requests to localize the pain). SI joint pain has a referred pain area inferior to the ipsilateral posterior superior iliac spine and measures approximately 3×10 cm [10, 25, 33]. Referred pain from the SI joint may cause radiation below the knee, with pain reported in the lower limb and foot in 28 and 12 % of patients, respectively [25].

As noted earlier, in a formal study to evaluate the validity of the history and physical exam, no single or constellation of examination findings were able to predict a positive or negative response to SI joint block from local anesthetic [10]. A subsequent meta-analysis of 18 studies using a positive response to two separate anesthetic injections demonstrated some discriminative power of the thigh-thrust test, the compression test, and three or more positive SI stress tests. In the thigh-thrust test, the patient is in the supine position and the examiner flexes and adducts the patient's hip. Pressure is then applied as an axial load to the femur in order to produce a posterior shear stress on the sacroiliac joint. In the compression test the pain is reproduced when the patient is in the supine position and the examiner applies pressure to spread the anterior superior iliac spines to cause compression of the SI joint. The thigh-thrust test has a sensitivity of 91 % and specificity of 66 %; the compression test has a

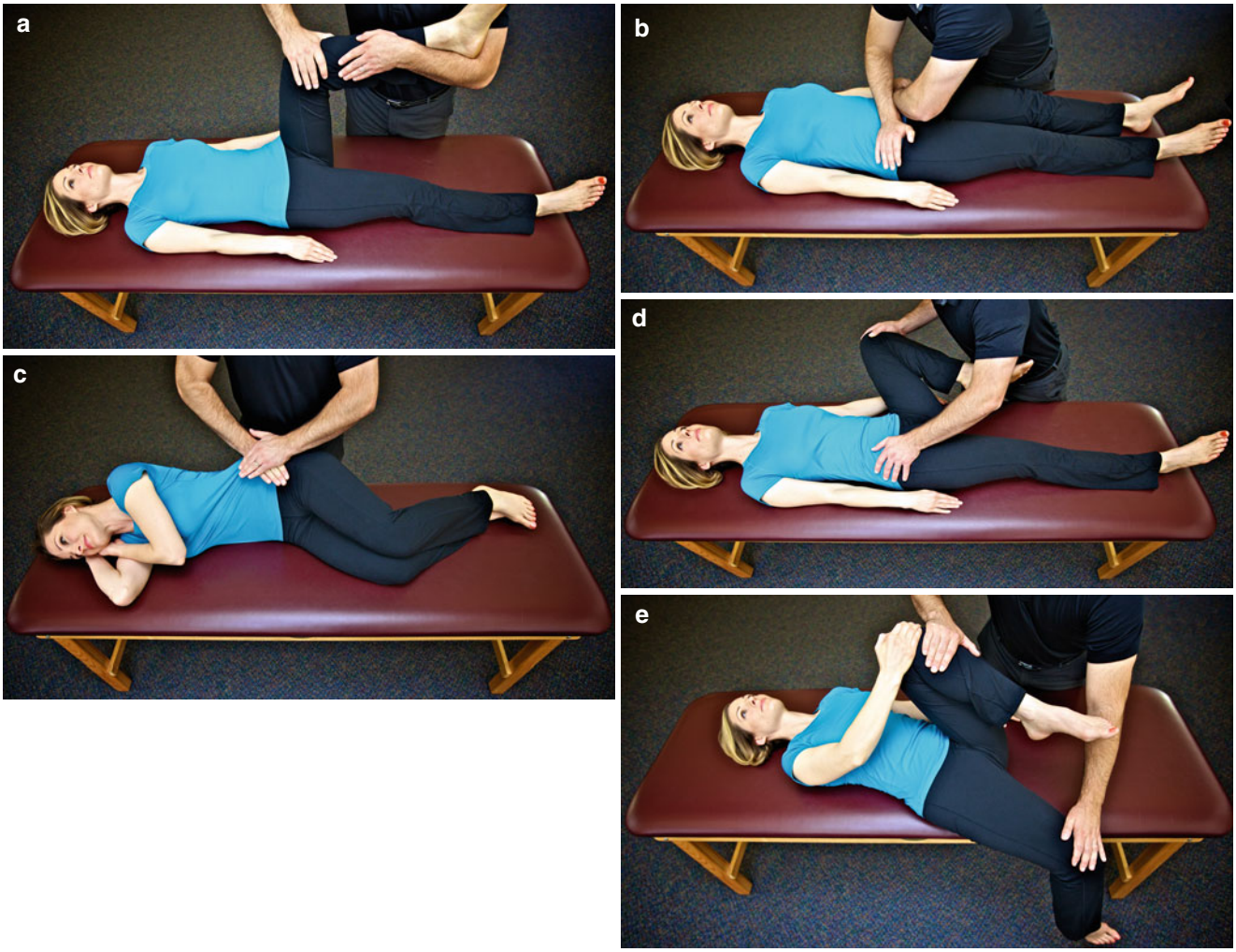

Fig. 22.1 (**a**) In the thigh-thrust maneuver, a posterior shear stress on the SI joint can be placed by placing the patient in a supine position with a flexed and adducted hip and then applying an axial load to the femur. (**b**) The SI joint can be compressed by spreading the anterior superior iliac spines. (**c**) The SI joint can be distracted by applying a compressive, downward pressure on the anterior portion of the ilium. (**d**) SI joint pain can be reproduced when the hip is flexed, abducted, and externally rotated. (**e**) Gaenslen test involves having one hip maximally flexed and the contralateral side maximally extended (Copyright SI-BONE; used with permission)

sensitivity of 63 % and specificity of 69 %. Having three or more positive provocative tests has been shown to have a sensitivity of 85 % and specificity of 76 % [32].

The other tests, which have not been proven to be useful independently, may be useful to contribute to the criteria of "3 or more positive stress tests." These include *distraction of the SI joint* which can be performed by placing the patient in the lateral decubitus position and then applying a compressive, downward pressure on the anterior portion of the ilium, causing the SI joint to distract; the *sacral thrust*, in which the prone patient receives an anterior pressure on the sacrum; *the Patrick* (*or FABER*) *test*, where pain is reproduced when the hip is flexed, abducted, and externally rotated; and the *Gaenslen test*, which involves having one hip maximally flexed and the contralateral side maximally extended. This can be done by having the patient lie supine at the edge of the examination table, having the patient dangle one leg over the side of the table and then having the patient actively flex and hold the contralateral leg to his or her chest. The examiner can then apply a downward force on the extended leg to further stress both SI joints. See Fig. 22.1.

Diagnostic Blocks

Response to diagnostic injection of local anesthetics into the SI joint remains an important tool for the diagnosis of SI joint dysfunction. Due to the difficulty of injecting into the SI joint even under computed tomography (CT) guidance, multiple blocks may be necessary to rule out or in the contribution of the SI joint to the patient's pain. Additionally, it is important to realize that extravasation can occur from three

different sites: (1) posterior extravasation into the dorsal sacral foramina, (2) superior recess extravasation at the sacral alar level into the fifth lumbar epiradicular sheath, and (3) ventral extravasation to the lumbosacral plexus [13]. To help with an unclear diagnosis, anesthetics of varying duration (i.e., minutes to hours) should be considered and tried. In this setting, this should be used as a test, not a treatment, with the duration of pain relief consistent with the medication used. Furthermore, the patient can/should be asked to do activities that reproduce the pain before and after the injection.

Nonoperative Management

The initial management of SI joint dysfunction starts with the treatment of underlying pathology, if one is identified. Examples include shoe lifts for a leg-length discrepancy or disease-modifying antirheumatic drugs for patients with a spondylarthropathy, more often seronegative. For the majority of patients with no clear underlying pathology, symptomatic treatment is the first option. Initially, nonsteroidal anti-inflammatory medications and non-opiate analgesics should be used. Physical therapy can be prescribed with a goal for functional stabilization, perhaps in coordination with manual therapy over a course of 4–6 weeks. External stabilization through pelvic belts can provide proprioceptive feedback and help improve symptoms.

If these noninvasive therapies are not effective, intra-articular injections with steroids and local anesthetics are the next line of treatment. Radiographically guided SI joint injections have been shown to have good to excellent pain relief lasting several months in observational, randomized, and placebo-controlled studies [6]. Viscosupplementation has been reported being successful in four patients [30], but this study did not have a control group for comparison, nor are there additional studies to support this finding. Further research will be needed given the variability in localization of SI joint injections as well as the asymmetrical cartilage on each side of the joint combined with the challenges related to the variability in anatomy anteriorly/posteriorly and superiorly/inferiorly.

Radiofrequency (RF) ablation has also been described for patients with SI joint pain that recurs after corticosteroid/local anesthetic block. This can be done both within the joint itself as well as indirectly by targeting the surrounding nerves. RF ablation is only able to target the posterior portion of the joint and not the anterior portion, where the majority of findings are usually suggested by CT scan [24]. A large meta-analysis demonstrates that there is support for RF ablation in improving patient's symptoms at 3 and 6 months [2]. However, with variability in results and uncertainty about innervation, further validation is required.

Surgical Treatment

Once the diagnosis of sacroiliac joint dysfunction has been established, and attempts at nonoperative treatment have been unsuccessful, the patient may be a candidate for surgical treatment. Stabilization/arthrodesis should be reserved for patients who have disabling symptoms unresponsive to aggressive nonoperative care. There are various descriptions of open sacroiliac joint fusions, including anterior, posterior, and lateral approaches [7]. The anterior approach allows for direct exposure of the ventral and cranial synovial aspect of the sacroiliac joint and does not disrupt the primary sacroiliac joint stabilizing ligaments. The posterior approach has limited access to the sacroiliac joint surfaces. There are modifications of this approach described, including use of an iliac bone window (removing the PSIS) to allow increased access to the articular surface, thereby allowing for improved decortication and direct fusion. Possible complications include damage to the superior gluteal nerve and artery and weak hip abduction leading to abnormal gait. The modern lateral approach based upon Smith-Petersen's work involves removing a rectangular or cylindrical core of ilium and sacrum (across the joint), removing the cartilage and then turning the graft over, and impacting it back in so the thicker iliac component sits across (through) the joint for a fusion [27, 28]. This may or may not include supplemental screw fixation. There are numerous complications reported for open approaches, including injury to the erector spinae muscle insertions, iatrogenic injury to the dorsal sensory nerve roots, sacral plexus, and internal iliac vessels [15]. With open procedures, the patient's postoperative weight bearing is restricted for approximately 3 months.

Recently, minimally invasive sacroiliac joint stabilization/fusion procedures have been reported with increasing frequency. The two most common techniques of performing minimally invasive sacroiliac joint stabilization/arthrodesis are either fluoroscopic guided or CT/computer guided. There is an increasing variety of instrumentation and implants specifically designed for minimally invasive fusion techniques, and these can be applied to both fluoroscopic- and CT-guided techniques.

Prior to any less invasive fusion (or instrumentation) of the sacroiliac joint, the surgeon must have a thorough and detailed understanding of the pelvic anatomy. Appropriate, good quality images must be obtained and studied preoperatively. These include pelvic AP, inlet and outlet views, and a CT scan. Images should be reviewed, with particular attention paid to the possibility of a dysmorphic sacrum. The following radiographic findings are consistent with a dysmorphic sacrum [21]:

- The sacrum is not recessed within the pelvis on the outlet image. The dysmorphic upper sacrum at the level of the lumbosacral disc is colinear with the cranial aspects of the iliac crests.

- Mammillary processes are seen on the outlet image.
- The upper sacral foramens are dysmorphic on the outlet image. They appear larger, noncircular, misshapen, and irregular.
- The alar slope of the dysplastic sacrum is more acute than the nondysmorphic sacrum on the lateral view. This allows for less bone available for safe implant placement.
- A residual disc space between the upper two sacral segments is seen on the outlet image due to unusual fusion patterns during development.
- "Tongue-in-groove" articulations at the sacroiliac joint are seen on the axial images of CT scan.
- The pelvic inlet view reveals an anterior cortical indentation, decreasing the safe zone for placement of the implant.

Minimally invasive sacroiliac fusion is done with the patient in the prone position on a radiolucent table. Rolls are placed under the patient's chest. Care is taken to pad all bony prominences. The arms are placed in an abducted/externally rotated position, rather than adducted at the patient's side, in order to allow for lateral fluoroscopic imaging. Biplanar c-arms may be used. If two c-arms are used, one c-arm is used in the AP plane and one in the lateral plane. If one c-arm is being used, it is helpful to mark both the position of the c-arm machine on the floor as well as the various angles on the "C" of the c-arm with tape. This allows for translating the c-arm proximally and distally for the inlet and outlet views, using the tape on the floor for proper location and changing angles for the perfect inlet and outlet views with tape on the machine. It is also helpful to have the height of the table set high enough to allow for a good lateral sacral view, as changing the height of the table during the case may change the predetermined angles for the inlet and outlet views. Sequential compression devices are placed on both lower extremities, preoperative prophylactic antibiotics are administered, and a time-out is performed to confirm appropriate patient, position, side, implants, etc.

The ability to obtain proper imaging views must be ensured prior to initiation of the surgery. Consideration for a preoperative bowel prep should be given to maximize visualization on fluoroscopic views. When a single c-arm is used, it is positioned on the opposite side of the surgical site. If using two c-arms, the c-arm on the opposite side is most conveniently positioned to obtain the inlet and outlet AP directed views. The inlet view is deemed ideal when all sacral bodies are overlapped. The outlet view is best when the S2 foramen is seen immediately cephalad and adjacent to the superior aspect of the superior rami. The c-arm is then brought to a position to view the sacrum in the lateral view, or a second c-arm is brought into position from the same side as the surgical site to achieve the lateral view. The perfect sacral lateral view is seen when the greater sciatic notches are perfectly overlapped. The sacral lateral view is critical to understanding the sacral alar slope. The alar slope is best estimated by the iliac cortical density (ICD) and delineates the anterior extent of the "safe zone" if the implant is posterior and caudal to it [23]. Care must be taken in patients with a dysmorphic sacrum. In these patients, the sacral alar cortical bone limit is not represented by the iliac cortical density due to the more acute slope of the sacral ala. The sacral alar cortical line is cephalad and anterior to the ICD.

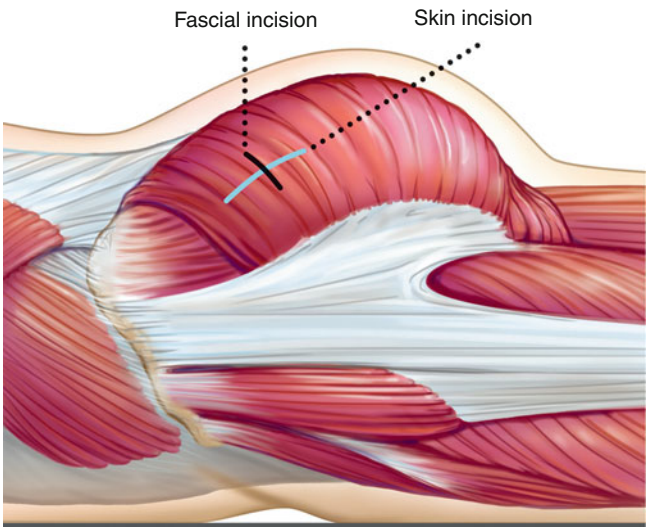

Fig. 22.2 The incision is localized using the sacral lateral view beginning at the S1 superior end plate and extending distally approximately 3 cm in line with the posterior cortex of the sacral canal. The facial incision is typically perpendicular to the skin incision (Copyright SI-BONE; used with permission)

The affected gluteal region is prepped and draped in the usual sterile fashion. Draping should extend from midline to the greater trochanter and from the gluteal crease to proximal to the iliac crest. Using the sacral lateral view for establishing the appropriate landmarks, the incision is made beginning at the S1 superior end plate and extending distally approximately 3 cm in line with the posterior cortex of the sacral canal (Fig. 22.2). Blunt tissue dissection is carried down onto the outer table of the ilium.

Various methods have been described to place percutaneous fusion devices. Depending on the system chosen by the surgeon, this may involve a cannula through which one can accomplish a technique to debride the sacroiliac joint (*SImmetry™ Zyga Technology*) or a percutaneous technique using cannulated wires, broaches, and triangular titanium coated implants without debriding the chondral surfaces (*iFuse Implant System®*, *SI-Bone*). The goal of the latter is to create stability by bony on growth to the implant, not necessarily bone growth across the SI joint, though anecdotally this has been observed. Various reports describe a variety of other implants used for such minimally invasive, fluoroscopically placed implants. Hollow modular anchorage screws

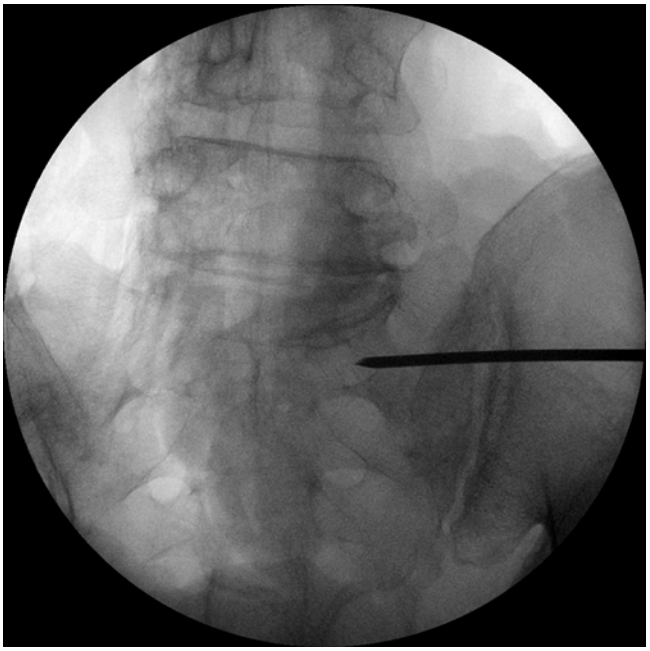

Fig. 22.3 In this outlet view, the guide pin is located between the S1 foramen and superior end plate of the sacrum and is parallel to the superior end plate of S1 (Copyright SI-BONE; used with permission)

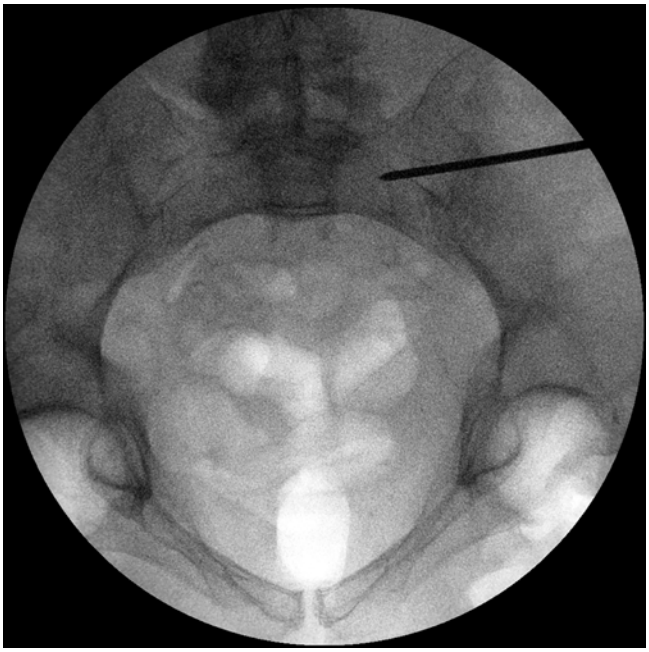

Fig. 22.4 On this inlet view, the guide pin is aimed from slightly posterior to anterior with care being taken not to violate the sacral canal or exit the front of the sacrum (Copyright SI-BONE; used with permission)

filled with bone substitute have been described by Khurana et al. [19].

For a cannulated system, typically two to three implants are inserted. The first cannulated guide wire placed should be the most cephalad wire. The goal is to center the guide pin between the S1 foramen and superior end plate of the sacrum on the outlet view while maintaining the guide pin parallel to the superior end plate of S1 (Fig. 22.3). On the inlet view, the guide pin should be aimed from slightly posterior to anterior, care being taken not to violate the sacral canal or exit the front of the sacrum (Fig. 22.4). In order to avoid the L5 nerve root, which drapes across the anterior sacrum just medial to the sacroiliac joint, the guide pin should be distal to the iliac cortical density. The pin should be parallel to the S1 end plate and aiming from posterior to anterior on the lateral view (Fig. 22.5). Sequential drilling, broaching, measuring, and ultimately placement of the implant follow as per individual company's technique guide. The two more caudal implants are placed with similar technique, each ending lateral to the foramen (Figs. 22.6 and 22.7).

There is no literature evaluating venous thromboembolism (VTE) prevention following percutaneous SI fusion/stabilization. At our institution, we have not encountered any wound or neurologic complications with the use of low-molecular-weight heparin (LMWH) in the immediate postoperative period. The selection of a pharmacologic agent and duration of therapy should be based upon the patient's underlying risk for VTE. At our institution, the duration of VTE prophylaxis is 2 weeks with LMWH.

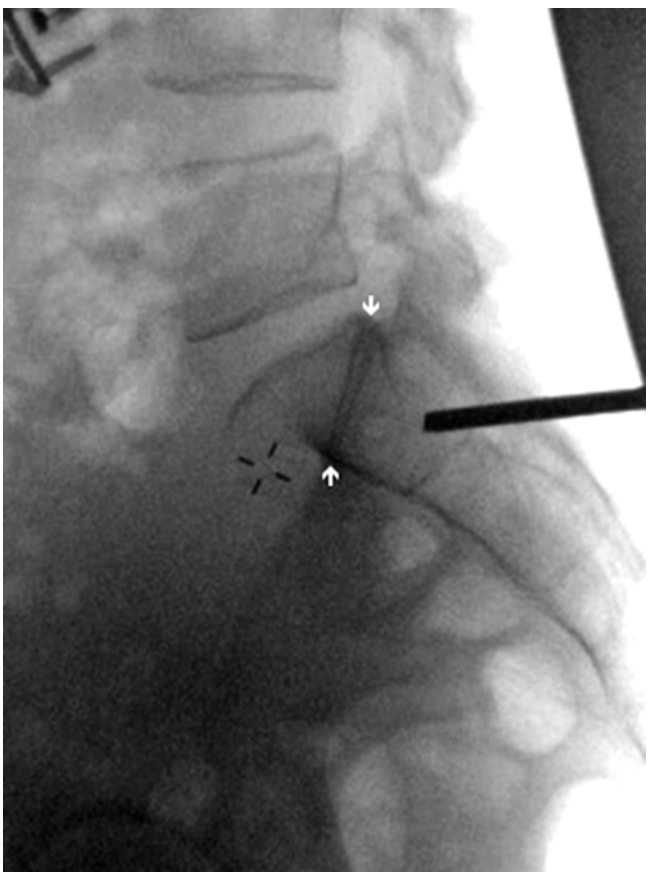

Fig. 22.5 Sacral lateral view demonstrating guide pin caudal to iliac cortical density (*white arrows*)

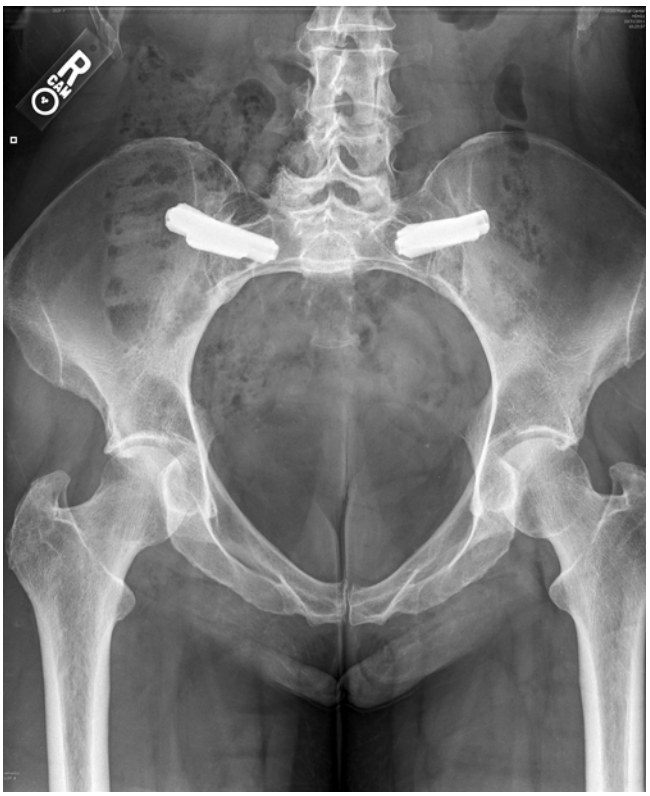

Fig. 22.6 Postoperative inlet view (15 months post-op on the left and 8 months post-op on the *right*)

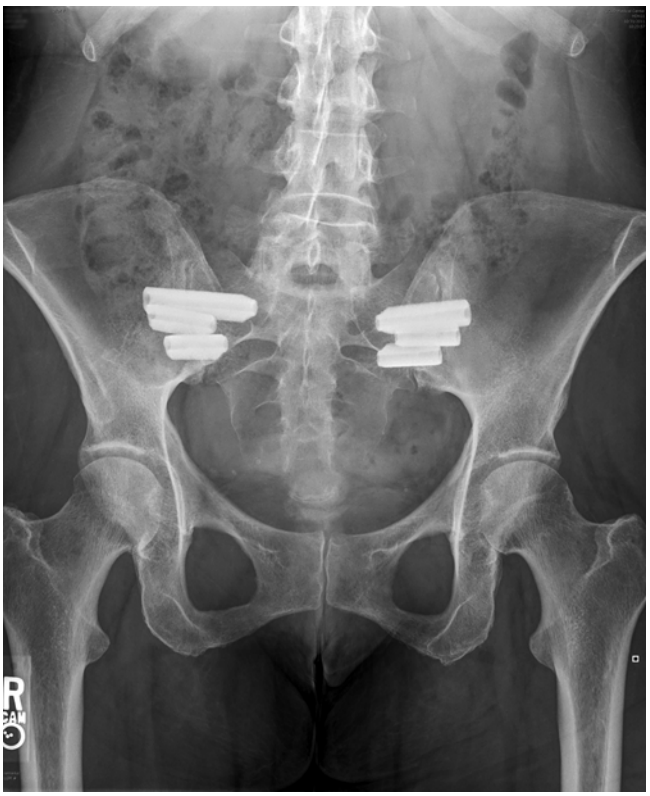

Fig. 22.7 Postoperative outlet view (15 months post-op on the left and 8 months post-op on the *right*)

Patients are kept toe-touch weight bearing postoperatively for 3–6 weeks. Afterward, patients can progressively increase their weight-bearing activity. Even though there is a relatively low morbidity from the percutaneous SI fusion/stabilization procedure itself, bilateral surgeries done under the same hospitalization are not recommended or practical due to the restrictions with postoperative mobility. In patients with bilateral symptoms, we recommend performing the procedure on the more symptomatic side first and then allowing the patient to fully recover from the first procedure before considering stabilization of the contralateral SI joint. In our experience, some patients report considerable improvement of the contralateral, nonoperative SI joint after unilateral fusion/stabilization.

An alternative to fluoroscopic-guided placement of implants is minimally invasive, CT-guided stabilization/arthrodesis. There are a variety of software programs that allow for percutaneous placement of these implants under intraoperative CT guidance. Each system will not be detailed in this section. However, a technique of sacroiliac stabilization/arthrodesis using percutaneously inserted fusion cages, placed coaxially/longitudinally with the SI joint, and filled with bone morphogenic protein has been reported by Wise and Dall [34]. I do not have any personal examples but thought this would be a reference the reader could use if he had the technology.

Wise used preoperative CT to assess the area in which most of the bone is available on both the sacral and iliac sides of the joint. This was considered the "safe zone." Using the software in the CT scanner, these margins were marked on the AP scout film of the pelvis and spine. Under anesthesia, the patient is placed prone on a translucent frame in the same position as in the CT scanner. After appropriate marking, a longitudinal incision was made extending caudal about 1 cm and cephalad about 4 cm. A calibrated Steinman pin was inserted through the PSIS into the sacroiliac joint. A cannulated drill was then used. Finally the cage was placed, after being filled with bone morphogenic protein. This group achieved a fusion rate of 89 %, verified with a 6-month postoperative CT scan. One nonunion patient required an open arthrodesis, and the other was asymptomatic. There were no infections or neurovascular injuries. Visual analog scores were improved at 24-month follow-up. Thirty-eight percent of patients had the procedure as an outpatient. Seventy-seven percent patients stated they would go through the procedure again.

A study by Geisler et al. evaluated 52 patients treated with minimally invasive technique with triangular porous-coated implants [14]. Eighty-five percent of patients would choose to have the procedure again. Pain scores improved in 75 % of patients. There was no data on neurologic complications or length of hospital stay.

Glaser et al. retrospectively reviewed radiographic and surgical outcomes of sacroiliac joint stabilization/arthrodesis using triangular porous-coated implants in 31 consecutive

patients [16]. Eighty-seven percent of patients expressed overall satisfaction with the procedure with 97 % reporting good, excellent, or complete pain relief. Only four patients had complications. Two had postoperative hematomas complicated by infection. One had L5 nerve root irritation and one patient had L5–S1 discitis. At 6 months, 19 patients had CT scans available. Ninety-five percent had radiographic evidence of bone ingrowth and 42 % had bone into or across the SI joint. Lucency was seen in at least one implant in 26 % of patients, although the clinical significance of this finding was not clear. All 39 patients were discharged on postoperative day one.

Conclusion

Although sacroiliac joint stabilization/arthrodesis remains controversial, there are certain conditions where surgery may be indicated after nonoperative treatment fails. Patient selection is critical for success of this procedure. Relative indications include degenerative sacroiliitis, inflammatory sacroiliitis, and sacroiliac joint instability. New techniques of minimally invasive sacroiliac joint stabilization/arthrodesis may allow for less traumatic surgery, shorter hospital stays, and earlier weight bearing. Complete and thorough understanding of sacroiliac joint anatomy, including the dysmorphic sacrum, is mandatory for any of the techniques described.

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Part V

Disease-Specific Approaches

Cervical Herniated Nucleus Pulposus and Stenosis

23

Pablo R. Pazmiño and Carl Lauryssen

Abbreviations

ACDF	Anterior cervical discectomy and fusion
ADR	Artificial disc replacement
AECD	Anterior endoscopic cervical discectomy and fusion
MAST	Minimal access spinal technique
MED	Microendoscopic discectomy
MIS	Minimally invasive surgery
OPLL	Ossification of the posterior longitudinal ligament
PECD	Percutaneous endoscopic cervical discectomy
PN	Percutaneous nucleoplasty

Introduction

The diagnosis and consequent appropriate treatment of cervical myelopathy and radiculopathy may pose a challenge. A broad range of pathologies exist, and these each require individualized surgical approaches that have various prognostic and therapeutic consequences. An effective evidence-based approach or standardized guidelines for each subset of pathologies will ultimately be needed. A crucial step in achieving appropriate outcomes with consistent reproducible results is based on the approach to pathology.

During the past decade, there has been notable progress in MIS (minimally invasive surgery, cervical surgery) instrumentation and techniques, which have become the method of choice for certain cervical procedures. The theoretical appeal of MIS approaches includes considerably less postoperative pain secondary to minimal soft tissue trauma, improved cosmesis, reduced blood loss, shorter operative times, recovery, and length of hospitalization. The concept of successfully decompressing the spinal column through a microscopic approach has been advocated since 1967 [1]. Williams and Henderson et al. first reported the technical feasibility of a microcervical posterior foraminotomy in 1983 [2, 3]. Concerns associated with minimal access surgery are related to visualization, the adequacy of pathological resection, instrumentation, illumination, learning curves, cost efficacy, and the added time required to perform the procedure during the learning curve. There are no multi-institutional randomized controlled trials comparing the effect of MIS surgical techniques of the cervical spine versus standard open procedures detailing complications and outcomes. Moreover, there are numerous subcategories of MIS procedures and approaches including endoscopy, anterior foraminotomies, selective laminoplasty, and laminoforaminotomy. The purpose of this chapter is to assess the scientific rigor of the literature involving MIS approaches to the cervical spine, the overall quality of the reporting, indications for various procedures, complications associated with each approach, and the extent to which the outcomes can relate to clinical practice. Although the techniques and equipment were at first cumbersome, MIS procedures have become a reality with technological developments and our improved acquisition of skills. In this chapter we focus on minimally invasive cervical procedures. We organize the topic by approach (anterior

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One of the authors (PRP) is a clinical instructor for iO-Flex/Baxano and in the past was a consultant for LANX.
One of the authors (CL) is a clinical instructor for iO-Flex/Baxano and is a consultant of stock or equity in the following companies Alphatech, Amedica, Depuy Spine, Intrinsic Orthopedics, K2M, Medtronic-Kyphon, Pioneer, Orthocon, Paradigm, Replication Medical, Spinal Elements, Spinal Motions, Spinal Kinetics, and Spineology.

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and posterior), and for each route we evaluate the surgeries used to treat herniations and stenosis.

Anterior-Based Approaches

1. Microsurgical anterior foraminotomy for radiculopathy
2. Microsurgical anterior foraminotomy for cervical spondylotic myelopathy
3. Percutaneous nucleoplasty
4. Anterior endoscopic cervical fusion (AECD)
5. Percutaneous endoscopic cervical decompression (PECD)
6. Endoscopic laser cervical fusion

Herniations

The basic surgical principles of both calcified and noncalcified cervical herniation management through anterior approaches include complete discectomy and decompression with or without anterior column support and fusion. Current surgical treatment involves a conventional open exposure through an anterior Smith-Robinson approach with placement of graft material, spacers, and instrumentation.

Microsurgical Anterior Foraminotomy

Indications

1. Bony spondylosis
2. Cervical radiculopathy
3. Single or multiple levels
4. Posterolateral disc fragments
5. Residual foraminal stenosis following an index procedure

In general inclusion criteria for anterior foraminotomy include patients with contained disc herniations and complaints of radicular pain, with minimal or no neck pain, who have failed a minimum of 6 weeks of conservative therapy. Criteria for the operation are limited to cervical radiculopathy. The anterior foraminotomy can be considered for single-level or multilevel radiculopathy stemming from pathology in the lateral recess or foramen. Bilateral pathology is not a contraindication. Examples of situations which lend themselves to this approach include posterolateral bony spondylosis, posterolateral disc fragments, or residual foraminal stenosis after incomplete decompressions following a laminectomy/foraminotomy or ACDF. Furthermore, the anterior foraminotomy can be considered a viable option for patients with predominant radiculopathy and a small component of neck pain they can live with.

Limitations

Relative contraindications to utilization of anterior foraminotomies include extensive ossification of the posterior longitudinal ligament (OPLL), myelopathy, vascular abnormalities (e.g., tortuous vertebral artery), predominant axial neck pain, bony canal, or diffuse osteophytic spinal canal stenosis. In each of these situations, an anterior fusion or alternatively a combined anterior-posterior procedure may be warranted.

Approach

Positioning is similar to that of a standard anterior discectomy with the patient in the supine position on a radiolucent table. Because the cervical disc naturally inclines cephalad in the anterior-posterior direction, further extension of the cervical spine with bolsters is avoided during patient positioning [4]. Traction is not necessary. The skin localization incision is determined by preoperative lateral fluoroscopy with a spinal needle taped to the skin in line with the proposed disc space. The surgical technique employs a standard ipsilateral Smith-Robinson approach to the vertebral level and side responsible for the radicular pain. The lateral one third of the vertebral column is delineated with mobilization of the longus colli and placement of retractors in standard fashion. Next the medial and lateral bony margins of the uncinate process are delineated with a combination of cautious bovie cautery, kittner dissection, and a freer elevator. The appropriate level is confirmed with fluoroscopy, and self-retaining retractors are placed deep to the lateral longus colli and esophagus. Alternatively for endoscopic visualization, tubal retractors can be anchored in line with the longitudinal axis of the uncinate process. Exposure is complete when the entire uncinate process with the lateral third of the cranial and caudal vertebral bodies and disc is within the visual field (Fig. 23.1). In this scenario multiple adjacent levels can easily be managed from the same skin incision. Because of the potential damage to neural and vascular structures, the remainder of the procedure is performed under microscopic magnification. Because of the increased risk of injury to neurovascular structures, Loupe magnification is unacceptable for visualization and illumination [5].

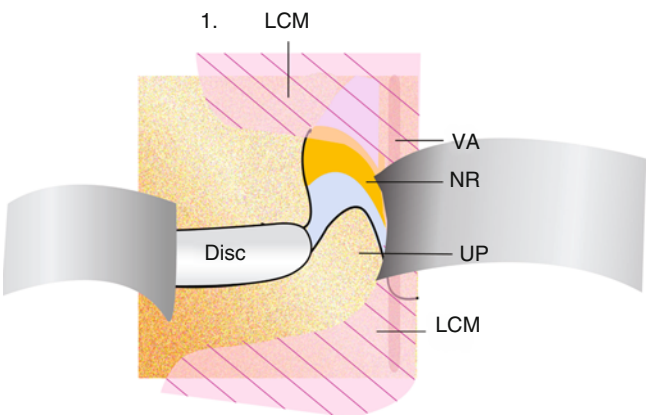


Fig. 23.1 Anterior operative field. *LCM* longus colli muscle, *VA* vertebral artery, *NR* nerve root, *UP* uncinate process

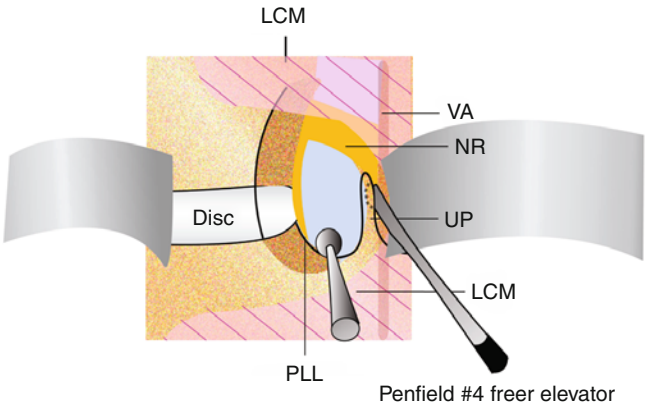


Fig. 23.2 Anterior foraminotomy (drill, Penfield #4/freer elevator placed lateral to uncinate process). *PLL* posterior longitudinal ligament, *LCM* longus colli muscle, *VA* vertebral artery, *NR* nerve root, *UP* uncinate process

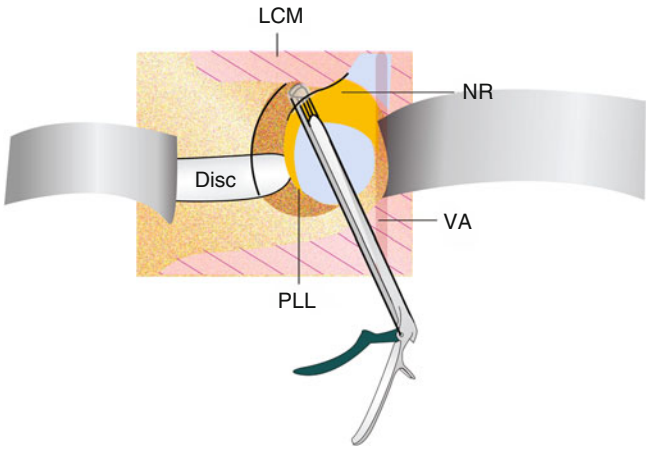


Fig. 23.3 Drilling is advanced while remaining parallel to the end plates; once all cancellous bleeding has diminished, the posterior longitudinal ligament (*PLL*) is next identified. With a combination of microsect curettage and Kerrison rongeurs, all overlying bony margins, osteophytic spurs, lateral margin of the posterior longitudinal ligament, cartilage, and periosteum are resected from the underlying nerve root

Excellent illumination and magnification are essential to avoid complication and ensure ideal decompression.

Foraminotomy

A blunt freer elevator, but preferably a Penfield #4, is used to dissect the lateral margin of the uncinate process, of the caudal vertebral body, from its investing longus colli and soft tissue attachments. Hugging the lateral border of the uncinate, dissect a soft tissue plane to place a Penfield #4 between the uncinate and the vertebral artery. Once complete the concave curve of the Penfield #4 should be along the uncinate's lateral margin. This serves as an internal metallic medial barrier to the vertebral artery (Fig. 23.2). Next resection of the uncinate process is performed using a long-handled high-speed drill with an AM8 ball-shaped diamond cutting burr (Anspach®, Palm Beach Gardens, Fla., USA/*Midas Rex*® Legend® Fort Worth, Tex., USA). Drill a 6-mm circle of bone, keeping 1–2 mm of bone between the drill and the Penfield #4. The drilling is negotiated along the anterolateral course of the uncinate process with judicious saline rinsing and intermittent placement of bone wax along any bleeding cancellous margins. Fluoroscopic guidance may initially be used to ascertain trajectory and depth. If desired a wider margin can be obtained by resecting a thin lateral margin of the disc itself in attempts to acquire a paracentral disc fragment. The approach vector should be inclined cephalad based on preoperative planning in order to reach the neural elements posteriorly. A straight forward vector trajectory should be avoided as this would only lead toward the superior pedicle margin and away from the intended pathology. Drilling is advanced judiciously along the posterior cortical uncinate bed and posterolateral rostral end plate (Fig. 23.2). Next identify the posterior longitudinal ligament (PLL), and create a plane between the back of the vertebral body and the PLL. Using a combination of curettage with a 1-, 1.5-, or 2-mm Kerrison rongeur, all overlying bony margins, osteophytic spurs, lateral margin of

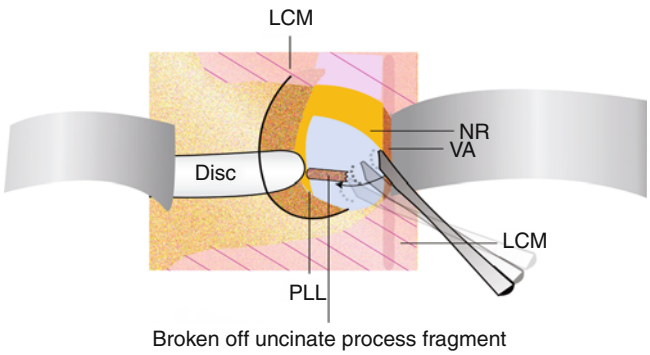


Fig. 23.4 The lateral uncinate wall is thinned with a diamond-tipped burr until a fragment of cortical bone remains which is "flicked" off from lateral to medial with a Penfield #4 or a freer elevator

the posterior longitudinal ligament, cartilage, and periosteum are resected from the underlying nerve root (Fig. 23.3). Continue thinning the lateral uncinate wall with a diamond-tipped burr until a fragment of cortical bone remains which can be removed near its base by snapping it or "flicking it" off from lateral to medial with a Penfield #4 or a freer elevator (Fig. 23.4). Some authors prefer to leave this margin as a landmark and protective layer for the underlying vertebral artery [6]. Meticulous hemostasis of epidural bleeding or drainage from the anterior internal venous plexus is obtained with a combination of judicious bipolar cautery usage and the use of hemostatic agents.

At this point the path of the nerve root is decompressed along its entire length from its emergence near the cord to its lateral extent behind the vertebral artery. A blunt nerve hook or small ball-tipped probe is passed along the nerve through the now patent foramina to ensure all disc fragments have been withdrawn and that an adequate decompression has

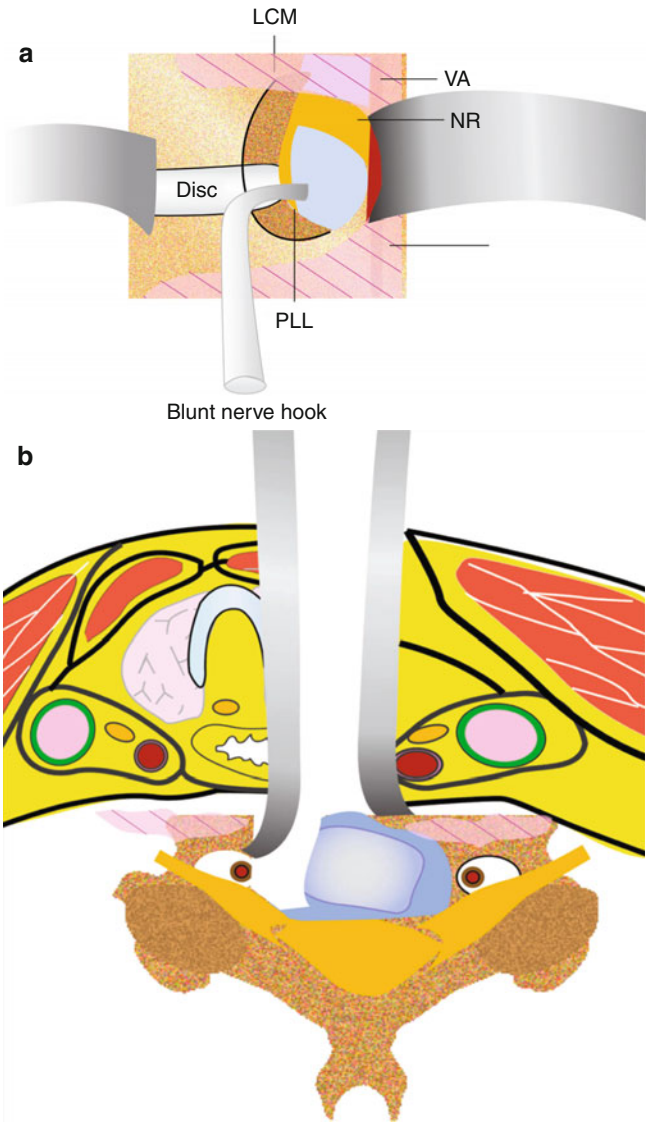


Fig. 23.5 (**a**) A short blunt nerve hook can be passed along the nerve through the now patent foramina to ensure all disc fragments have been withdrawn and that an adequate decompression has been performed. (**b**) Axial view depiction demonstrating the completed anterior foraminotomy

been performed (Fig. 23.5). Great care must be taken not to retract the root or place further pressure on the already compromised root during the procedure as this may predispose to neurologic injury. If there is pathology medial to the uncinate or compressing the spinal cord, it can be resected using the techniques mentioned previously.

Complications

Given the proximity of the cervical sympathetic chain to the lateral margin of the longus colli, Horner's syndrome can result if the sympathetic is sectioned or stretched during dissection through the longus colli. There are only two reports of a transient Horner's syndrome in the literature which occurred in a series of 104 patients [4, 7]. In order to avoid this complication, we minimize horizontal transection of the colli and elevate the colli with blunt dissection using a freer elevator. Jho's recommendation to avoid this injury entails incision of the colli medial to the anterior tubercle of the transverse process [8]. There is one report of discitis seen in a series of 104 patients which resolved with antibiotics and went on to spontaneously fuse [8]. Jho encountered one case of transient hemiparesis which he states resulted from a presumed neck hyperextension posture during surgical positioning [8]. Review of the literature revealed one case of temporary superior laryngeal nerve palsy in a series of 21 patients [9]. There is one case report of an incidental durotomy that required surgical repair [10]. Spinal instability was noted in four patients who demonstrated lateral collapse, frontal-plane tilt, and rotary instability presumably as a result of generous decompression secondary to excessive removal of lateral intervertebral anatomy [4, 10]. Hacker also noted a high incidence (four patients) of recurrent herniation which has been attributed toward excessive iatrogenic disruption of the disc's integrity [4, 10]. There is one reported instance of postoperative nerve root injury weakness which was addressed by a posterior foraminotomy [9].

Vertebral artery injury, while relatively uncommon, poses catastrophic consequences. Anatomical analyses have determined a relative anterior and lateral position of the artery with respect to the neuroforaminal entrance [11]. During standard ACDF, the rates of vertebral artery laceration range from 0.3 to 0.5 % [12, 13]. In our series of approximately 200 cases and in published reports on anterior foraminotomies, there are no instances of vertebral artery injuries and/or lacerations. This can be attributed to proper patient selection, preoperative planning, and surgical technique. In order to avoid vascular injury, we advocate a thorough preoperative review of the vertebral arterial location within the foramina and throughout the transverse process to rule out an abnormal tortuous course or kinking of the vertebral artery. As this procedure requires considerable technical skill in order to minimize complications, decrease the learning curve, and optimize surgical comfort, this procedure can be refined in the cadaver lab before clinical adoption.

Case Study: Anterior Foraminotomy (Courtesy of C. Lauryssen M.D.)

A 53-year-old right-hand-dominant male presented with a 9-month history of intractable radiculopathy and weakness in a C6 distribution. He described 90 % radicular arm pain and minimal 10 % axial neck pain. Despite a prolonged course of conservative management which included NSAIDS, traction, chiropractic management, physical

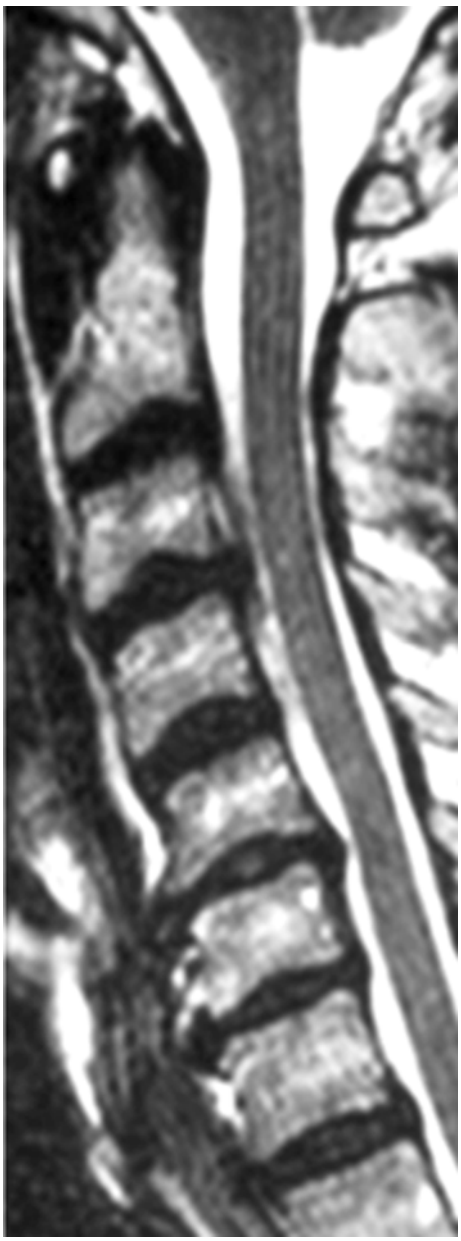


Fig. 23.6 Anterior foraminotomy preoperative sagittal MRI in a patient with severe foraminal stenosis at cervical 5/6 and predominant right-sided radiculopathy

therapy, oral steroids, epidurals, and selective nerve root blocks, he presented with intractable arm pain and commensurate weakness in a C6 distribution. Preoperative MRI demonstrated right-sided more than left-sided C5/6 foraminal stenosis (Figs. 23.6 and 23.7). The patient underwent a right-sided C5/6 anterior foraminotomy. The patient remains symptom-free at his 2-year follow-up appointment with flexion-extension radiographs which demonstrate no evidence of any instability. Postoperative anterior-posterior and oblique radiographs (Fig. 23.8) demonstrate the foraminotomy aperture.

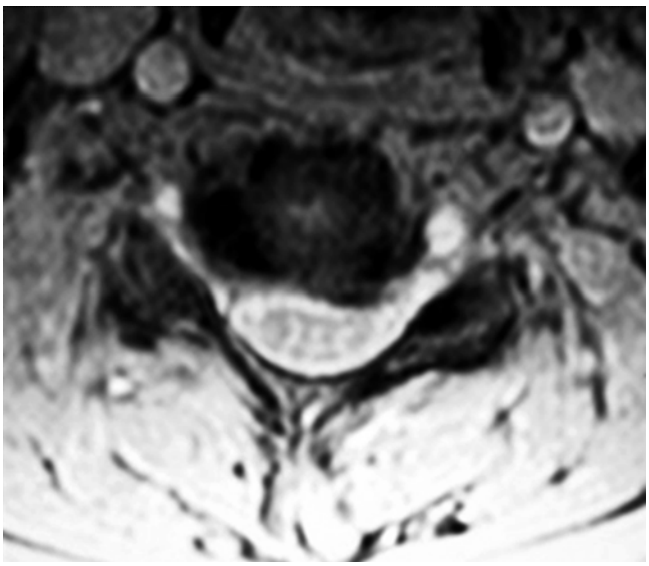


Fig. 23.7 Preoperative axial MRI demonstrating severe neuroforaminal stenosis at cervical 5/6 and predominant right-sided radiculopathy

Unilateral Single-Level or Multilevel Microsurgical Anterior Foraminotomy for Cervical Spondylotic Myelopathy

Jho described a unilateral approach using multilevel foraminotomies to decompress the length of the spinal cord and canal in patients with cervical spondylotic myelopathy [14]. An anterior foraminotomy similar to that described in the prior section is fashioned at multiple levels, and a tunnel is created afterward connecting the foraminotomy chambers. A diagonal trajectory is prepared by crossing the midline toward the contralateral nerve root and lateral margin of the spinal cord. Next the posterior longitudinal ligament, osteophytes, and disc fragments are resected, and the spinal cord is decompressed throughout the length of its entire transverse axis. In this manner the canal's dimensions are enlarged without requiring bony fusion or immobilization.

Indications

The indications of this procedure are patients with single- or multiple-level cervical stenosis leading to cervical spondylotic myelopathy with their compressive pathology anterior to the cord.

Outcomes

At the time of this writing, the technique has been documented in 14 patients. In this initial subset of patients, all were discharged on postoperative day 1, and there were no major complications. In the short term all patients demonstrated stability on flexion-extension films. Given the severe spondylosis the investigators anticipated eventual fusion. At this time there is no long-term data on the maintenance of motion, need for further surgery, or the development of

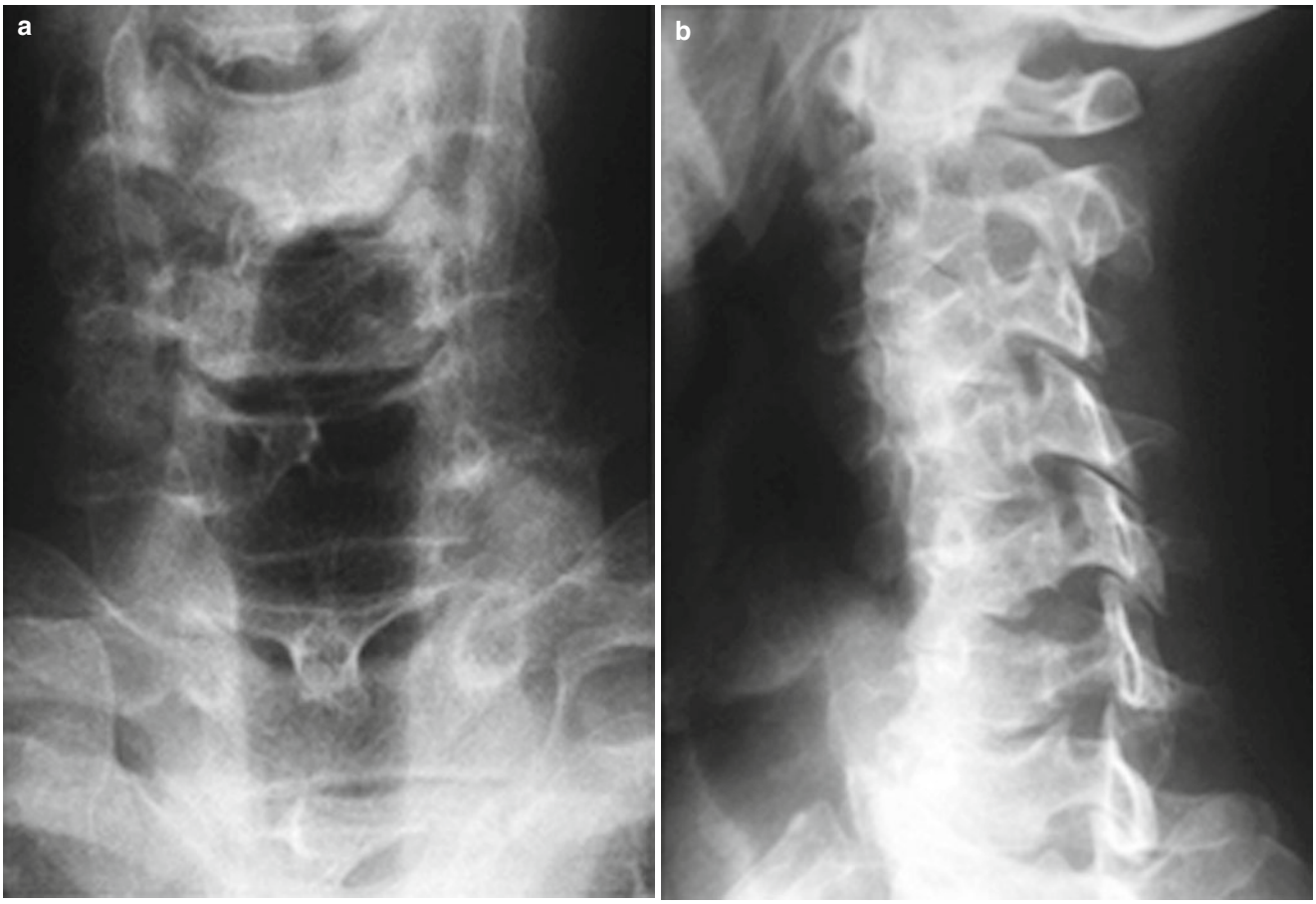


Fig. 23.8 (**a**) Postoperative anterior-posterior and (**b**) oblique radiograph demonstrating completed right-sided anterior foraminotomy at cervical 5/6

potential instability. The literature demonstrates this procedure is in its nascent phase and demands further study focusing on specific indications, long-term outcomes, and complications. The procedure by nature commands a high learning curve, bears a significant risk profile, and should be mastered on cadavers before its application in the clinical setting.

Percutaneous Nucleoplasty

The studies reported by Nardi et al. and Li and colleagues [15, 16] have described a percutaneous nucleoplasty (PN) procedure. For the purpose of this analysis, these studies will be discussed together. During this procedure an 18-gauge needle is inserted via a right-sided approach near a point of entry adjacent to the medial border of the right sternocleidomastoid muscle, while the larynx and trachea are displaced medially and the carotid artery laterally. After manual palpation the spinal needle is used to puncture the disc space under fluoroscopic guidance. The fiber of a percutaneous SpineWand is then inserted through the 18-gauge needle and is connected to a standard power generator. The protocol described is nuclear ablation at 3 W with 1-s coagulation [16]. Provided there is no pain during the coagulation, coblation is then performed for 15 s. During this segment of the procedure, the Perc-D SpineWand is moved around and within the disc under fluoroscopic guidance. Afterward the Perc-D SpineWand is advanced to the posterior annulus where coagulation for 1 s is applied to shrink the surrounding collagen and widen the appropriate channel. This sequence is repeated four to six times during the procedure.

Indications

Inclusion criteria for percutaneous nucleoplasty include patients with contained disc herniations and complaints of radicular pain, with or without neck pain, who have failed a minimum of 6 weeks of conservative therapy. Exclusion criteria are often cited as any extruded disc fragment, spinal canal stenosis, ossification of the posterior longitudinal ligament (OPLL), prior surgery at the proposed level, any significant antero- or retrolisthesis, myelopathy, and a known hemorrhagic diathesis.

Outcomes

Li performed a prospective study of 126 consecutive patients who underwent PN over a 4-year period, with no descriptions of the follow-up period [16]. In this series all patients

selected had no signs or symptoms of instability or myelopathy. Inclusion criteria were limited to patients with disc herniations, complaints of radicular pain with or without neck pain, and no improvement with at least 6 weeks of conservative therapy. The VAS score was decreased after sequential follow-up. The rate of excellent and good results was 83.7 %. Gebremariam conducted a comprehensive systematic review and scored the quality and effectiveness of the Nardi study comparing percutaneous nucleoplasty to conservative controls (nonsteroidals, cortisone, therapy, and collar) [17]. In his rating system the PN papers were deemed a low-quality RCT because of low numbers enrolled ($n=70$). Sixty days after surgery, 80 % of the patients treated with PN reported complete resolution of symptoms ($p<0.001$), whereas in the conservative treatment group, 20 % of the patients had complete resolution of symptoms ($p=0.172$). No statistical comparison was made between the 2 groups. Therefore, he found no evidence for the difference in effectiveness between PN and conservative treatment in the short term.

Complications

One reported complication was a Perc-D SpineWand broken needle tip which was left inside the disc space in one patient with no consequences as of yet. Another patient reported persistent neck pain, radiculopathy, and numbness throughout the left upper limb afterward. Post-procedural MRI demonstrated a loss of distinction between the end plates at C5–6 with a decreased signal intensity in the adjacent vertebral bodies on the T1-weighted images and increased signal intensity on T2-weighted images.

Anterior Endoscopic Cervical Fusion (AECD)/ Percutaneous Endoscopic Cervical Decompression (PECD)

Endoscopy has gained recent popularity as an adjunctive procedure for the treatment of patients with cervical herniations and radiculopathy. Rigid and flexible variants of the endoscope have served to traverse the therapeutic gap between percutaneous and traditional open modalities. The studies described by Hellinger, Yao, Chiu, and colleagues have described newer methods of anterior cervical discectomy with or without concomitant fusion via an endoscopic approach [18–21]. For the purpose of this analysis, these studies will be discussed together.

Anterior Endoscopic Cervical Discectomy and Fusion (AECD) Indications

The selection criteria are based on patients with soft contained disc herniations and complaints of radicular pain, with or without neck pain, who have failed a minimum of 6–12 weeks of conservative therapy. The ventral edge of the intervertebral space must be at least 4 mm to prevent approach-related injury. Any craniocaudal sequestrations should be limited to less than half the vertebral body. The herniation itself should be located medial to the lateral edge of the cord, as this would contraindicate the patient for a posterior approach. In some cases authors describe performing discography beforehand or intraoperatively for difficult or multilevel cases. Several authors note that a favorable response to cervical traction has corresponded well with postoperative outcomes from endoscopic procedures. Contraindications include myelopathy, severe cervical spinal canal stenosis, OPLL, significant free disc fragment migration in relation to the disc level, advanced spondylosis with significant collapse, disc space narrowing, and osteophytes blocking entry to the disc space.

Percutaneous Endoscopic Cervical Decompression (PECD) Indications

The selection criteria for PECD are similar to those of AECD and are geared toward treating patients with soft contained disc herniations and complaints of radicular pain, with or without neck pain, who have failed a minimum of 6–12 weeks of conservative therapy. Contraindications include myelopathy, severe cervical spinal canal stenosis, OPLL, hard discs or sequestrated disc fragments, advanced spondylosis with significant collapse, segmental instability, disc space narrowing, and osteophytes blocking entry to the disc space.

Surgical Methodology and Technique

The principles of endoscopic microsurgery are to minimize access morbidity through a narrow transdiscal endoscopic portal while preserving a portion of the annulus fibrosus and the intervertebral disc. The transdiscal route for a percutaneous endoscopic cervical decompression (PECD) selectively targets and removes the nucleus pulposus and any offending ventral pathology while leaving the periphery of the disc and its remaining annulus fibrosus. Through a similar approach an anterior endoscopic cervical discectomy and fusion (AECD) is performed where a spacer is inserted to provide a form of stabilization. Allograft/autograft bone dowels, carbon fiber, or an expandable implant can be employed (Fig. 23.9a–c).

Through a 5-mm incision an anterior Smith-Robinson trajectory is employed with blunt dissection in a contralateral approach and trajectory to that of the herniation. The trachea and esophagus are displaced medially and the carotid sheath laterally as an 18-gauge spinal needle is inserted into the proposed disc space. After biplanar fluoroscopic localization confirms the intended disc space, a guidewire and sequential dilators are passed through the incision over the needle and docked onto the intervertebral disc. The procedure consists of performing a small 2-mm anulotomy anteriorly with cannula-supported instrumentation, endoscopic monitors, and frequent fluoroscopy guidance (Fig. 23.9d). Next using a

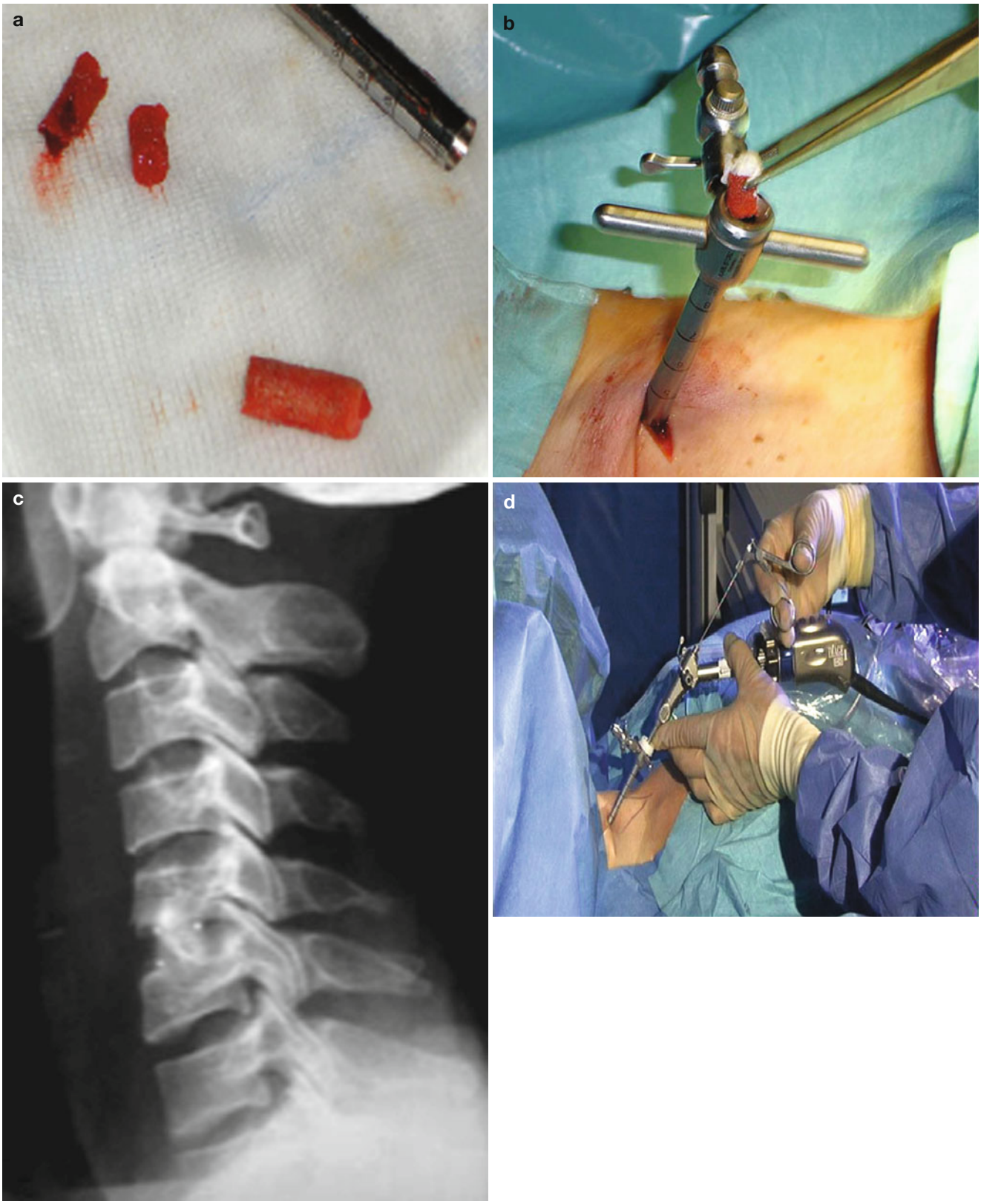


Fig. 23.9 (**a**, **b**) Autograft bone dowels (From Hellinger [20]). Used with permission. (**c**) Carbon fiber-reinforced polymer cage (From Yao et al. [19]; used with permission). (**d**) Exterior view of the surgeon performing an arthroscopy discectomy with a pituitary

series of dilators, ultimately a 6.5-mm working sleeve is advanced over the last obturator and stationed within the anterior annulus fibrosis. If distraction is needed a dilation sleeve can be inserted and rotated to achieve sufficient end plate spread and separation (Fig. 23.10a). This initial position of the dilator is confirmed on anterior-posterior fluoroscopy. The remainder of the procedure is performed under endoscopic visualization with lateral fluoroscopic guidance. A discectomy is accomplished through a series of endoscopic intradiscal instruments such as endoscopic forceps, rongeurs, radiofrequency monopolar, burrs, trephines, and shavers (Fig. 23.10). Swiveling the 25° oval endoscope (3.3 mm × 5.3 mm) provides expansive lateral visualization near the uncovertebral joints (Fig. 23.11a–e). Rim osteophytes and the posterior longitudinal ligament can be resected using a combination of forceps, Kerrisons, and ring curettage. For improved visualization within the dorsal disc space, gas mediums can also be used to provide imaging similar to microscopic visualization. Thorough decompression can be confirmed and substantiated with a bayoneted nerve hook. An AECD fusion can be performed through a variety of autograft/allograft bone dowels or implants which

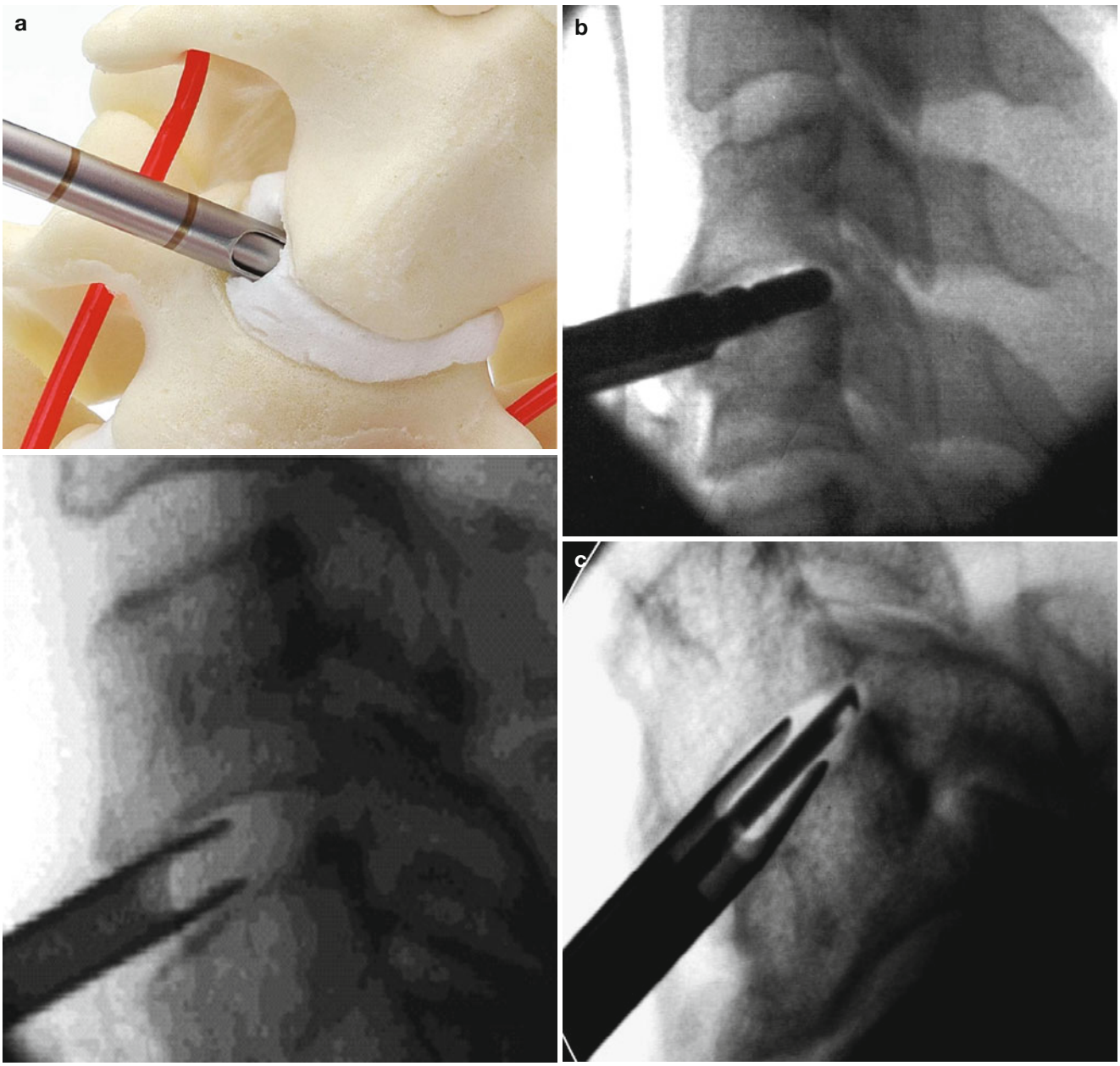


Fig. 23.10 (**a**) Dilation sleeve; (**b–f**) fluoroscopic preparation of the end plates with special rasps, burr, Kerrisons, probes, and forceps (From Hellinger [20]. Used with permission)

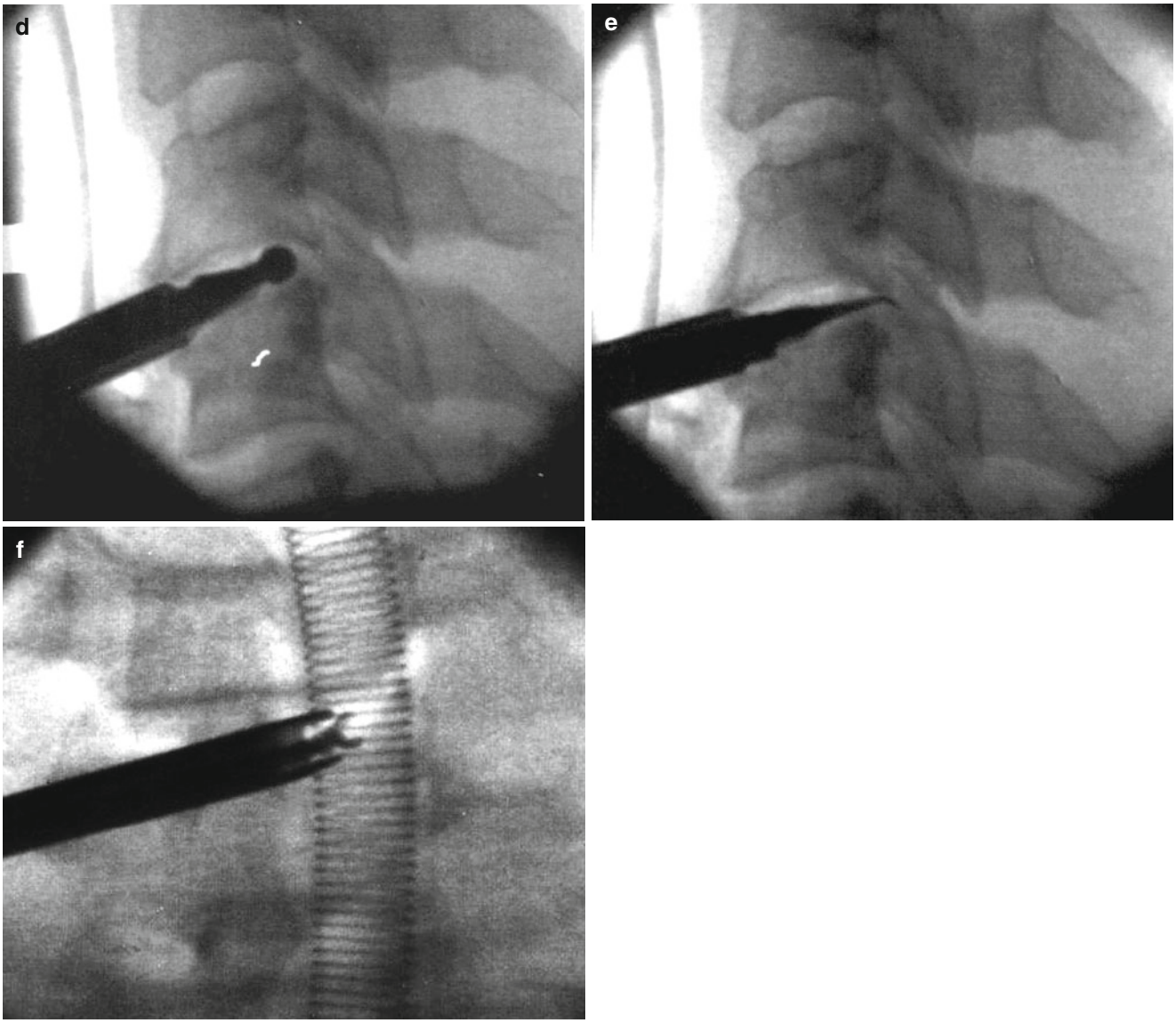


Fig. 23.10 (continued)

are inserted with small tamps under fluoroscopic guidance through the working sleeve (Fig. 23.9a, b).

Outcomes and Complications

Limited data is readily available to assess the relative merits of these endoscopic discectomy procedures. It is not entirely feasible to realistically compare the Level IIIB and IV endoscopic evidence with the extensively researched outcomes from the standard open anterior cervical discectomy and fusion which consistently garners good to excellent results in studies and in our clinical practices. We now have Level I and Level II data available from five US Food and Drug Administration (FDA) investigational device exemption (IDE) studies involving ACDF as the control procedure against stand-alone fusion devices and three studies comparing fusions to arthroplasties [22, 23]. Reoperation rates for the ACDF control in these studies ranged from 12.7 to 18.1 % without plating and 4.1–8.5 % with plating. There is a 10 % overall reoperation rate for single-level ACDF as a result of pseudoarthrosis, adjacent level breakdown, or revision. Patients demonstrated a median VAS satisfaction score at 92.9; fusion rate for ACDF at 2 years was 95 %, an 88 % neurological success; and 80.9 % of ACDF patients indicated they would choose to have the same surgery again [22–24]. The clinical overall success rate of ACDF with allograft and plate at 2 years was 70.8 % percent [24]. There is insufficient evidence to make strong recommendations regarding the relative benefit of AECD versus standard open ACDF, and more studies must be done to investigate whether there is a broader clinical role for AECD. Ideally, there

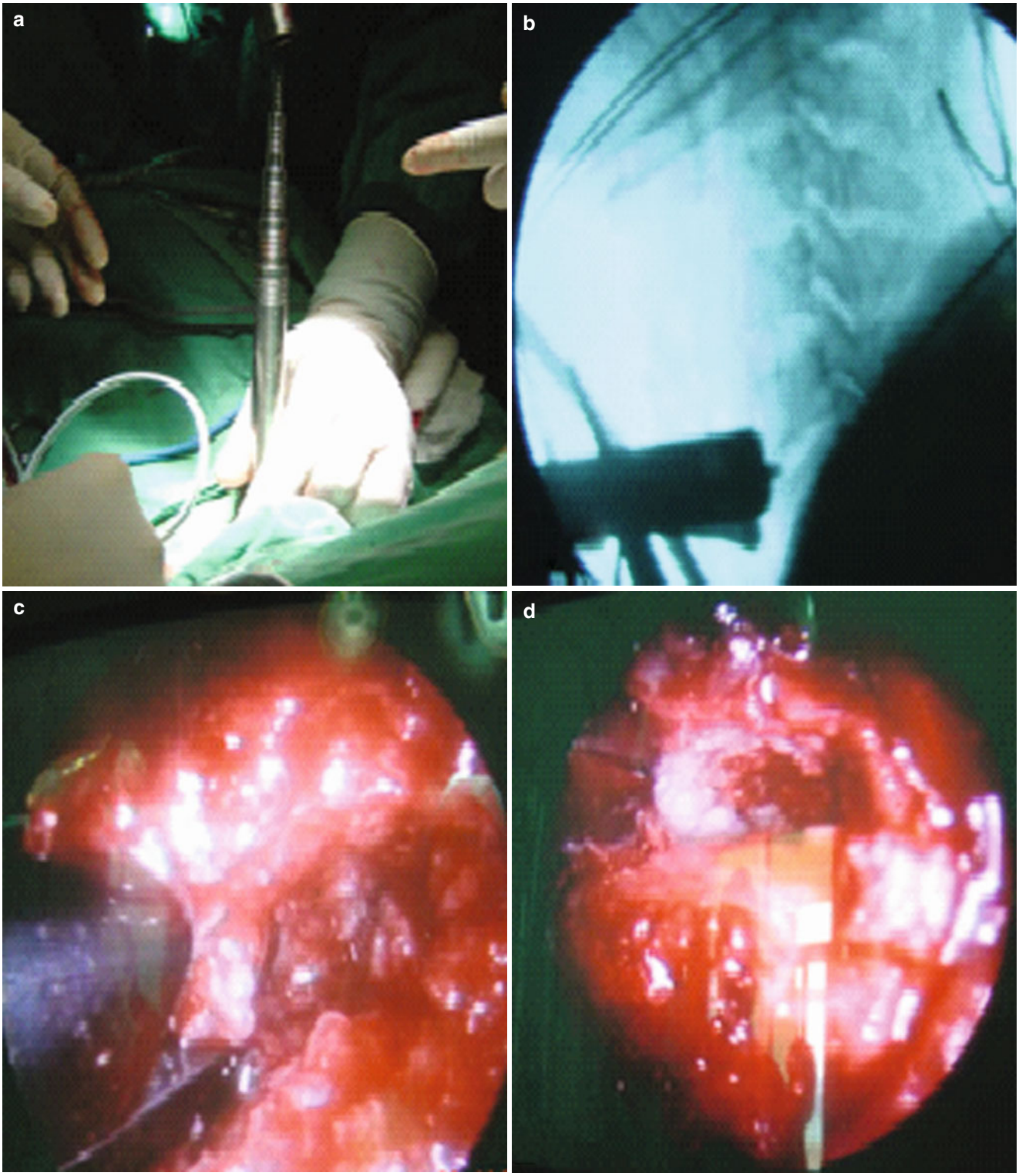


Fig. 23.11 Intraoperative endoscopic views. (**a**) Endoscopic dilators were introduced sequentially between the carotid artery and the esophagus. (**b**) Working channel was set up under fluoroscopic control. (**c**) The anterior osteophyte of vertebral bodies adjacent to the disc was removed endoscopically by a small Kerrison. (**d**) Endoscopic view after removal of intervertebral disc (From Yao et al. [19]; used with permission)

should be more data from methodologically sound RCTs. Further research is needed on whether the balance of advantages and disadvantages of endoscopic surgery varies within subgroups based on the different stages and locations of pathology. Research relating to the effect of experience on performance is also required. More data is needed from

surgeons in the community currently performing endoscopic fusion and discectomy to truly understand the procedure from the standpoints of its safety, economics, and efficacy.

Proponents for the endoscopic procedures describe a success rate ranging from 85 to 94 % in their Level IIIB and IV studies with negligible complications [18, 19]. This procedure has been described as a modification of the original Cloward procedure with the advantage of limited exposure-related trauma, dysphagia, analgesic requirements, and faster rehabilitation [20]. There is a high learning curve associated with the procedure. The initial case series and retrospective studies reported by proponents of this approach demonstrate these endoscopic procedures have a low complication profile and therefore may be suited within our spectrum of procedures; however, they demand further research before widespread adoption into clinical practice. Complications have included infections, conversion to open procedures, and vascular injuries (external jugular) requiring an open exposure and closure by vascular surgeons. Therefore, a randomized, prospective study directly comparing the minimally invasive endoscopic approach and open surgical procedures would be necessary to comprehend and identify the value of this minimal access approach for use in cervical fusion.

Case Study: AECD (Courtesy of N. Yao M.D./W. Wang, M.D.)

A 50-year-old female who presented with a predominance of axial neck pain rated VAS 8/10. In addition there was a pain radiation into the left arm in a C6 distribution. The radiographs demonstrated showed mild spondylosis (Fig. 23.12a). The MRI demonstrated a left-sided disc extrusion at C5–6 (Fig. 23.12b). Despite a prolonged course of conservative management, she developed intractable pain requiring definitive management. She underwent an anterior endoscopic

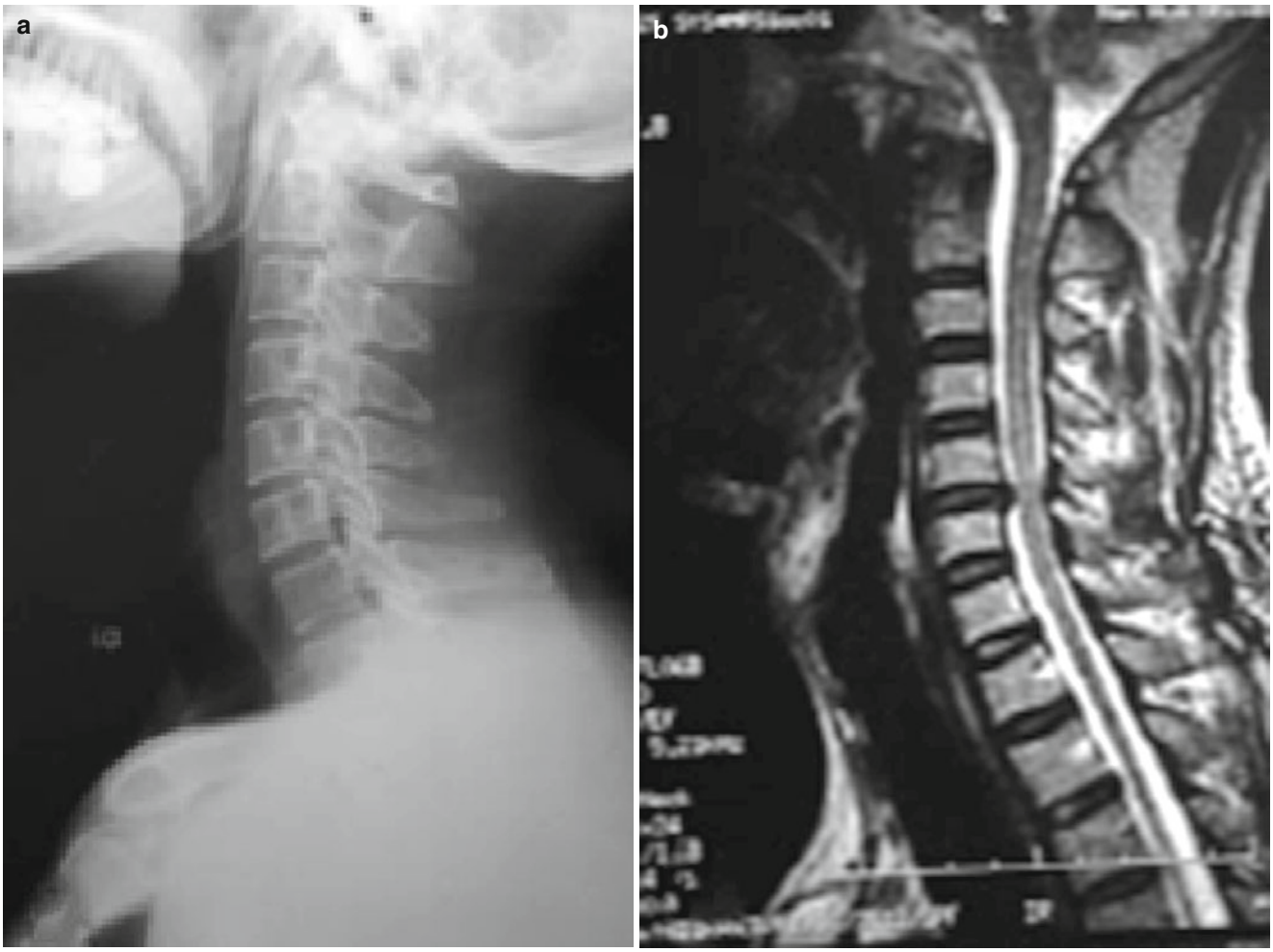


Fig. 23.12 (**a**) Preoperative lateral cervical radiograph. (**b**) Preoperative cervical MRI: sagittal slice demonstrating a C5–6 herniation with compression on the spinal cord. (**c**) Postoperative AECD demonstrating initial radiograph with carbon fiber PEEK-reinforced cage. (**d**) Postoperative cervical MRI demonstrating decompression following removal of herniation at C5–6. (**e**) Final 7-year postoperative cervical lateral radiograph demonstrating bony fusion and solid incorporation of the PEEK cage at C5–6 (From Yao et al. [19]; used with permission)

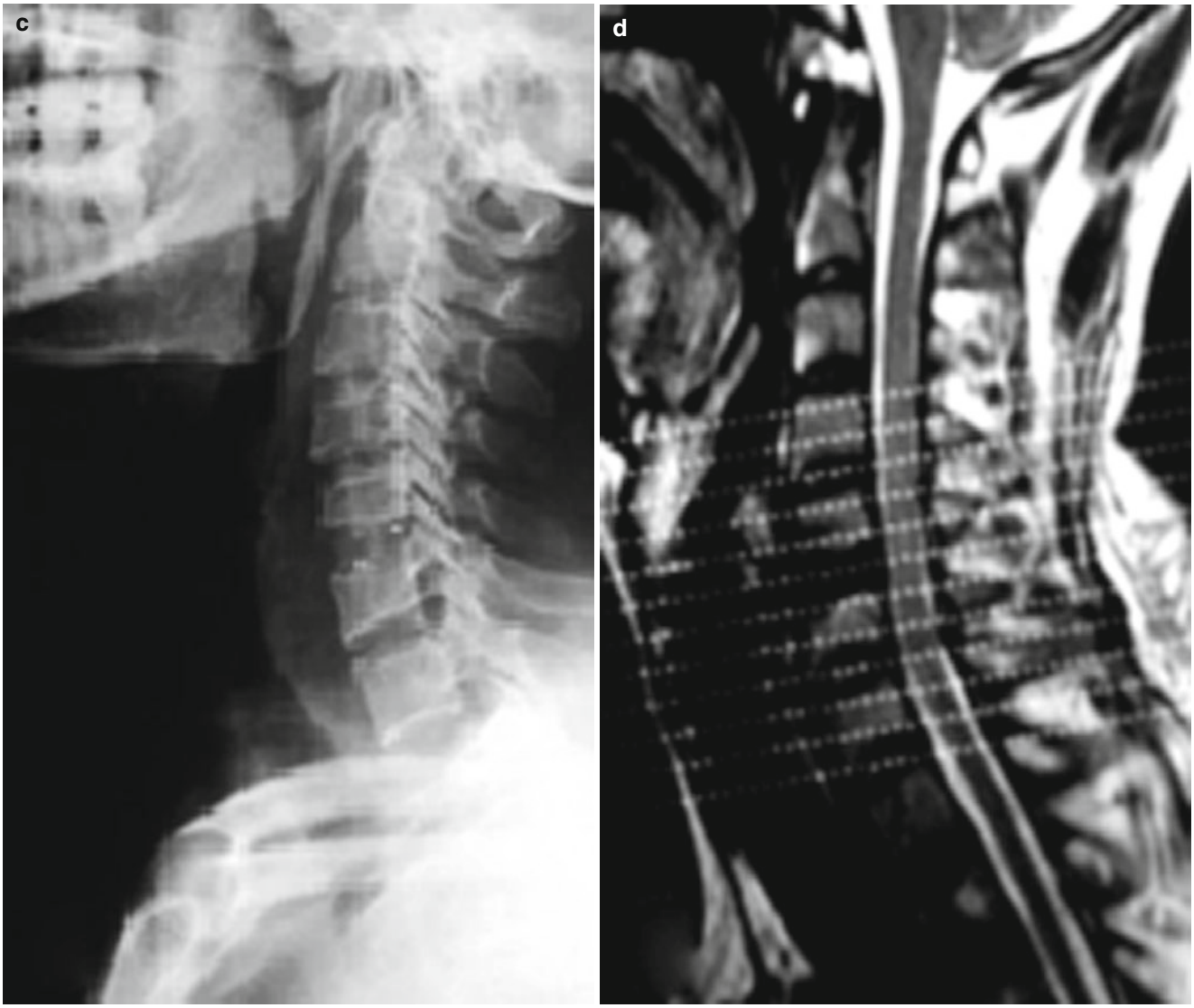


Fig. 23.12 (continued)

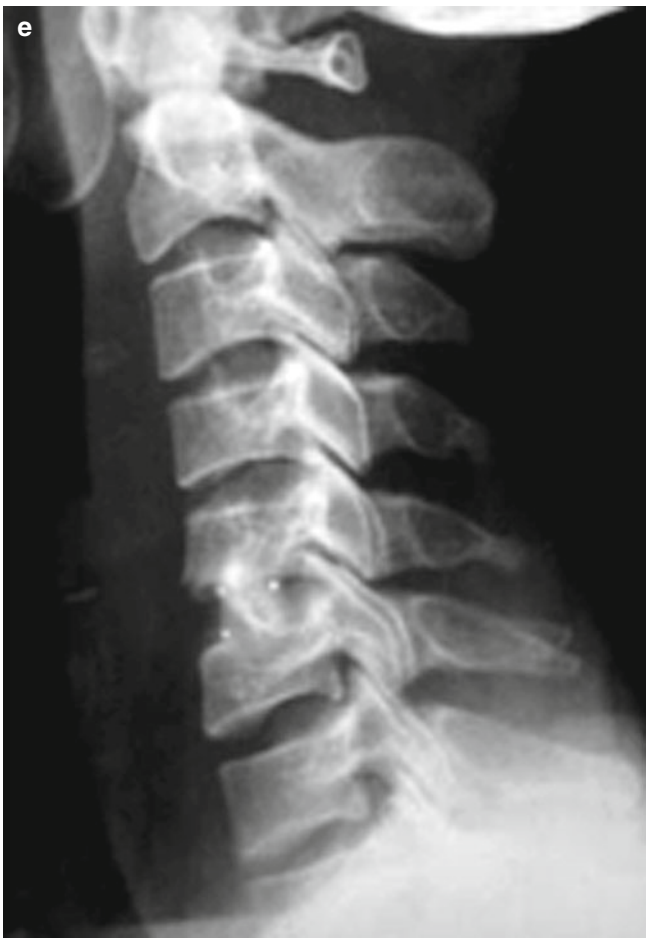


Fig. 23.12 (continued)

cervical discectomy and fusion with carbon fiber-reinforced cage (Fig. 23.12c). Postoperatively her VAS neck pain was rated 1/10. She noted only a moderate occasional scapular pain with excellent outcomes otherwise. Postoperative cervical MRI demonstrates decompression at C5–6 (Fig. 23.12d). Postoperative radiographs at 7 years demonstrated appropriate bony consolidation and some loss of lordosis, and the dynamic radiographs demonstrated no instability (Fig. 23.12e).

Laser Anterior Endoscopic Cervical Fusion

Ryan performed the first histological study to assess the flexible delivery of CO_2 laser energy to brain tissue and demonstrated the ability to cut and coagulate with a single instrument, without the need for excessive tissue manipulation and with minimal adjacent thermal effects [25]. The studies described by Desinger [26] and colleagues have described a combined laser and ultrasound surgical therapy (LUST) device suitable for endoscopic coagulation and tissue fragmentation.

The use of lasers in the cervical spine is for the most part reported in its own literature and journals. Percutaneous laser disc decompression (PLDD) [27] was first used in 1986 and received approval from the US Food and Drug Administration in 1991. This percutaneous procedure is performed without endoscopic visualization and only with fluoroscopic guidance and cannulas. Since then PLDD has increased in popularity, with reportedly over 30,000 PLDD procedures performed since 2001. PLDD is performed under local anesthesia via a laser fiber or radiofrequency wand percutaneously inserted into the nucleus pulposus. Radiofrequency is performed with 800–1,200 kJ dispersed with a holmium:yttrium-aluminum-garnet (Ho:YAG) laser. Laser energy is then applied through the fiber, resulting in vaporization of nucleus pulposus and disc contents, which is thought to simultaneously encourage tissue ingrowth.

Surgical Technique

The anterior minimally invasive endoscopic approaches are typically performed through a similar anterior transdiscal corridor. This procedure is often performed under conscious intravenous sedation, but general anesthesia can be used for the restless patient. The standard anterior Smith-Robinson plane is employed, and an 18-gauge spinal needle is placed transdermally into the proposed disc space. After fluoroscopic localization confirms the intended disc level, a discogram is performed at this time if it had not been done preoperatively. Next a 3-mm incision is made around the needle, and a narrow guidewire stylet is passed over the needle into the disc space. From there cannulas are sequentially introduced over the stylet, and a trephine is used to incise the outer annulus. Essentially the procedure consists of performing a small anulotomy anteriorly with cannula-supported instrumentation, endoscopic monitors, fluoroscopy guidance, and a discectomy through a series of endoscopic intradiscal instruments. These include standard instruments for mechanical disc decompression such as radiofrequency or side-firing Ho:YAG laser delivery. The Ho:YAG laser is a side-firing probe used at nonablative levels at 10Hz for 5 s on and 5 s off (first stage 8 W/300 J, second stage 5 W/200 J) [18]. Afterward endoscopy is used to confirm discectomy and laser thermodiscoplasty. Neuroforaminal decompression is performed with a series of discectomies, forceps, microrasps, microtrephines, and microcurettes. Bupivacaine 0.25 % is applied locally, and an adhesive bandage is placed over the incision. Patients are encouraged to ambulate within 1 h of the procedure. They are discharged home hours after the procedure and employ a soft cervical collar for comfort as needed within the next 3 days. Neck exercises are started on postoperative day 2, and they are allowed to return to work in 2 weeks.

Laser Anterior Endoscopic Cervical Fusion Outcomes and Complications

1. Discitis
2. Dysesthesia
3. Breathing difficulty

4. Horner's syndrome
5. Motor/sensory deficits
6. Postoperative hoarseness
7. Additional secondary procedures
8. Vascular complications: hematoma evacuation

The International Multicenter Cervical Minimally Invasive Surgery Study focused on complications incurred in over 3,000 patients. The study focused on complications incurred in these patients. The reported patient satisfaction ranged from 90 to 94.5 % [18]. There were five reported cases of discitis, six cases of motor/sensory deficit, one case of dysesthesia, and zero cases of cerebrospinal fluid leaks. The study described 37 s operative procedures which varied according to center. One center reported one patient necessitating an additional procedure, some ranged between 4 and 8 patients requiring an additional surgery, and another center reported 16 patients who underwent a secondary procedure. Reuter described a series of complications during the intraoperative phase [21]. One patient had breathing difficulty secondary to anesthesia. Two patients developed vascular complications necessitating an emergency airway and hematoma evacuation. He found a 4 % fusion rate after the index discectomy. Chiu reports one case of transient postoperative hoarseness and one case of transient Horner's syndrome which lasted 1 day, out of 1,200 cases of AECD [17]. There have also been several anecdotal reports of postoperative bony lysis and disintegration as a result of laser thermal energies.

The use of lasers near the spinal cord poses considerable obvious risks and demands a high learning curve, so their transition into our regular practice should be considered carefully before their implementation. Again a randomized, prospective study comparing this minimally invasive laser procedure with open surgeries would be necessary to fully appreciate any theoretical benefits of this approach to cervical fusion.

Case Study: Laser Complication (Case Study with Revision Courtesy of R. Rabbani M.D./G. Tepper M.D.)

A 53-year-old male, otherwise healthy, presented 7 weeks after multiple level percutaneous laser surgery to the cervical spine for neck and arm pain. The patient complained of an acute worsening of neck pain and a new-onset kyphotic neck deformity with a concomitant aggravation of arm pain. The patient demonstrated upper motor neuron signs: hyperreflexic/spasticity/Hoffman's/Romberg's sign on exam with diffuse weakness in upper extremities—Grade 4/5 throughout the biceps, brachioradialis, wrist extensors, interosseous, and finger extensors.

Postoperative imaging from the percutaneous laser procedure was limited due to the patient's body habitus. Postoperative MRI and computed tomography revealed bony osteolysis involving C5, C6, and the upper half of C7 (Fig. 23.13). There was also a kyphotic deformity present with multilevel spinal cord compression stemming from deformity of the bone and disc. The patient underwent a two-stage operation. Stage I consisted of C5 and C6 corpectomy with placement of PEEK device with autologous bone from C4 to C7 and anterior cervical plating from C4 to C7. Intraoperatively the bone appeared to be liquified; cultures were sent which were negative. Stage II consisted of C4 to C7 posterior spinal instrumentation and fusion with lateral mass fixation and iliac crest bone graft (Fig. 23.14).

Posterior-Based Approaches

Herniation

Microscopic and Endoscopic Laminoforaminotomy

Charles Elsberg first described the standard open laminoforaminotomy in 1925 for the localization and decompression of spinal cord tumors [28]. This approach is now widely used as a means for the decompression of lateral pathology such as stenosis, herniations, and/or osteophytes while allowing for the preservation of normal biomechanics. A trend toward MIS endoscopic laminoforaminotomy commenced after techniques using tubular retractors were first described by Roh and adapted for use in the clinical practice by Adamson in 2001 [29, 30]. This approach is usually performed for soft foraminal disc herniations when the largest part of the herniation is lateral to the margin of the spinal cord.

Microscopic Tubular-Assisted Posterior Laminoforaminotomy

Indications: Foraminal Compression of the Nerve Root

1. Synovial cysts
2. Unilateral pathology
3. Foraminal soft disc herniations
4. Stenosis from arthropathy or osteophytic spurs
5. Single level or two contiguous nerve root levels
6. Persistent foraminal stenosis after an anterior procedure
7. Multiple level foraminal stenosis without central stenosis
8. Root compression where anterior approaches are difficult or contraindicated (i.e., tracheostomy, radiation, cervicothoracic junction)

Microscopic Tubular-Assisted Posterior Laminoforaminotomy Surgical Technique

The procedure can be performed with the patient prone or in the sitting position with the neck secured in a Mayfield head holder in a slightly flexed position (Mayfield head holder: Integra Life Science, Plainsboro, NJ). Under anterior-posterior fluoroscopy, the line of the spinal joints is marked,

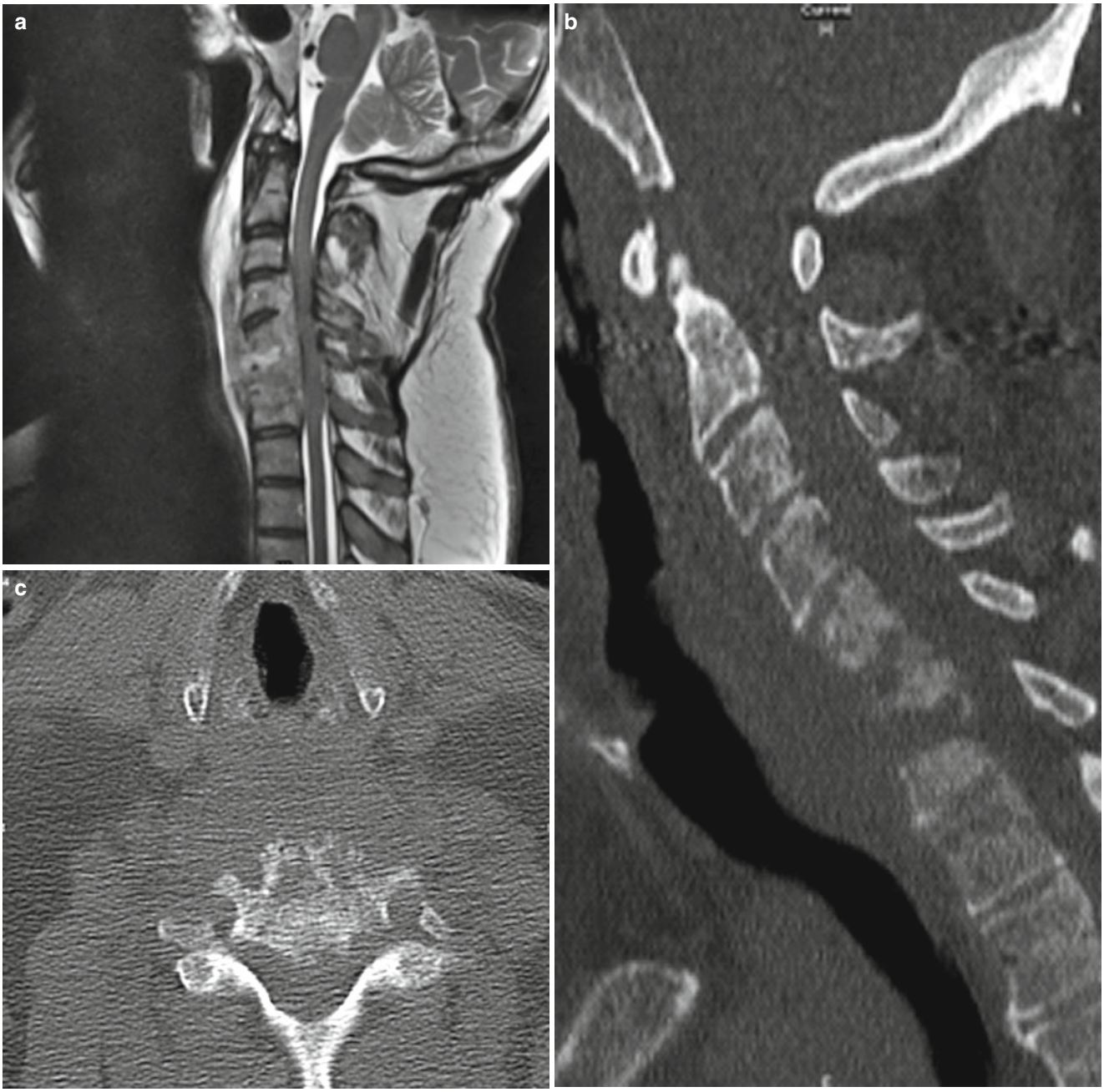


Fig. 23.13 (**a**) Postoperative MRI: postoperative cervical MRI demonstrating bony osteolysis and significant spinal cord compression following percutaneous laser discectomy. (**b**, **c**) Postoperative computed tomography demonstrating bony osteolysis and kyphotic deformity secondary to percutaneous laser surgery

and the remainder of the procedure is performed under lateral fluoroscopy. An 18-gauge needle is placed in line with the correct foraminal level and confirmed on lateral fluoroscopy. With the standard approach, a 1.5-cm posterior midline skin incision is employed by cutting through the raphe and allowing for symmetrical retraction of the paraspinal musculature. Alternatively a paramedian 1.5-cm incision based on lateral fluoroscopy can be made ~2 cm off midline for a unilateral foraminotomies. Once the paraspinal fascia is incised, a series of blunt dilators are advanced through the soft tissue until they lie on the desired laminae and lateral masses. Next tubular dilators allow for soft tissue mobilization and ultimately the placement of a tubular port. A confirmatory radiograph is obtained prior to bony exposure. Using a combination of soft tissue dissection with bovie and bipolar cautery, the interlaminar space is identified under microscopic visualization. A small keyhole laminotomy is performed in standard fashion using a long-handled high-speed drill with an AM8

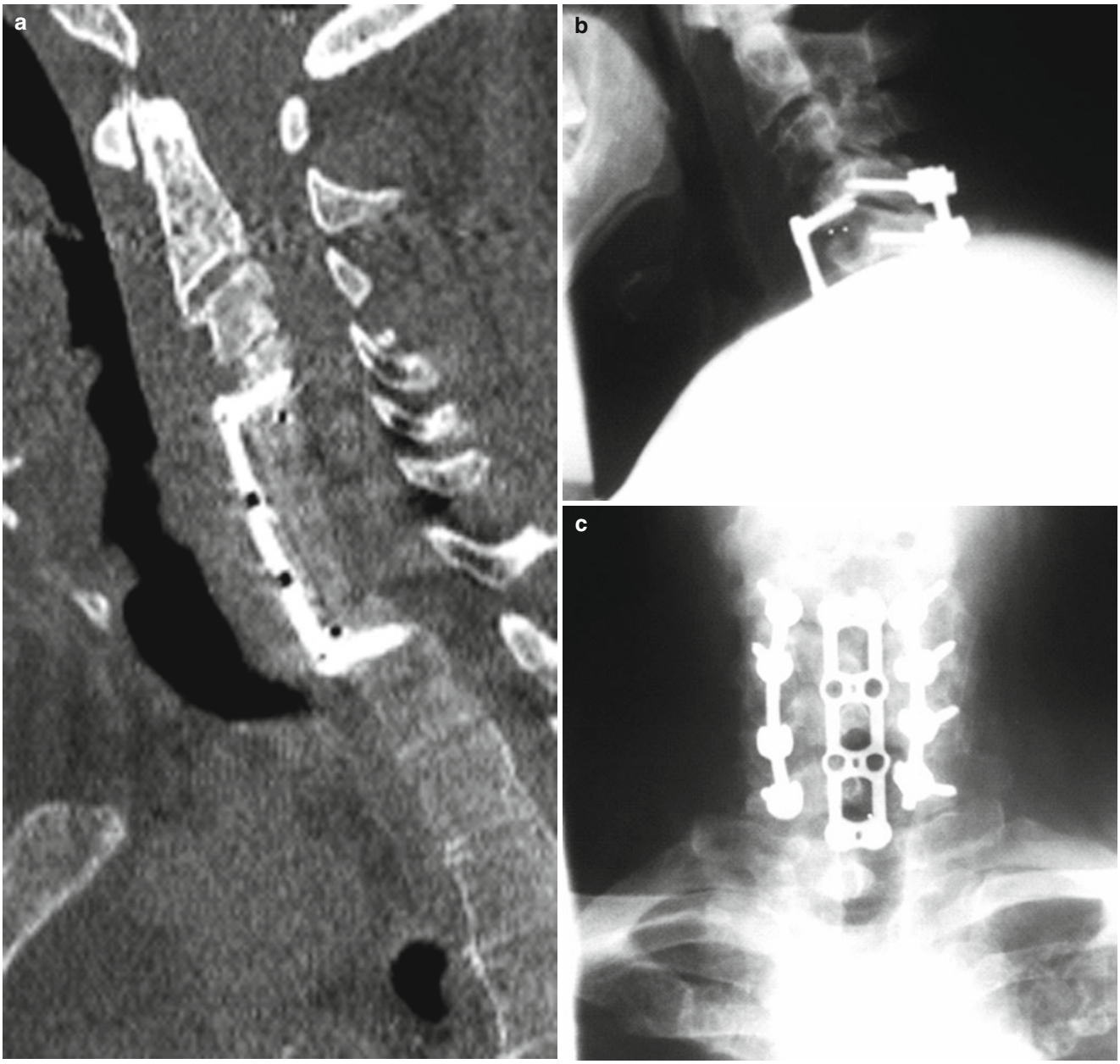


Fig. 23.14 (**a**) Final postoperative CT; (**b**, **c**) final postoperative anterior-posterior and lateral radiographs

ball-shaped diamond cutting burr (*Anspach*®, Palm Beach Gardens, Fla., USA/*Midas Rex*® Legend® Fort Worth, Tex., USA). The medial third of the facet joint is removed with a burr. Next the pedicle must be identified and palpated with a nerve hook in order to determine the lateral extent of the dissection and to confirm the orientation. The lateral margin of the spinal cord is visualized near the origin of the affected root, and a foraminotomy is performed removing accessible osteophytes. The underlying root is carefully mobilized and hemostasis is maintained. For soft lateral disc herniations, the underlying fragment is visualized, and a discectomy is performed with a combination of nerve hooks and pituitaries. The wound is copiously irrigated, and the tubular retractor is removed under microscopic visualization to ensure proper hemostasis. Prior to closure the area is flushed with saline, and a hemostatic agent can be applied if needed.

Endoscopic Laminoforaminotomy Surgical Technique

The procedure is identical with the exception of visualization. The manufacturing of small-diameter high-resolution glass rod endoscopes has allowed for improved visualization through narrow portals, while allowing access for bayoneted surgical instrumentation and their manipulation

(Fig. 23.12d, e). The 25° endoscope is mounted within the tubular retractor allowing for visualization of the interlaminar space and facet joints.

Microscopic Tubular-Assisted Posterior Laminoforaminotomy (MTPL)

One small prospective randomized trial, from Korea, demonstrated reduced analgesic requirements and hospital stays for the MTPL group with similar clinical improvements [31]. In a follow-up study Winder et al. compared MTPL to traditional open laminoforaminotomy in a retrospective review with moderate numbers [32]. They found no significant difference between open and MPTL in the realms of surgical time or complication rates. There were however statistically significant differences seen in blood loss, recovery, discharge analgesia requirements, and length of hospital stay. Mean blood loss was 233 cc for the open group versus 96 cc for the tubular cohort. The average length of hospital stay was shorter for the tubular group at 26.9 h versus 58.6 h in the open cohort. Recovery room analgesia and discharge analgesic requirements were similarly less for the tubular group versus open. Sixty two percent of patients who underwent tubular foraminotomy were discharged the same day of the procedure compared with 9.2 % for the open group. Clarke noted that with open foraminotomy, same-segment disease developed in 10 of 303 procedures or 3.9 per 1,000 person-years at risk which is similar to the rate of disease at a non-operated level.

Endoscopic Laminoforaminotomy Versus ACDF

Differences between ACDF and foraminotomies include approach-related morbidities, the pathology being targeted, and postoperative patient recovery. Experience will determine whether this procedure could lessen or eliminate some risks seen with traditional ACDF such as the risk of laryngeal nerve injury (3.1 %) (superior or recurrent), dysphagia (9.5 %), aspiration, hematoma (5.6 %), esophageal injury/perforation (0.25 %), graft site complications, unilateral Horner's syndrome (0.1 %), spinal cord injury (0.001 %), cerebrospinal fluid (CSF) leak (0.5 %), and major vascular injury [33]. Ruetten et al. performed a prospective randomized controlled study comparing results of cervical discectomies in full endoscopic posterior laminoforaminotomies with the conventional microsurgical anterior decompression and fusion [34]. Inclusion criteria for the study were patients with unilateral radiculopathy with arm pain and an MRI/CT demonstrating lateral or foraminal localized monosegmental disc herniation. Patients with instability, deformities, isolated neck pain, or medial localization of the disc herniation were excluded. One hundred seventy-five patients were studied with a 2-year follow-up period and found to have similar clinical results and no significant differences in their complication or revision rates. The mean operating time for the endoscopic group was 28 min compared with 68 min for the ACDF cohort. There was no appreciable blood loss for the endoscopic group due to constant lavage and bipolar cautery, where the ACDF group totaled less than 10 mL intra- and postoperative. Both groups demonstrated equal reduction in radicular pains, and no differences were observed in other functional, physiologic, or perceived outcomes. In total ten patients (four in the ACDF group and six in the endoscopic group) underwent revision surgery for persistent arm pain, recurrence of arm pain, or implant failure. In the short term surgery resulted in 93.7 % subjective satisfaction with a willingness to have surgery again. There were no significant complications with either arm of the study. The ACDF group had three cases of dysphagia and one case each of a surface hematoma and a cosmetically disruptive scar. The endoscopic cohort had three patients (3 %) who complained of transient dermatomal-related hypesthesia [34]. Overall the preliminary literature demonstrates that for the well-indicated patient, endoscopic techniques may maintain mobility, while minimizing soft tissue trauma, and have the potential for improved postoperative rehabilitation and possibly less adjacent level pathology.

Advantages

1. Illumination
2. Reduced bleeding
3. Rapid rehabilitation
4. Maintained mobility
5. High patient acceptance
6. Reduced soft tissue trauma
7. Facilitated revision operations
8. Low postoperative costs of care
9. Less operation-related neck pain
10. Less adjacent level breakdown
11. Expanded field of vision (25° optics)
12. High-definition image monitoring for training
13. Reduced risk of access-related complications
14. Economical procedure (no hardware, shorter operative time, fewer postoperative visits)
15. Eliminates risks unique to ACDF (Horner's syndrome, RLN injury, esophageal, dysphagia, major vascular)

Disadvantages

1. High learning curve
2. Limited field of view
3. Same-level degeneration
4. Limited to lateral pathology
5. Limited instrument maneuverability
6. Limited possibility to expand the operation
7. Inability to simultaneously address neck pain
8. No reconstruction of the intervertebral space

9. No direct decompression in ventrally caused stenosis
10. Kyphosis secondary to excessive partial resection of the facet joint

Endoscopic Laminoforaminotomy Versus Open Laminoforaminotomy

The classic open laminoforaminotomy commands a high success rate (92.8–95 %) and patient satisfaction with a low morbidity in the literature. The literature already documents high success rates for the classic open laminoforaminotomy (up to 92.8 %), where morbidity remains low [35–37]. The primary patient complaint associated with the open procedure was a transient peri-incisional pain and spasm, as a result of muscular stripping, which limited initial activity for weeks after the surgery. Recent studies of the microendoscopic approach report several complications which may relate to the high learning curve associated with the procedure. The frequency of cerebrospinal fluid fistulas is in the range of 2–8 %. Questions remain as to whether posterior foraminotomies may lead to same-level degeneration with kyphosis as a result of excessive partial facet joint resection [30, 38].

Otherwise the literature comparing endoscopic and traditional open approaches consistently demonstrates comparable outcomes [38]. When the pathology demands multilevel or bilateral foraminal decompressions, it may not be necessary to perform the procedure endoscopically. Other variables to take into account in making the decision to incorporate this procedure into a surgical practice should include the added risks associated with the high learning curve and sacrificing instrument maneuverability and visibility for comparable patient outcomes.

Complication Profile and Pearls [38, 39]

1. Dural tearing
2. Nerve root injury
3. Splitting the nerve
4. Blood loss (1 pt >800 cc)
5. Recurrent disc herniation
6. Intraoperative durotomy
7. Superficial wound infection
8. Same-segment degeneration
9. Contralateral neurogenic thoracic outlet syndrome
10. Spinal cord injury with and without K-wire misplacement

In multiple studies endoscopic and open foraminotomies yield similar outcomes and share similar complication profiles. Zdeblick demonstrated it was possible to create segmental hypermobility in vitro with more than 50 % resection of the facet joints [40]. A significant reduction in blood loss has been noted in the sitting position compared with the prone position [38, 41].This is advantageous because shoulder relaxation improves visualization on fluoroscopy and excess blood can easily drain from the cylindrical retractor without pooling and impeding visualization. For cases of intraoperative durotomy, Fessler and Khoo performed 2–3 days of lumbar drainage and observed no long-term sequelae such as pseudomeningocele, a CSF leak, or related symptoms [38]. Furthermore, serious complications are also avoided by eliminating the use of Kirschner guidewires during the process of soft tissue dilation. Given the limited size of the exposure, the risk for air embolus is negligible, but if this remains a concern a central line or precordial Doppler can be placed beforehand.

Stenosis and Myelopathy

Expansive Open-Door Laminoplasty (ELAP) Operations Versus Selective Laminoplasty

The standard expansive open cervical laminoplasty was initially developed as a treatment for ossification of the posterior longitudinal ligament (OPLL) by Oyama in 1982, and several modifications for the procedure have since been developed [42]. The laminoplasty procedure has been widely studied and demonstrated 86 % good to excellent results compared with 66 % with laminectomy [43]. Over the course of its 30-year track record, it has met with drawbacks during the perioperative and postoperative period. These include reports of postoperative hematoma, cervical malalignment, kyphosis, decreased range of motion, persistent axial neck pain, and segmental motor paralysis. Often laminoplasties are performed at C3–6/7; however, there are no specific criteria delineating the number of laminae which must be involved in the final construct. In response to this, Tsuji described selective laminoplasty, where open-door laminoplasties are performed from one level above the most cranially stenotic level(s) to a partial dome laminectomy performed near the most caudal stenotic level.

Indications

1. OPLL
2. Developmental spinal canal stenosis(<13 mm)
3. Multilevel compression cervical spondylotic myelopathy
4. Spinal canal stenosis caused by posterior elements such as the ligamentum flavum

Outcomes

Tsuji et al. conducted a retrospective cohort study following 42 consecutive patients who underwent selective expansive open-door laminoplasty (ELAP) and 22 patients who underwent conventional C3–7 ELAP and served as controls. For both groups laminoplasties were performed using Hirabayashi's open-door method [44]. With the selective ELAP group, a mean of 3.2 laminae were addressed surgically, resulting in less soft tissue trauma to the facet joint,

ligaments, and paraspinal musculature than the conventional C3–7 ELAP cohort. The study assessed canal stenosis, analgesic use, percent range of motion, mean preoperative C2–7 angle, an axial symptom scoring system (i.e., posterior neck pain, posterior neck stiffness, shoulder pain, shoulder stiffness), and JOA scores.

There was no significant difference among the recovery rate, the JOA score, C2–7 angle, and %ROM between the two groups studied.

There was a statistically significant improvement in the mean axial symptoms score for the selective ELAP group at 1 and 2 years postoperatively in comparison to the C3–7 ELAP group. The analgesics needed postoperatively in the selective ELAP group were significantly less than those used by the C3–7 ELAP group at 1 year after surgery, but not significantly different at 2 years after surgery. The incidence of segmental motor paralysis in the selective ELAP group (0 %) was significantly lower than that in C3-7 ELAP group (13 %, $p<0.037$). For the C3–7 ELAP patients who developed a C5 nerve root palsy, spontaneous recovery was observed in two out of three cases at 5 and 6 months after surgery. There was a distinct statistical correlation between the number of expanded laminae, subsequent enlargement of the space anterior to the cord, and a postoperative nerve root palsy.

Complications

Incomplete decompression as evaluated on postoperative MRI was noted in 8 % of selective ELAP patients and in 15 % of the C3–7 ELAP group. Further analysis revealed a correlation between size of the anterior compression mass on the preoperative sagittal MRI and incomplete decompression afterward. Moving forward, this understanding has led to the recommendation to expand the procedure an extra lamina in the case of an anterior compression mass measuring more than 6 mm.

A randomized, prospective study comparing the selective and standard ELAP surgeries would be necessary to fully ascertain any potential benefits of this minimal access approach for cervical laminoplasty.

Case Study: Selective Laminoplasty (Courtesy of C. Lauryssen M.D.)

A 53-year-old male who underwent a prior ACDF of C5–6 and C6–7 8 years ago developed new-onset pains along his neck, arms, and shoulders, with weakness throughout his upper extremities and hand intrinsics, with intermittent numbness and tingling. Preoperative radiographs (Fig. 23.15) demonstrated prior ACDF C5–6 and C6–7 and foraminal stenosis at C3–4 and C4–5. Preoperative MRI demonstrated severe stenosis of the spinal cord secondary to thickening of the posterior longitudinal ligament posterior to the body of C3–4, near the rostral aspect of the vertebral body of C5, with consolidation of fusion at C5–6 and C6–7 (Fig. 23.16). A preoperative cervical computed tomography (CT scan) demonstrated severe spinal cord compression behind the vertebral body of C3–4 secondary to ossification of the posterior longitudinal ligament, which had formed a bony ventral bar anterior to the cord leading to cord deformation and flattening (Fig. 23.17).

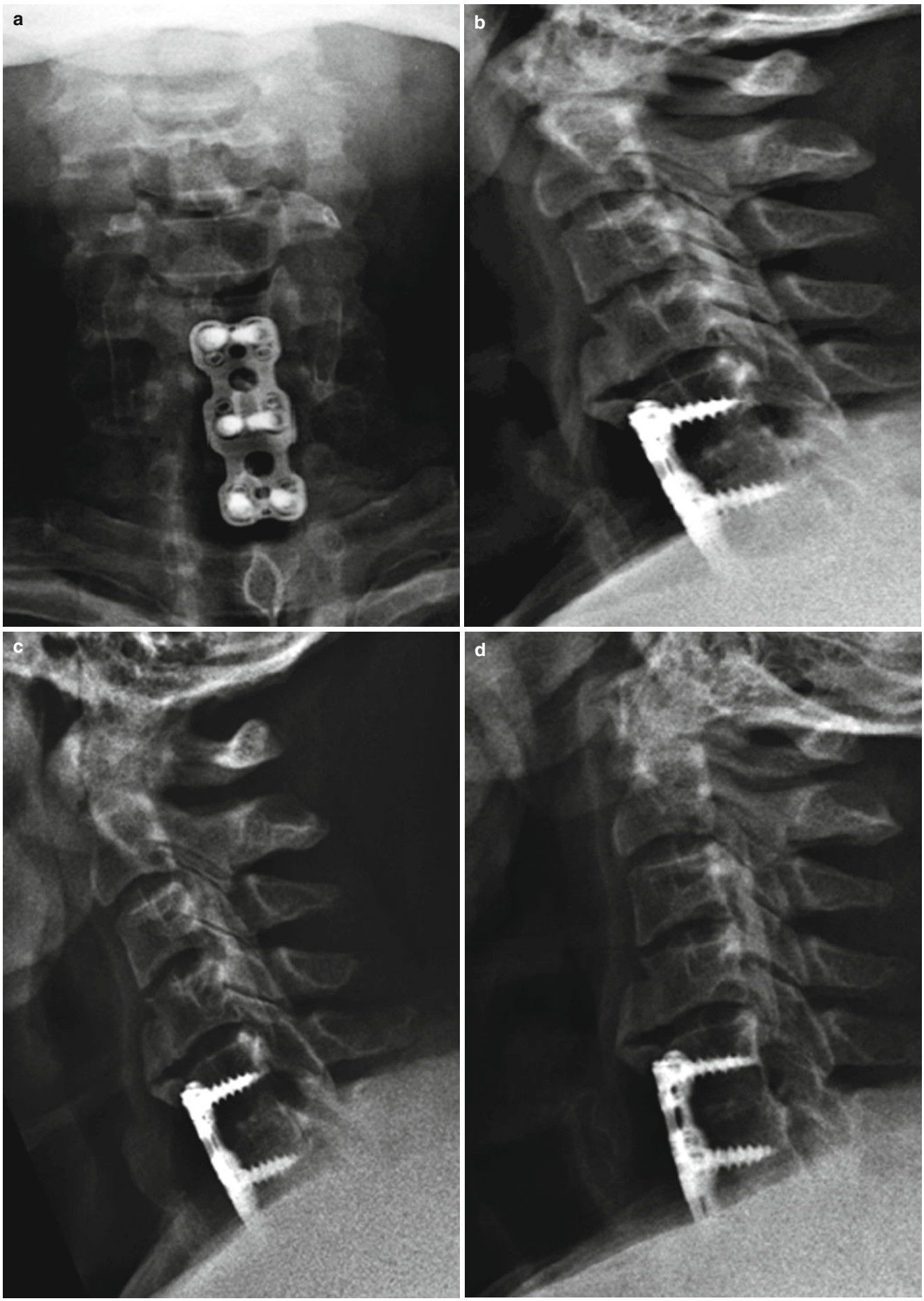
The patient underwent a selective laminoplasty of cervical 3 and cervical 4 with a half dome laminectomy of cervical 2 and cervical 5 with bilateral foraminotomies of C2, C3, C4, and C5 neuroforamina. At each laminoplasty site, an 8-mm allograft was secured to a 10-mm Aesculap laminoplasty plate and secured to the lateral mass of C4 and C3 on the left-hand side using an 8-mm screw, and a contralateral 6-mm screw secured to the lamina of C3 and C4 on the left-hand side (Fig. 23.18). The patient noticed improvement in his neck pains and resolution of his radiculopathy. Postoperative radiographs demonstrate maintenance of overall cervical alignment, with hardware intact in good position.

Skip Laminectomy

Skip laminectomy was conceived as a less invasive option to the standard open laminoplasty while allowing for adequate decompression of the spinal cord [45]. With the standard laminoplasty, patients can develop postoperative persistent neck pain, restricted range of motion, and shoulder stiffness as a result of extensive surgical exposure and dissection. Shiraishi demonstrated significant atrophy on postoperative MRI near the enthesis of these muscles despite a firm closure. With a skip laminectomy the posterior extensor mechanism is preserved as the attachments of the semispinalis cervicis and multifidus musculature to the spinous process are left untouched while the laminae are exposed [46]. This exposure involves only intermuscular corridors preventing damage to their epimysium while preserving the mobility and stability of the cervical spine [46, 47].

With this technique a standard midline incision is performed in line with the spinous processes, and this is continued through the deep cervical fascia and nuchal ligament to expose the layout and arrangements of the deep extensor muscles and their intermuscular planes. An interval between the tips of the spinous processes is developed under microscopic visualization. The lamina and lateral masses are exposed by creating an intermuscular plane between the adjacent upper and lower semispinalis cervicis and the interspinalis (Fig. 23.19). In the upper cervical spine the same exposure can be obtained with blunt dissection through the intermuscular plane between the semispinalis cervicis and the obliquus capitis inferior muscle.

Fig. 23.15 Selective laminoplasty figures. Preoperative radiographs (**a**–**d**) demonstrated prior ACDF C5–6 and C6–7 and foraminal stenosis at C3–4 and C4–5. Anterior broad-based bony spurs and adjacent level pathology at C4–5


a
b
c
d

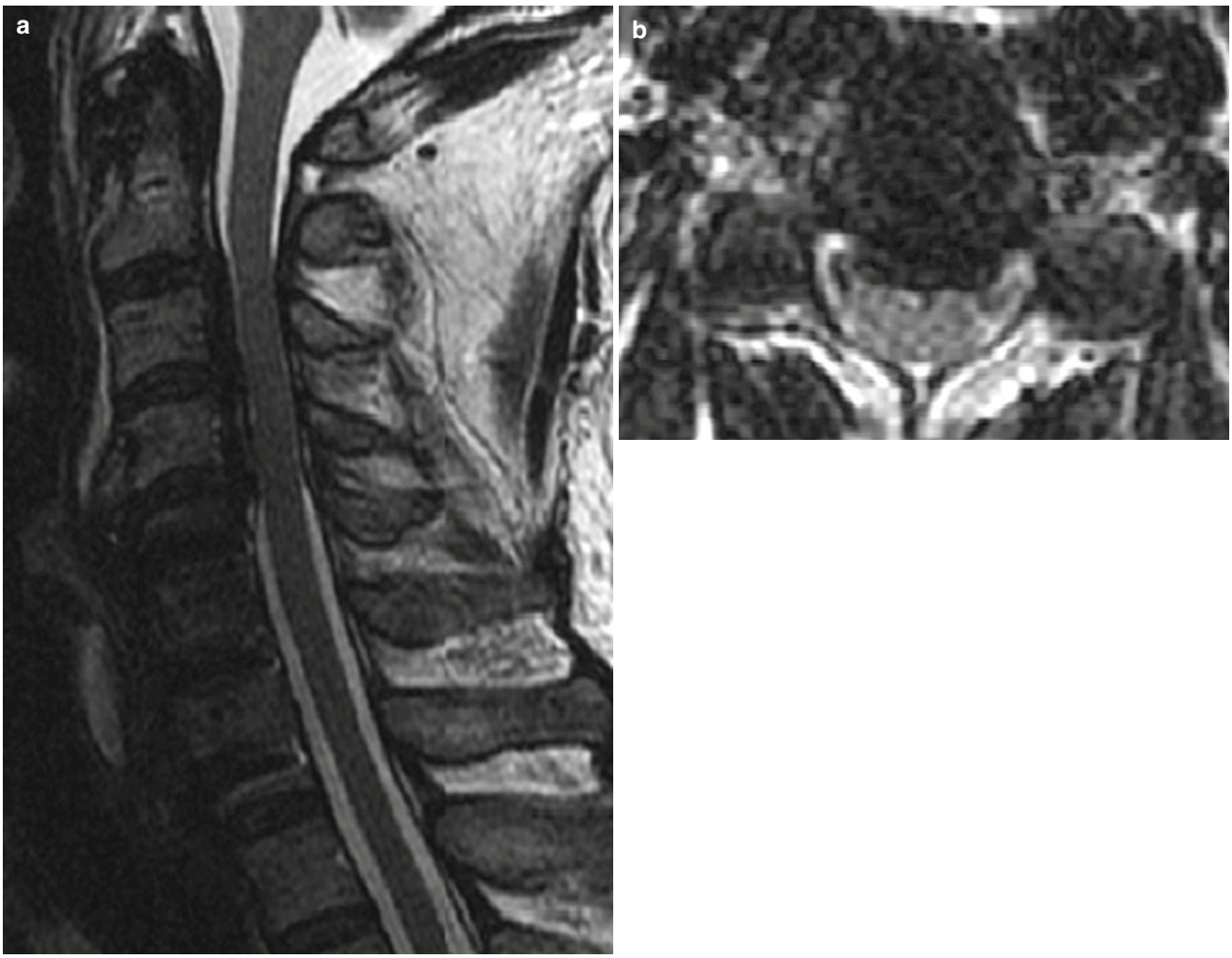


Fig. 23.16 (**a**, **b**) Preoperative MRI demonstrated severe stenosis of the spinal cord secondary to ossification of the posterior longitudinal ligament posterior to the body of C3–4, near the rostral aspect of the vertebral body of C5, with consolidation of fusion at C5–6 and C6–7

In this manner the interlaminar spaces, upper and lower ridges of each spinous process, lamina, and ligamentum flavum can be exposed from C2–3 to C6–7. As an example, skip laminectomies of the C4 and C6 laminae are removed with a fine 3-mm diamond-tipped burr in standard fashion leaving the enthesis of the semispinalis cervicis and multifidus intact bilaterally (Fig. 23.20). Removal of the C4 lamina allows access to all areas of stenosis and the ligamentum flavum spanning from the caudal aspect of C3 to the cephalad portion of the C5 lamina. The lower two levels are decompressed in a similar manner with a C6 laminectomy.

Indications

1. Congenital stenosis
2. Calcification of yellow ligament (CYL)
3. Multisegmental cervical spondylotic myelopathy
4. Segmental or localized ossification of posterior longitudinal ligament (OPLL)

Skip Laminectomy Versus Laminoplasty Outcomes

Shiraishi performed a retrospective review comparing his skip laminectomy patients to his open-door laminoplasty patients over a 2-year period [45]. In the short term there was no significant difference in recovery rates with either surgery. None of the skip laminectomy patients developed neurologic complications, whereas 3 open-door laminoplasty patients developed C5 paresis, which resolved in two patients. Shiraishi found significantly less blood loss, less axial neck pain, and improved range of motion with the skip laminectomy group. There was also a significant difference in the deep extensor muscular atrophy rate seen with the skip laminectomy group 13.6 % versus 59.7 % with the laminoplasty cohort. Skip laminectomy may provide an alternative to laminoplasty while reducing complications of standard expansile laminoplasty such as persistent axial symptoms, C5 paresis, bony union near the facet joint/hinge junction, postoperative restriction of motion, and loss of lordosis.

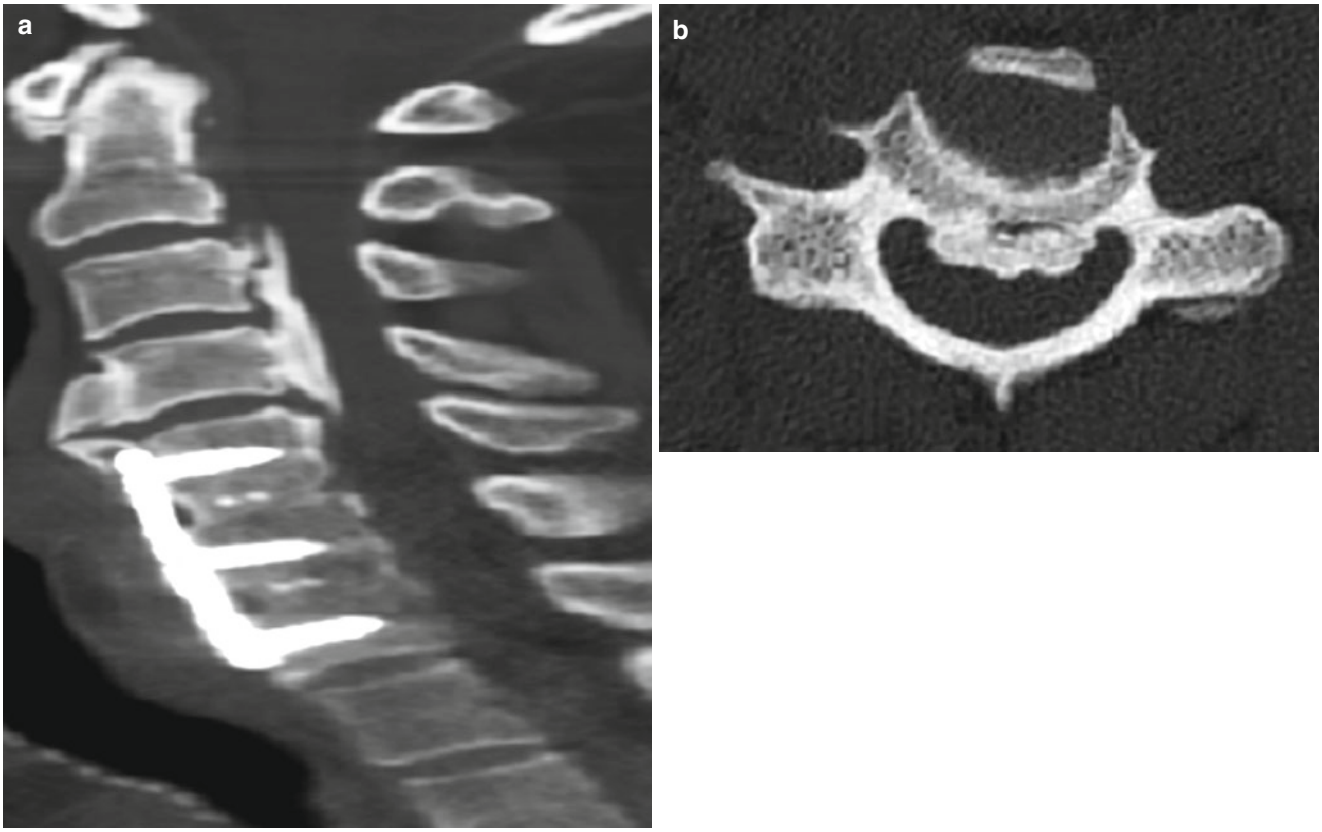


Fig. 23.17 (**a**, **b**) Preoperative CT scan image demonstrates severe spinal cord compression behind the vertebral body of C3–4 secondary to ossification of the posterior longitudinal ligament, which had formed a bony ventral bar anterior to the cord leading to cord deformation and flattening

Employing the standard midline open exposure, Yukawa et al. performed a randomized prospective study comparing skip laminectomy and laminoplasty for the treatment of compressive cervical spondylotic myelopathy [48]. In this study the skip laminectomy group experienced a better recovery of postoperative range of motion. There was no significant difference in the clinical results, postoperative axial neck pain, or blood loss. Perhaps this demonstrates the significance of the muscle-sparing approaches of Shiraishi and the importance of the dynamic stabilizers of the cervical spine.

Complications

As a result of excessive bone resection for partial laminotomy, two patients sustained a unilateral and one a bilateral fracture of the preserved lamina. All instances of postoperative laminar fractures healed within 6 months of surgery. On postoperative MRI two patients had CSF leakage which had resolved within 1 year of surgery.

Case Study: Skip Laminectomy (Courtesy of T. Shiraishi M.D.)

A 78-year-old male who initially described numbness and clumsiness in both hands was treated conservatively for $1^{1/2}$ years. He then began noticing problems with his handwriting, using chopsticks, and buttoning his shirt. He sought further treatment as his gait began to steadily worsen, and he developed a tendency for falling. Upon referral he had already developed severe cervical spondylotic myelopathy with preoperative JOA score of 8/17. Preoperative imaging demonstrated developmental canal severe stenosis with myelomalacia and high-signal-intensity changes throughout the spinal cord at C4/5, C5/6, and C6/7 on T2-weighted sagittal MRI (Figs. 23.21 and 23.22). In order to halt the progression of the disease, he underwent C4 and C6 skip laminectomy.

An intraoperative photo of C4–C6 laminoplasty with C5 spinous process and its attached muscles preserved (Fig. 23.23).

He started to stand and walk without neck support of any kind on the first postoperative morning followed by an uneventful postoperative course. MRI taken 4 months after surgery demonstrated adequate decompression of the spinal cord associated with subarachnoid space expansion (Fig. 23.24). His 1-year postoperative radiographs demonstrate a maintenance of cervical lordosis with no loss in range of motion (Fig. 23.25). His JOA score at recent follow-up in

February 2012 was 10/17 with a recovery rate of 22.2 % and a mild improvement in his gait, clumsiness, and walking.

Endoscopic/Percutaneous Posterior Fixation

The mandate for minimally invasive posterior fixation constructs has been restricted by the need to perform a concomitant decompression of the spinal cord across multiple segments and the difficulty associated with rod passage. However, for three or fewer spinal levels, tubular dilator retractors and endoscopic and percutaneous methods of fixation have emerged in the past decade. The perioperative complications of posterior cervical fixation have in part led to a trend toward minimally invasive options. Patient complaints of spasms and peri-incisional neck pain derive from the approach, which detaches the semispinalis cervicis and multifidus musculature. Postoperative imaging demonstrates muscular atrophy and unintended adjacent level fusions. There are also rare instances of cosmetic defects from muscular dehiscence and midline fascial retraction. In efforts to minimize the dissection, atrophy, and pain, tubular and endoscopic techniques have emerged as an alternative to the standard open exposure. While these new procedures offer the surgeon minimal access, they entail a high learning curve while surrendering some visualization and instrument maneuverability.

Endoscopic/Tubular Lateral Mass Screw Placement

Indications

1. Tumor
2. Trauma
3. Facet fractures

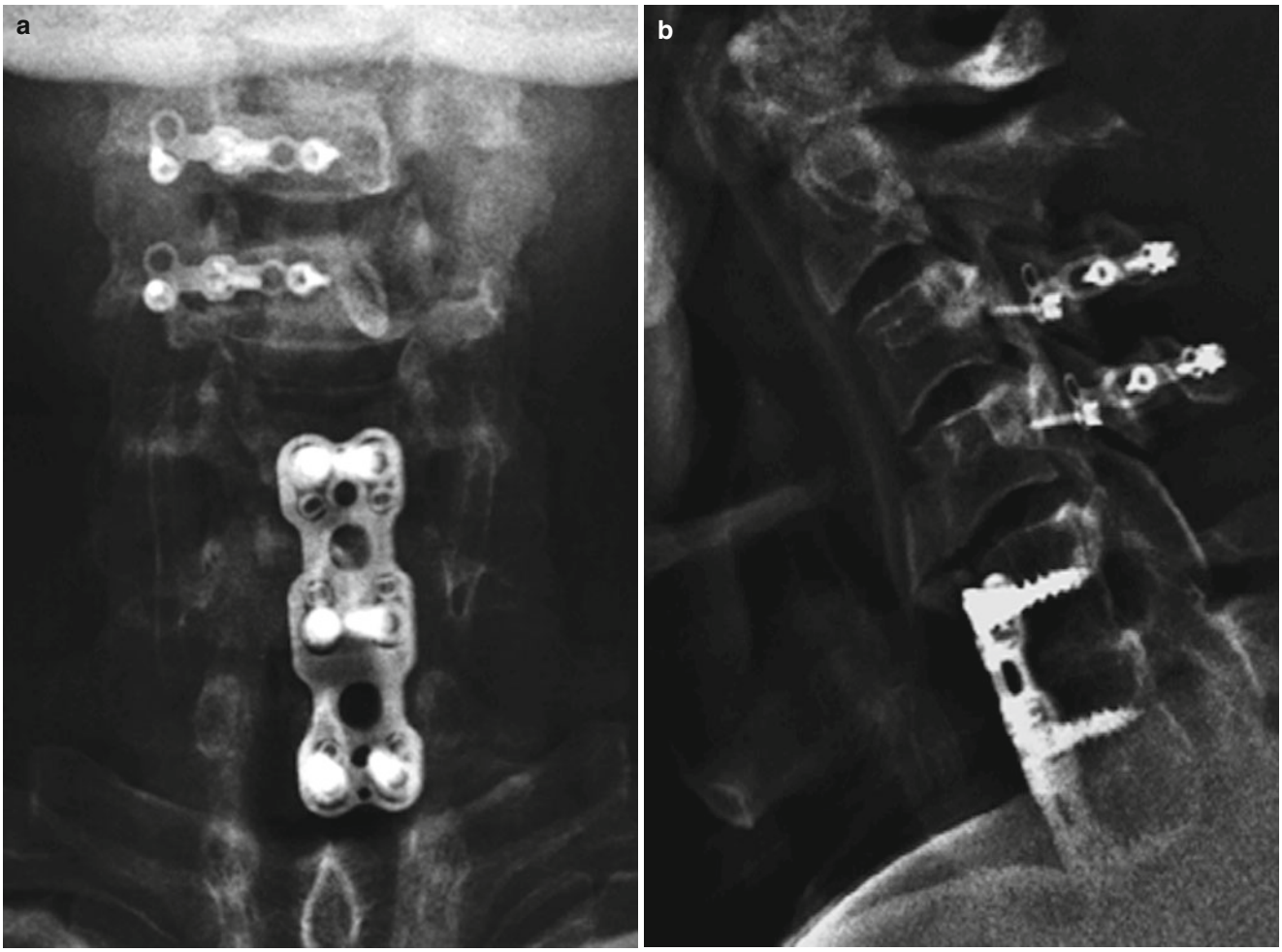


Fig. 23.18 (**a**–**c**) Postoperative radiographs

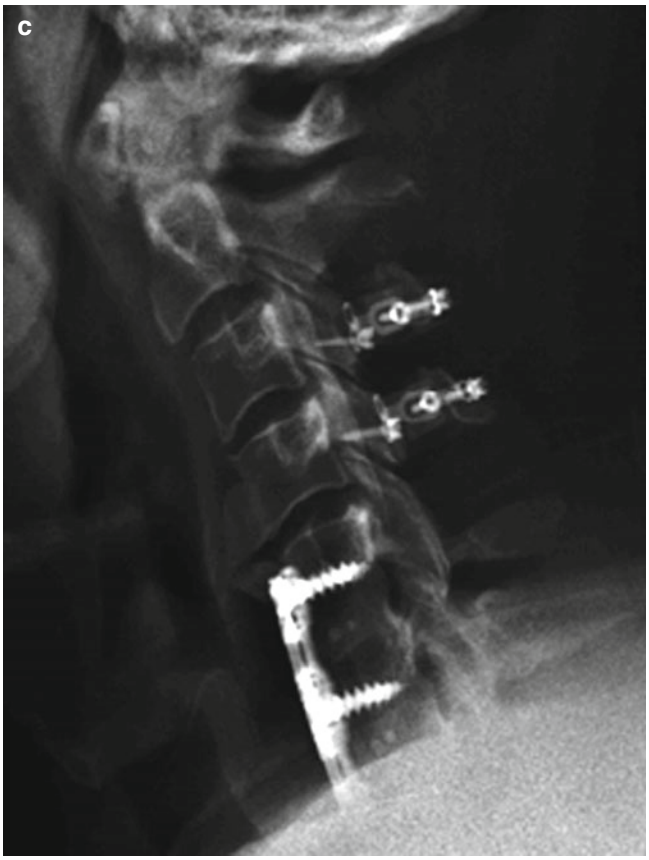


Fig. 23.18 (continued)

4. Facet dislocations
5. Osteoporotic bone
6. Anterior pseudoarthrosis

The minimally invasive technique does not differ from open methods after obtaining sufficient exposure; however, it is generally limited to three spinal levels. Otherwise its indications are identical to those used for standard posterior fixation. Examples of this include pseudoarthrosis, cervical spinal instability secondary to tumor, anterior columnar infection, trauma, cervical kyphotic deformity, reinforcement of an anterior corpectomy, fractures with disruption of the anterior and posterior column, and palliative stabilization of metastatic lesions in patients with lower life expectancy.

Technique

With the patient secured in Mayfield skull tongs in a prone position, the cervical spine is visualized from multiple perspectives to ensure neutral positioning and to eliminate any malrotation. A stab-wound incision with a No. 11 blade scalpel is made approximately three levels below the intended lateral mass. Next a blunted narrow dilator is placed through the incision and directed approximately 45° in a rostrolateral course parallel to the facet joints in their sagittal plane. Next a 1.5-cm–2-cm stab-wound incision is fashioned to accommodate the serial dilators or endoscopy instrumentation. Bulky or overgrown bifid spinous processes should be identified on preoperative imaging as they may restrict skirted tube position, drilling, or subsequent screw placement. Any overlying soft tissue is removed in standard manner for lateral mass exposure and visualization. The facet joints can be debrided manually with a curette or with a B1 drill bit placed within the joints to ensure complete cartilaginous removal (Anspach®, Palm Beach Gardens, Fla., USA/*Midas Rex*® Legend® Fort Worth, Tex., USA). The joints can then be packed with local autogenous bone, calcium carbonates, or demineralized bony matrix. The remainder of the procedure is performed under fluoroscopic guidance. Next landmarks are placed in accordance to one's preferred trajectories (Magerl, An, or Roy-Camille) by piercing the posterolateral mass cortex with the tip of a long-handled high-speed drill AM8 ball-shaped diamond cutting burr (Anspach®, Palm Beach Gardens, Fla., USA/*Midas Rex*® Legend® Fort Worth, Tex., USA). Our preferred starting point lies 1 mm inferior and 1 mm medial to the lateral mass quadrant bisection. Next the 2.4-mm cancellous drill, set at 12 mm, is seated in the starting hole and advanced in line with the facet joint under lateral fluoroscopy. If bicortical purchase is required, the drill can then be advanced to 14 mm or 16 mm for distal cortical purchase. Next a 14- or 16-mm-long x 3.5-mm-diameter polyaxial screw is placed through the skirted tube under direct vision. Until newer instrumentation is manufactured the difficulty with rod passage tends to limit this procedure to three levels. Prior to rod placement all cortical bone can be denuded to obtain a broad posterolateral fusion.

Complications/Hazards

According to the case series literature, the reported complications are limited to superficial skin infections and approach-related difficulty requiring open conversion. Hazards include nearby neurovascular structures (spinal cord, nerve, vertebral artery) and lateral mass fracture while placing screws.

Percutaneous Cervical Transfacet Screws

The percutaneous transarticular screw was first employed by Roy-Camille et al. in 1972 for use in lateral mass fractures [49]. In the cadaveric spine transfacet screws have demonstrated similar biomechanical properties to lateral mass screw and rod constructs. Their only biomechanical

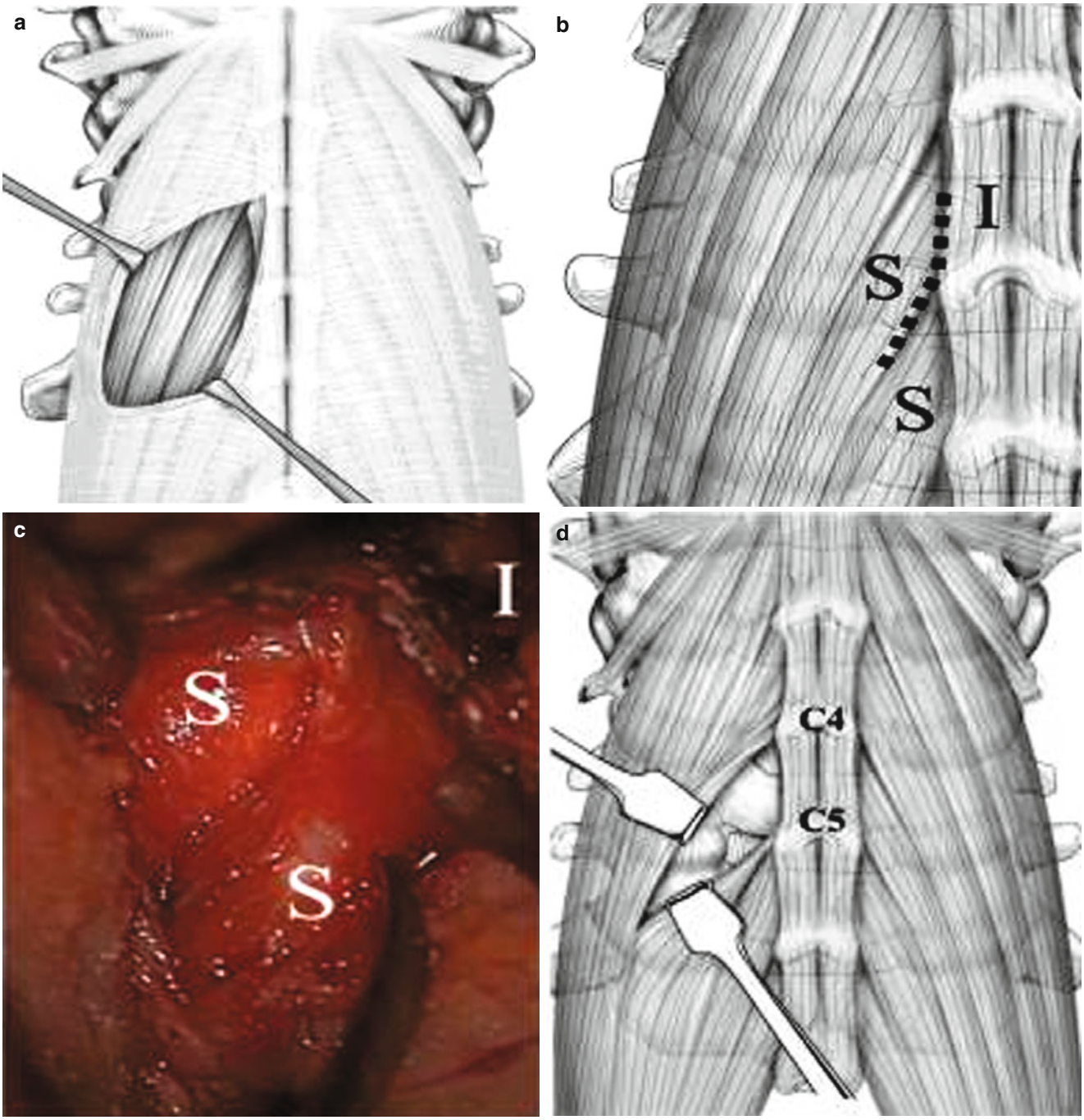


Fig. 23.19 (**a**–**e**) An interval between the tips of the spinous processes is developed under microscopic visualization. The lamina and lateral masses are exposed by creating an intermuscular plane between the adjacent upper and lower semispinalis cervicis and the interspinalis

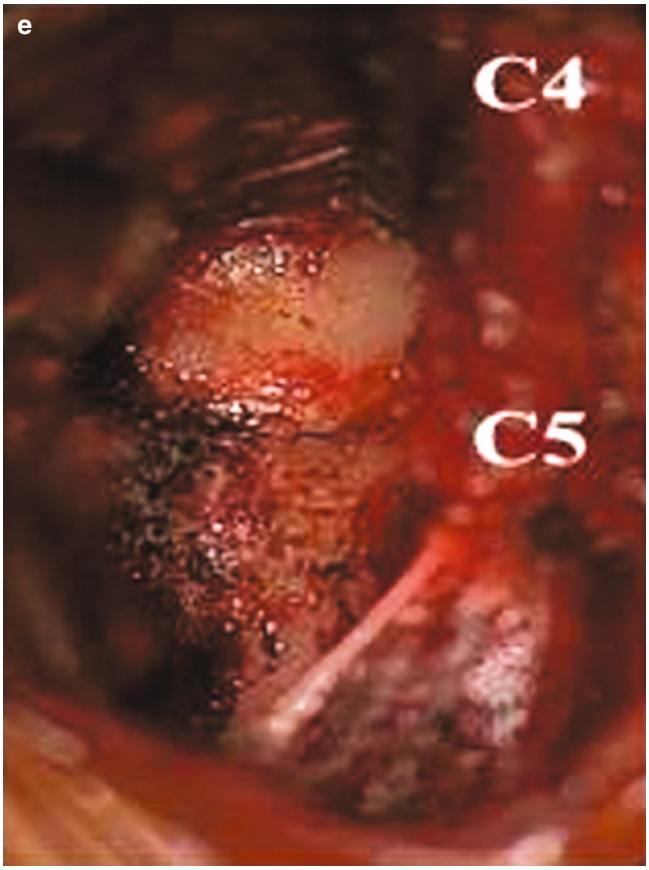


Fig. 23.19 (continued)

difference has been the superior pullout strength noted with the transfacet screws, which traverse four cortices.

A midline fascial incision is made proximal to the intended superior facet based on fluoroscopic localization. Next the cannulated drill guide and Kirschner wire are secured on the intended lateral mass with a trajectory perpendicular to the given facet articulation, favoring a far lateral course to avoid the vertebral artery. The recommended starting point is 1 mm medial to the midline of the lateral mass, with a 16 lateral and 37° inferior drilling angle [50]. After adequate K-wire placement is confirmed on fluoroscopy, a cannulated cancellous screw can be placed over the wire into three or four cortices.

Indications

1. Lateral mass fractures
2. Anchors for posterior fixation
3. Reinforcing anterior fusion constructs
4. Multiple-level cervical spine anterior fusion/corpectomies/osteoporotic bone
5. Single-level cervical spine fusions/pseudoarthrosis/osteoporotic bone
6. In conjunction with laminoplasty
7. Cervical facet dislocations/fracture dislocations
8. Failed/fractured lateral mass fixation

Limitations

Proximal cervical levels as the occipital bone protuberance may cause interference with the intended trajectory.

Outcomes, Complications, and Pearls

To date more than 50 cases/100 screws have been reported with no neurologic or vascular complications [51–54]. Hardware-related complications include loosening of screws used for anchoring due to partial breakage of the facets. In Takayasu's initial series, there has been no documented screw back out, lucency, or loosening on postoperative imaging. With longer screw lengths and a midpoint trajectory near the junction of the middle and upper third of the lateral mass, Zhao et al. demonstrated an increased incidence of facet fractures and an increased proximity and risk to the vertebral artery and exiting nerves [55]. Given the proximity of neurovascular anatomy, some recommend penetration of three cortices [54]. The main advantage to this technique is the posterior dynamic tension band and musculature are largely preserved while eliminating the need for rod/plate placement.

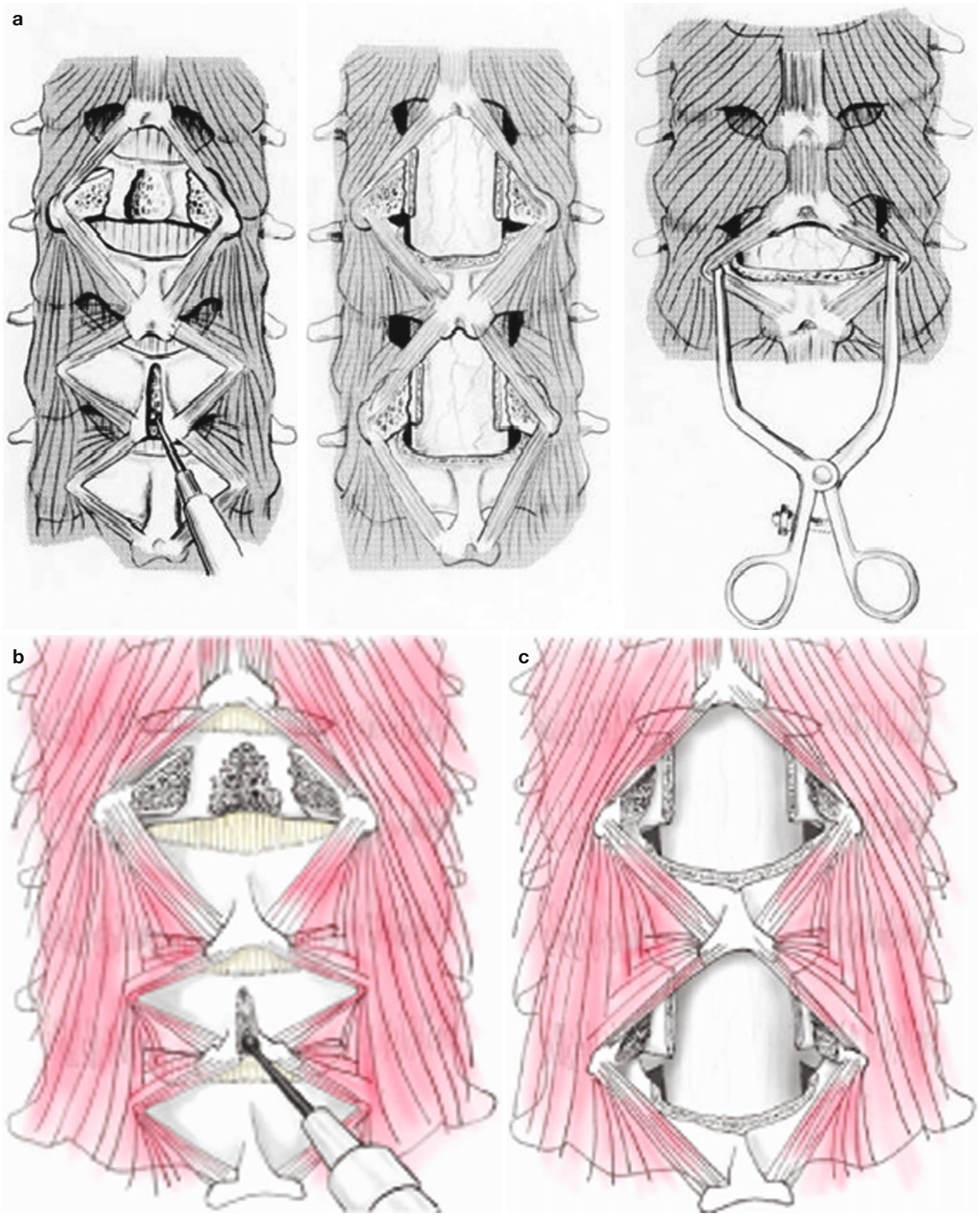


Fig. 23.20 (**a**–**c**) Exposure of the interlaminar spaces, the upper and lower ridges of each spinous process, lamina, and ligamentum flavum can be exposed from C2–3 to C6–7. As an example, skip laminectomies of the C4 and C6 laminae are removed with a fine 3-mm diamond-tipped burr in standard fashion leaving the enthesis of the semispinalis cervicis and multifidus intact bilaterally

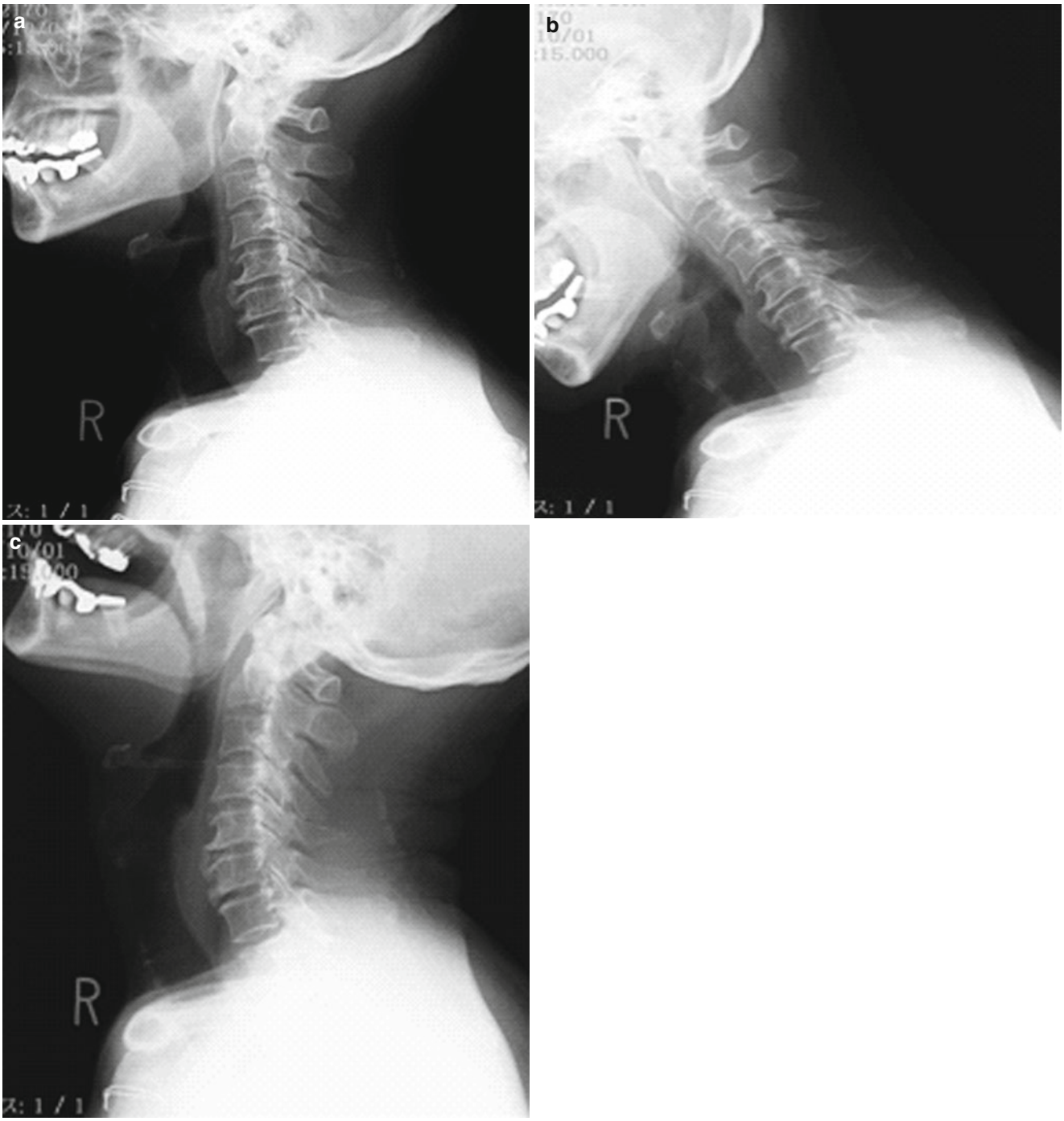


Fig. 23.21 Skip laminectomy. (**a**–**c**) Preoperative cervical radiographs

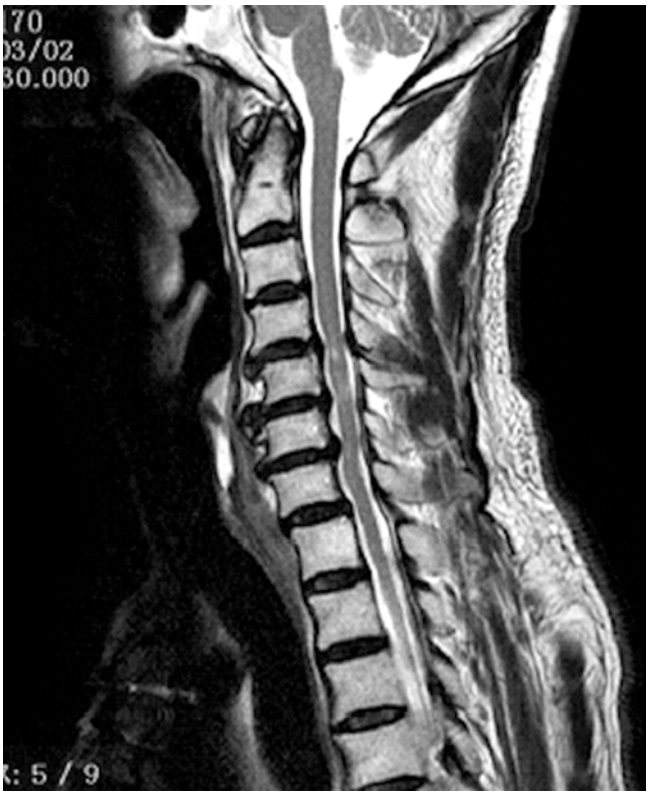


Fig. 23.22 Preoperative cervical MRI

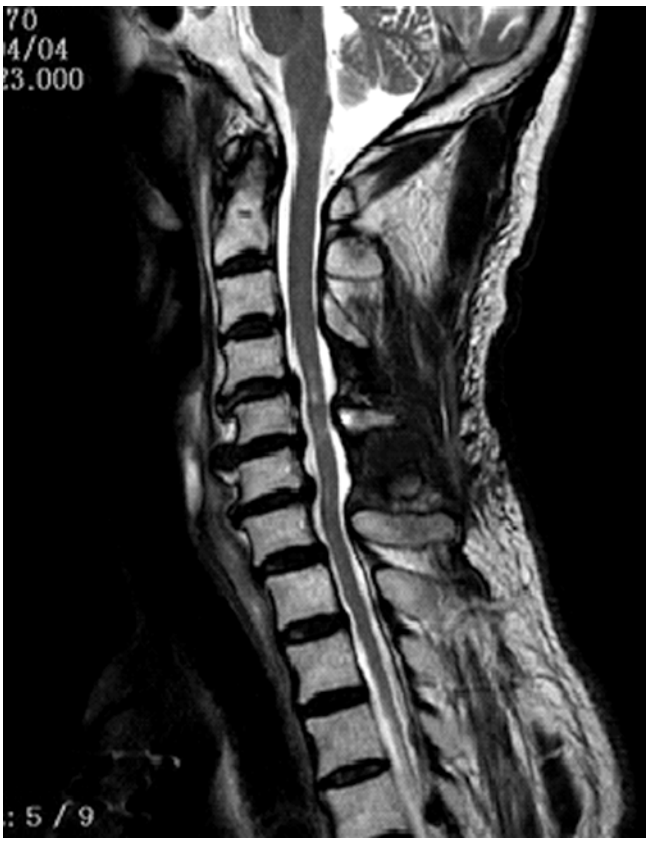


Fig. 23.24 Postoperative cervical MRI taken 4 months after surgery demonstrated adequate decompression of the spinal cord associated with subarachnoid space expansion

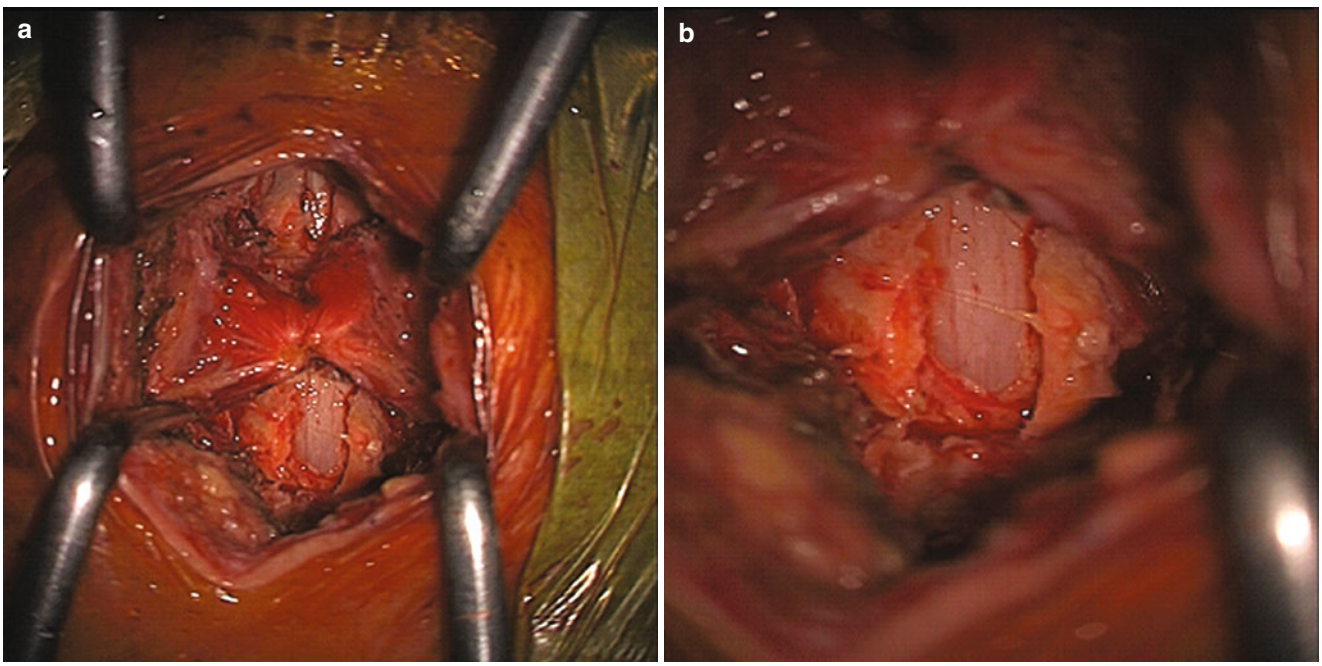


Fig. 23.23 (**a**, **b**) Intraoperative photo of C4 and C6 skip laminectomy with the C5 spinous process and its attached muscles preserved

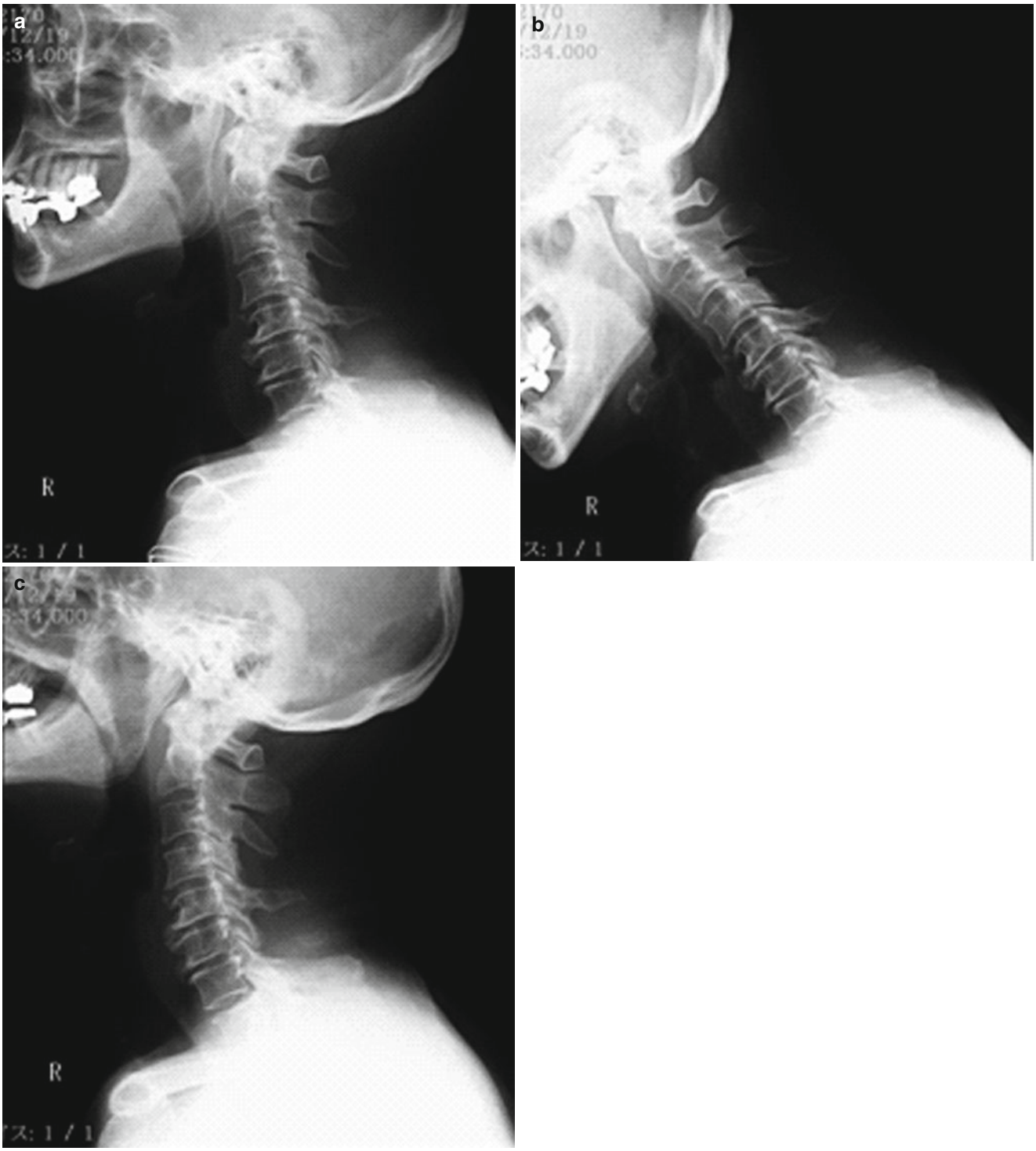


Fig. 23.25 (**a**–**c**) Cervical X-rays at 1 year postoperative demonstrate a maintenance of cervical lordosis with no loss in range of motion

Conclusion

Due to perceived advantages such as a lower rate of complications, minimal soft tissue trauma, and reduced blood loss, more spine procedures are being performed in a minimally invasive manner. Trends show that spinal procedures now entail a shorter hospital stay and in certain situations can be carried out on an outpatient basis. With further education, training, and research, more of our traditional open surgical procedures may be enhanced or supplanted by these minimally invasive technologies and approaches in the future.

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Thoracic Herniated Nucleus Pulposus

24

Jonathan D. Choi, John J. Regan,
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Case Example 1

A 52-year-old male with diabetes presented with several months of back pain radiating from the mid-back down to his lower back and sensory loss in the feet. He was limited in his activities and how far he could walk. Symptoms were worse with standing and walking. He did not complain of weakness or bowel or bladder abnormalities. On physical exam, he had hyperreflexia and clonus in bilateral lower extremities, along with sensory loss, a wide-based gait, and unsteady tandem gait. Magnetic resonance imaging (MRI) demonstrated a left T8–9 paracentral disc protrusion with deformation of the cord but no cord signal abnormality (Fig. 24.1). A computed tomography (CT) was obtained to assess whether the disc herniation was calcified. CT showed a calcified herniated disc at T8–9 narrowing the spinal canal to 5 mm (Fig. 24.2). Due to the paracentral location and presence of calcification, a transthoracic approach was used to have adequate and safe exposure to the ventral surface of the dura during discectomy. A left-sided, mini-open, transthoracic endoscopic discectomy was performed using a tubular retractor (MaXcess XLIF retractor system, NuVasive) and a 30° endoscope for visualization. A wedge-shaped defect was made in the superior and inferior end plates centered at the disc space to provide a cavity to pull the calcified herniated disc away from the dura (Fig. 24.3). A cage (CoRoent, NuVasive Inc.) was impacted into the discectomy site and a chest tube was placed. The chest tube was removed in the recovery room once a portable chest film ensured that there was no significant residual pneumothorax. Estimated blood loss was 25 mL and operative time was 180 min. The patient was discharged to home on postoperative day 3. Postoperatively, the patient had improved sensation in bilateral lower extremities and central back pain that gradually improved over many months. At his 2-year follow-up, he rated his back pain as 2/10 and had no progressive neurologic issues in his lower extremities.

Case Example 2

A 36-year-old chiropractor and former college soccer player presented with gradual onset right flank pain and progressive right extremity weakness and numbness. He had difficulty standing from a seated position with 3/5 quadriceps weakness in the right leg and 4/5 weakness in the distal musculature. He had clonus in the right ankle and positive Babinski in the right ankle. Thigh circumference was 48 cm on the right and 53 cm on the left.

Review of CT scan demonstrates large central disc herniation at T9–10 with rim calcification (Figs. 24.4 and 24.5). There were no cord signal changes on MRI scan.

Thoracoscopic discectomy and partial hemicorporectomy were performed with successful excision of the herniated disc. Because of the rib head resection and partial vertebral resection, spinal instrumentation and fusion were performed using lateral cage and vertebral screws and rod (Fig. 24.6). At 1 year after surgery, the patient has full recovery of neurologic function and is pain-free.

Clinical Presentation of Thoracic Disc Herniation and Indications for Operation

Symptomatic thoracic disc herniation is a rare clinical entity that affects men and women equally, typically in the middle to late adult life. While up to 15.2 % of individuals have been found to have thoracic herniated discs on MR imaging and

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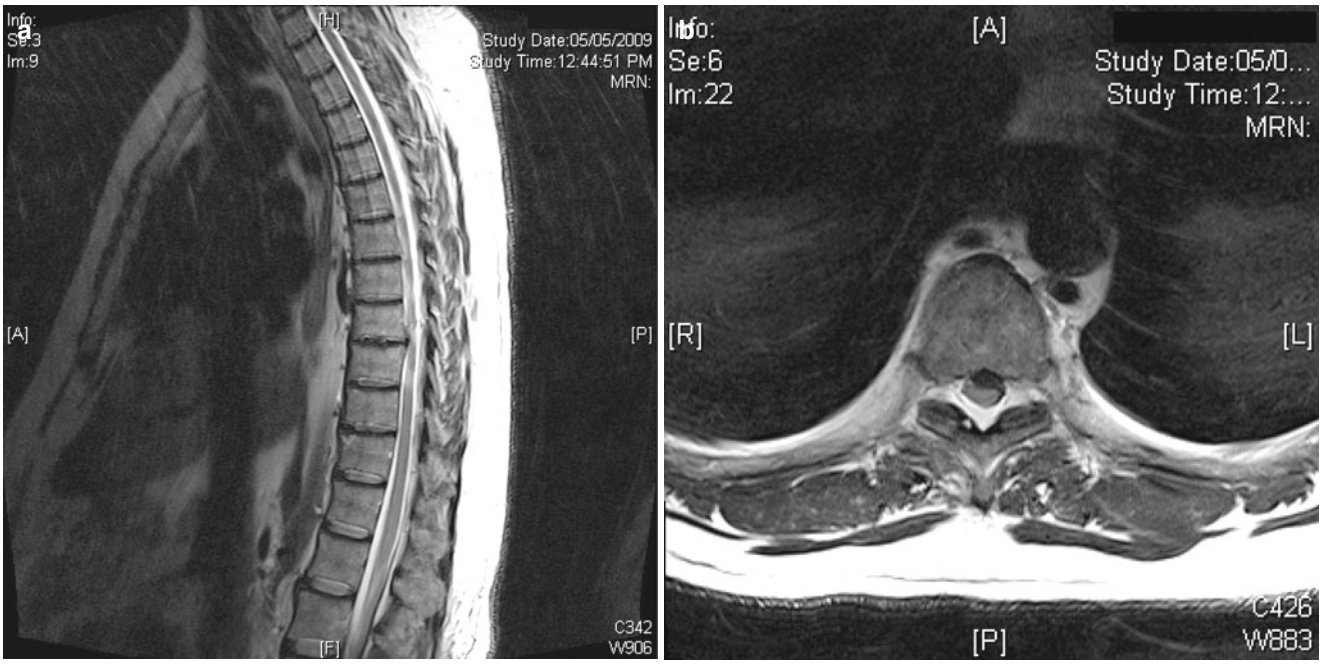

Fig. 24.1 Thoracic herniated disc on MRI. (**a**) A T8–9 herniated disc on sagittal MRI. (**b**) Axial MRI showing a left-sided paracentral disc at T8–9 deforming the spinal cord without significant cord signal abnormality

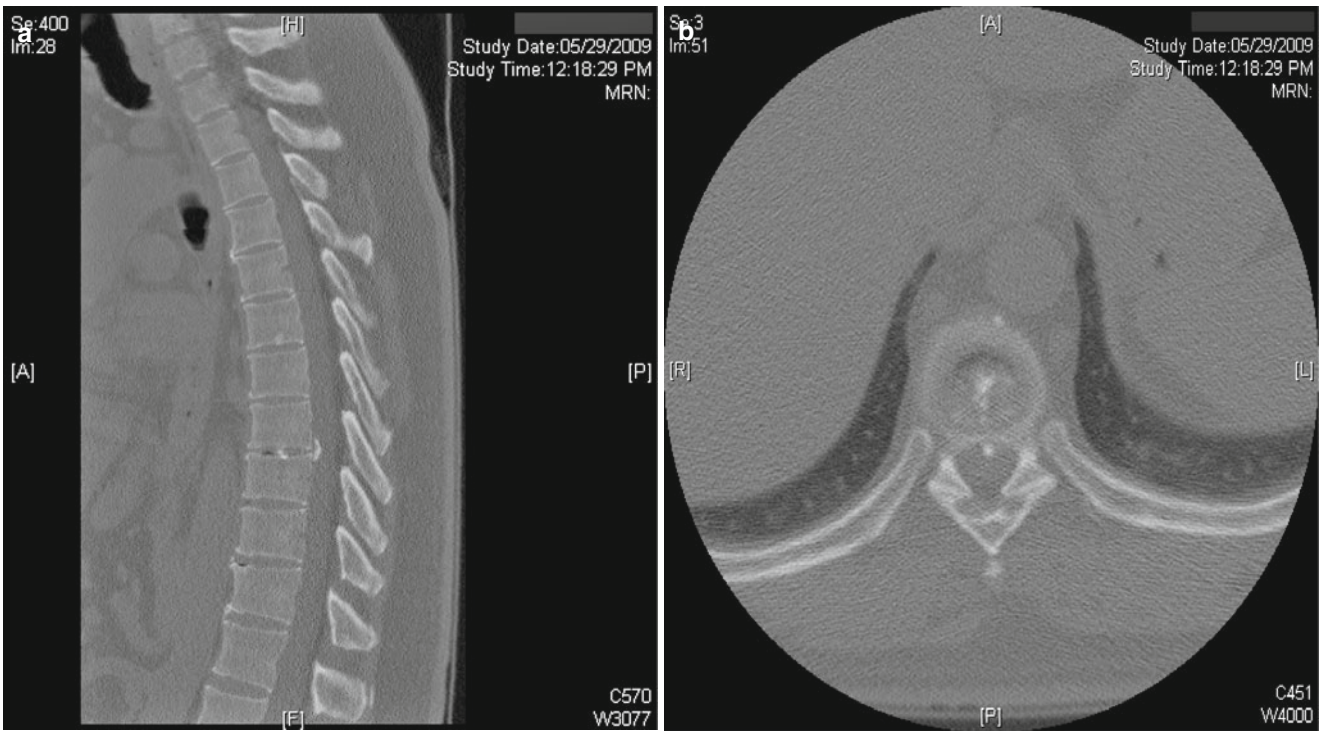

Fig. 24.2 Thoracic herniated disc on CT. (**a**) A T8–9 herniated disc on sagittal CT. (**b**) Axial CT showing calcification in the T8–9 disc herniation

postmortem findings, the prevalence of symptomatic thoracic herniated discs is estimated at 1:1,000,000 people [1–3]. Surgery for thoracic disc herniations accounts for only 0.15–4 % of the total number of spinal operations for herniated discs [2, 4–7]. The low number of symptomatic thoracic herniated discs compared to cervical and lumbar discs is attributed to the stability of the thoracic spine added by the rib cage [7, 8].

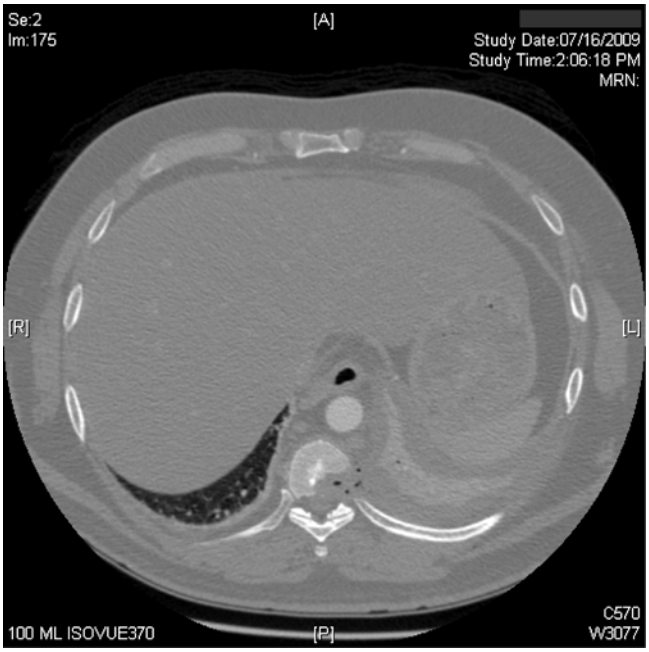

Fig. 24.3 Operative technique as seen on axial CT. A left-sided, mini-open, thoracic endoscopic discectomy was performed by drilling a wedge-shaped cavity in the posterior aspect of the vertebral body above and below the disc space. This provides a cavity to safely deliver the calcified disc away from the dura, avoiding any manipulation or retraction the spinal cord

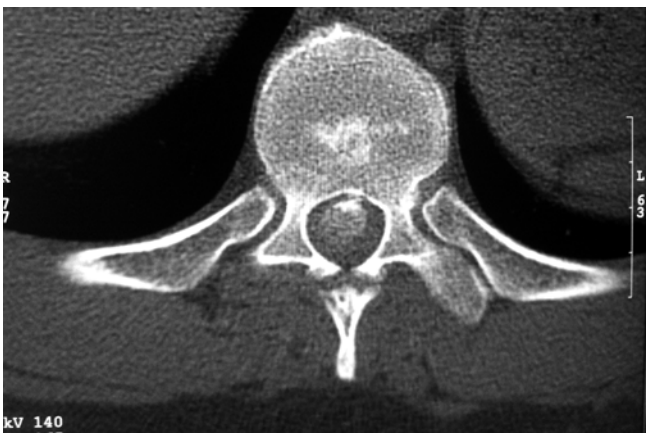

Fig. 24.4 CT axial image demonstrates partially calcified central thoracic disc herniation at T9–10 occupying greater than 50 % of the spinal canal

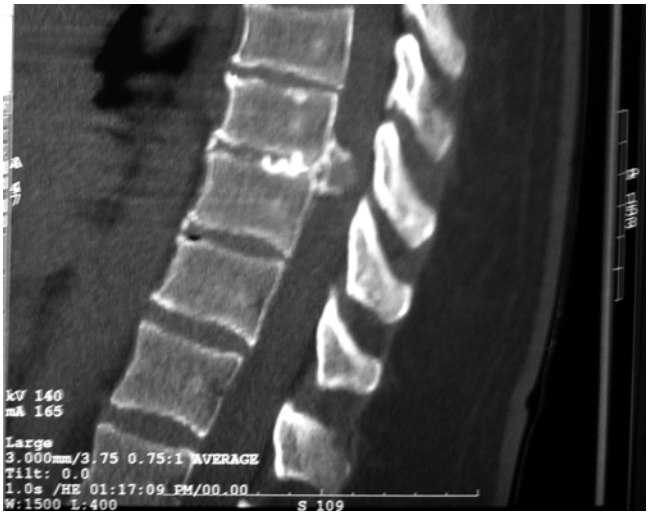

Fig. 24.5 CT sagittal image demonstrates calcified disc at T9–10 with severe canal narrowing

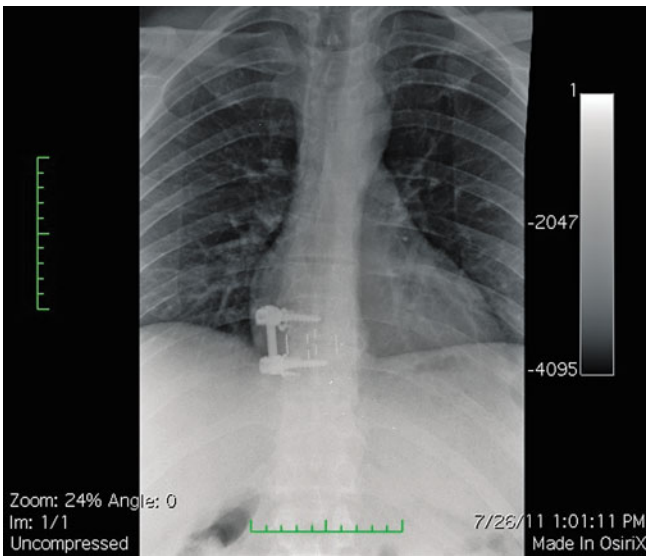

Fig. 24.6 Postoperative x-ray demonstrating spinal instrumentation with lateral cage and vertebral screws and rod

The presentation of symptomatic thoracic herniated discs is varied but consists of either myelopathy or pain or a combination of the two. The most common symptom is pain, affecting 76 % of patients in a study by Stillerman et al. [7]. Most of the patients with pain complained of localized axial back pain or axial back pain with radiation into the lumbar spine. A smaller proportion complained of radiculopathy. The pain can even mimic cardiac disease or present as abdominal or shoulder pain [9–11]. Sensory impairment occurred in 61 % and paraparesis and monoparesis occurred in 61 % of patients as well [7]. Spasticity and hyperreflexia were seen in 58 %. Bladder dysfunction occurred in a sizable minority of 24 % of patients. The time from onset of symptoms to diagnosis can range from an acute presentation to a delayed diagnosis several years later [2, 12, 13].

The rarity of symptomatic herniated thoracic discs and the variability in presentation make it difficult to predict if a patient's symptoms will progress or improve with time. In some cases, the symptoms can spontaneously resolve [14]. The decision to operate is based on clinical assessment and is reserved for severe or progressive myelopathy and for radiculopathy that fails conservative management.

Sheikh et al. recommend at least 6 months of a combination of steroid, nonsteroidal anti-inflammatory medications, epidural injection, intercostal nerve injection, physical therapy, and a hyperextension brace for patients presenting solely with pain complaints [15]. Only after this has failed should a patient be taken to surgery for symptoms consisting purely of pain.

Once the decision has been made that the patient needs surgical management, it is necessary to further characterize the herniated disc and the patient's anatomy. Both an MRI and CT are imperative to localize the anatomy that will be found in the OR. MRI is useful in characterizing the location within the spinal canal and CT in determining the amount of calcification within the herniated fragment. The location of the herniated disc, presence of calcification, and size dictate the surgical approach. In addition, the patient's comorbidities and vascular anatomy may also affect the choice of approach. Two-thirds of thoracic disc herniations occur between T8 and T11 and over 90 % occur between T6 and T11 [7]. Lateral herniated discs can be removed from the ipsilateral side by any of the three approaches: posterolateral, lateral, or transthoracic. However, centrally located herniated disc cannot be directly visualized from posterolateral approaches. In addition, the spinal cord and dura can be draped anteriorly around the herniated disc [7]. Manipulation of the herniated disc without direct visualization puts the thoracic spinal cord at risk for injury. The patient with cord signal changes on MRI scan presents a cord-at-risk scenario with increasing risk of paralysis with any cord manipulation which may occur in an attempt to remove an adherent calcified thoracic disc. For these reasons, centrally located discs are preferably addressed from the transthoracic approach where direct visualization of the dura from pedicle to pedicle can be obtained; however, some noncalcified, soft central herniated discs can be removed safely from the posterolateral approach [7, 16]. Calcified, centrally located herniated discs can erode through the dura and may require direct dural repair or placement of a dural graft and fibrin glue [17]. The patient's vascular anatomy can also dictate the approach and side used since the blood supply to the thoracic cord is tenuous and often delivered by a main radicular artery feeder, the artery of Adamkiewicz, that usually arises on the left side at T8–L2 [18]. Although not favored by our group commonly, some surgeons recommend obtaining a preoperative angiogram if the approach may dictate sacrifice of the left-sided thoracic radicular arteries [19]. Additional factors are dictated by the patient's comorbidities such as ability to undergo a large procedure and whether the patient has pulmonary compromise or previous lung surgeries and pleural adhesions making transthoracic approaches less than desirable.

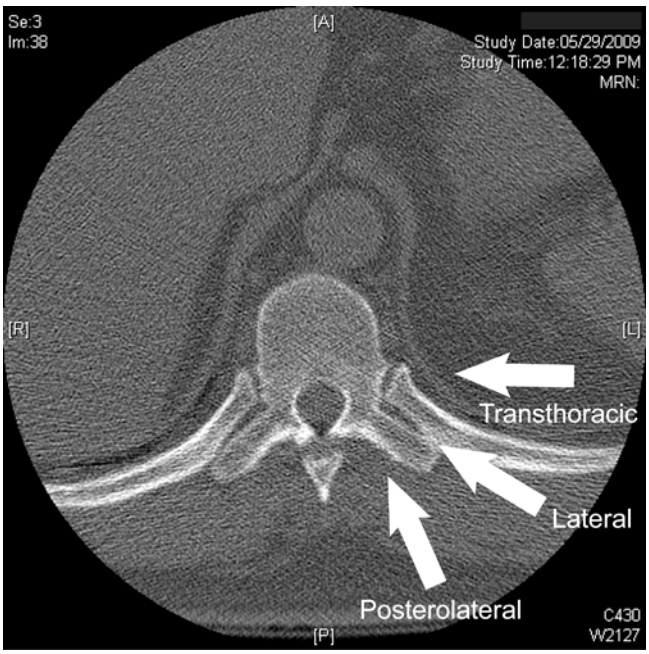

Fig. 24.7 Approaches. The approaches available to treat thoracic herniated discs are the posterolateral (transpedicular, transfacet), lateral (costotransversectomy, lateral extracavitary), and transthoracic (thoracotomy, mini-open XLIF, thoracoscopic). The approach is tailored to the location, size, and calcification of the herniated disc

Historical and Open Procedures

Historically, thoracic herniated discs were treated via a posterior approach by laminectomy with or without discectomy. In 1969, Perot and Munro compiled 91 cases of thoracic herniated disc treated from a dorsal approach. Of the 91 patients, 16 became paraplegic and 6 died [20]. Of the 91 patients operated on for central herniated discs (as opposed to lateral discs), the rate of paraplegia was 26 % and mortality was 9 %. The poor results were thought to be due to inadequate treatment of the anterior pathology with damage to the spinal cord by retraction. To obtain a more direct visualization of the herniated disc and minimize retraction of the spinal cord, posterolateral, lateral, and transthoracic approaches were developed. The transpedicular approach entails removal of the pedicle and facet to obtain a posterolateral access to the herniated disc fragment (Fig. 24.7) [21]. Centrally located herniated disc fragments cannot be directly visualized from the posterolateral approach. Stillerman described the transfacet pedicle-sparing approach that has the advantage of reducing postoperative axial back pain by preserving the pedicle [22]. The lateral approaches of costotransversectomy and extracavitary approach were developed to gain more anterior access and visualization (Fig. 24.7). Costotransversectomy is performed by removing

the transverse process and rib and sectioning the associated nerve root and radicular vessels [23]. The lateral extracavitary approach involves more extensive dissection including medialization of the paraspinal muscles and detachment of the pleural to obtain a more lateral angle of visualization [19]. The advantages of the lateral extracavitary approach include improved visualization and staying extrapleural throughout the procedure; however, this is at the expense of extensive soft tissue dissection, poor wound healing due to devascularization, and the increased possibility of postoperative kyphosis due to denervation of the paraspinal muscles [24].

Despite the improvements of the posterolateral approaches in operative angle, they have limited utility for removal of centrally located herniated discs and densely calcified herniated discs [16]. Direct visualization of the ventral dura was obtained by approaching ventrally through a thoracotomy (Fig. 24.7). Central disc fragments and densely calcified disc herniations can be removed without any retraction on the spinal cord. Any dural defects can be repaired primarily or with a graft. The disadvantages to thoracotomy are the need for a thoracic surgeon to assist with the approach, the need for a chest tube postoperatively, the high rate of intercostal neuralgia (reported to be as high as 50 %), and the risk of damage to the lung, heart, and great vessels [24, 25].

With the adoption of posterolateral, lateral, and transthoracic approaches and abandonment of laminectomies for thoracic herniated discs, mortality dropped to nearly zero and neurological recovery rates improved. In addition, the advent of spinal cord monitoring in the late 1990s, especially MEP, has improved the safety not only of thoracic pedicle screw placement but also the spinal cord monitoring in these technically demanding procedures. Monitoring in thoracic disc disease surgeries is most useful in patient positioning or any manipulation around the cord as vascular changes may occur. With modern approaches to thoracic disc herniations, Stillerman reports an 87 % improvement or resolution of pain (localized, axial, or radicular), 95 % improvement of hyperreflexia and spasticity, 84 % improvement in sensory changes, 76 % improvement in bladder dysfunction, and a 58 % improvement in motor deficits [7]. Despite these vast improvements in neurological recovery, pain relief, and operative mortality, the open surgical approaches had significant morbidity related to the approach itself. Fessler and Sturgill report comparable rates of complications across the open procedures with different morbidities associated with each approach [26]. For example, the transthoracic approach is associated with intercostal neuralgia, pneumonia, atelectasis, hemothorax, and chylothorax, while the posterolateral and lateral approaches are associated more with wound infections, poor wound healing, destabilization of the shoulder girdle, and postoperative kyphosis. In an effort to reduce the morbidity of the approach while retaining effectiveness and safety, minimally invasive alternatives to the posterolateral, lateral, and transthoracic open approaches have been developed.

Minimally Invasive Approaches

Surgeons who have appreciated the importance of minimally invasive surgery have worked hard to modify open surgical techniques to accommodate smaller incisions, and new procedures have been developed which exploit the advances of fiberoptic light sources, the versatility of spinal implants, and advances in computer-guided real-time imaging. In the analysis of the myriad of procedures developed in the past decade which purport to be minimally invasive, the technology to be successful must (1) minimize the approach-related trauma, (2) decrease the postoperative pain and morbidity, (3) decrease complications, and (4) lead to a more rapid recovery and return to normal function. Minimally invasive alternatives to the open approaches discussed above were developed recently, first with thoracoscopy in 1995 and followed by minimally invasive transpedicular, transfacet, extracavitary, and mini-open lateral approaches in the last decade [15, 24, 25, 27–35].

Thoracoscopy offers clear visualization of the anterior thoracic cord with significant improvements in technology over the past decade. In thoracoscopic surgery as in Case Example 2, the patient is intubated with a dual lumen tube for single-lung ventilation and is placed in the lateral position. C-arm fluoroscopy is used to localize the target level [24, 25]. Typically three to four ports are inserted, and the images are displayed on television screens at the head of the patient (Fig. 24.8) [36]. Pleural adhesions are taken down, and the ribs are counted internally to localize the target level again in addition to use of fluoroscopy. The patient is then rolled ventrally to let the lung fall away, and a fan retractor can be used to hold the lung out of view. The pleura over the target disc space is incised, and the segmental vessels are ligated and clipped. The proximal 2 cm of rib is then drilled and removed, saving the bone for autograft if needed. The superior half of the pedicle is drilled down to define the lateral aspect of the spinal canal. Then the disc is incised and disc material removed, leaving the posterior aspect of the disc to be removed later. A wedge-shaped cavity is then drilled by removing the posterior aspects of the superior and inferior vertebral bodies until normal dura is seen above and below the herniated disc fragment. For large herniated disc, this may require partial or full vertebrectomies above and below the disc interspace. After the cavity is formed, the herniated disc is carefully delivered into the cavity without

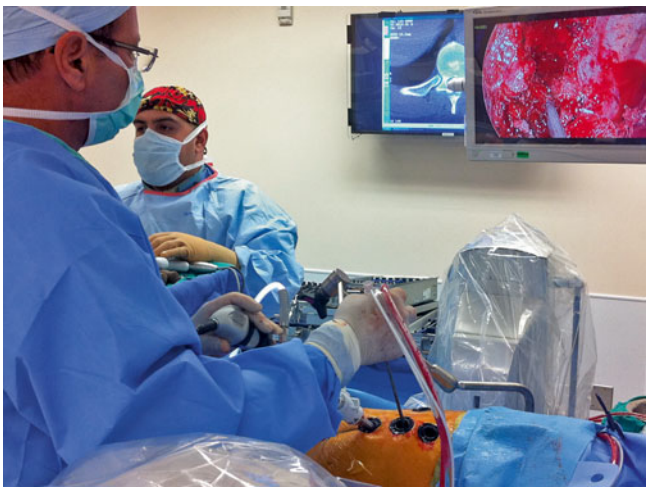

Fig. 24.8 Intraoperative photo shows the surgeon watching the monitor which displays the endoscopic view of the thoracic spine to the right of the CT images as he performs thoracoscopic discectomy. Four portals are placed after the patient is positioned in the right lateral decubitus position. The endoscope in the surgeon's left hand is manipulated into position and then locked into position with a holder or robotic arm. The surgeon's right hand holds the suction irrigator

manipulating the spinal cord. If a dural erosion is found after herniated disc removal, the dura can be primarily repaired or a dural graft with fibrin glue can be placed. Placement of an interbody graft is not necessary for small bony defects, as few patients require reoperation for loss of stability [24, 25]. However, if a large defect is created, a rib graft can be placed. Some authors advocate standard placement of an interbody graft after discectomy to minimize risk of delayed postoperative kyphosis and axial pain [29, 37–39]. A chest tube is then placed and the chest incisions closed. The chest tube is kept until output is less than 100 mL/day [25]. If a dural defect is encountered, the chest tube is kept on water seal only and a lumbar drain is placed.

Rosenthal and Dickman reported on 55 patients that underwent thoracoscopic herniated disc removal [25]. They found that mean operative time was 3 h and 25 min, 1 h less operative time than the average thoracotomy and 1.25 fewer hours than a costotransversectomy. In addition, when compared to thoracotomy, thoracoscopy resulted in one-half the blood loss (327 mL vs 683 mL), one-half the duration of chest tube drainage, and less than one-half of the length of hospital stay (6.5 days vs 16.2 days). Complications included hemothorax from intercostal vessel and segmental vessel bleeding, transient intercostal neuralgia, and two patients with retained fragments of disc material. Only 16 % of patients experienced intercostal neuralgia as opposed to the 50 % of patient who had a thoracotomy. This is accomplished in thoracoscopy by avoiding intercostal retraction. Thoracoscopy alleviates much of the morbidity of the open thoracotomy approach while maintaining effectiveness in treating the pathology. However, Dickman cautions that open thoracotomy should be used in treating ossified giant herniated discs as leverage on the calcified disc and subsequent damage to the spinal cord is more likely to occur during thoracoscopy [17].

Despite showing clear benefits in reducing approach-related morbidity, thoracoscopy has been slow to be adopted by spine surgeons for a number of reasons: lack of 3D visualization, minimal tactile feedback, steep learning curve requiring specialized training in the lab prior to clinical use, and expensive equipment and instrumentation [40–43]. The infrequency of thoracic herniated disc surgery compounds the difficulty in remaining proficient with the thoracoscopic techniques [16].

Recently, the technology developed for direct lateral transpsoas lumbar spine surgery has been adapted for thoracic spine surgery. Karikari et al. were the first to describe using the extreme lateral interbody fusion approach for treating pathology in the thoracic spine as was used in the Case Example [44]. Their study showed the feasibility and safety of using the XLIF approach to treat a variety of pathologies including thoracic disc herniation, pathologic fractures from tumor, degenerative scoliosis, discitis, and adjacent level disease from prior fusions. Uribe et al. focused on treating specifically thoracic disc herniations and reported on 60 patients treated at five institutions using a mini-open thoracic XLIF [27]. A 4 cm incision is used, and the spine can be approached via either an extrapleural approach or transpleural approach. Single-lumen intubation can be used and both lungs ventilated throughout the procedure. In the transpleural approach, the lung is deflated digitally, and a dilator is slid down the posterior rib cage until it is safely docked on the spine. Sequential dilators are place until a three-blade tubular retractor system (MaXcess XLIF-T system) is inserted and docked on the spine with the help of fluoroscopy. Limitation occurs with tube technology as one proceeds more cephalad in the thoracic spine. Floating ribs do not provide a significant obstacle to distraction, but only limited intercostal distraction is possible as one moves higher into the thoracic spine. Some authors suggest using thoracoscopy to take down adhesions and directly visualize placement of the tubular retractor to avoid injury to the lungs [28]. Once the system is docked, a microscope can be used with bayonetted instruments to provide 3D visualization of the anatomy or a 30° endoscope can be inserted as was used in the Case Example 1 performed by two of the authors. The discectomy is performed in the standard fashion of removing the rib head and superior aspect of the pedicle and creating a defect into which the disc is delivered. An interbody graft is then placed and chest tube is inserted if the approach is transpleural. The chest tube can be removed in

the postoperative recovery room if a portable film shows no residual pneumothorax.

In the study by Uribe et al., mean operative time was 182 min, estimated blood loss was 290 mL, and average length of stay was 5 days [27]. Complication rate was 15 % as compared to 28.4 % in previously reported minimally invasive approaches and 36.7 % in open approaches. Importantly, intercostal neuralgia was not experienced by any patient in the study. Outcomes were consistent with previous reports in the minimally invasive literature with 80 % with excellent or good outcomes, 15 % unchanged, and 5 % with poor outcomes. This exceeds the reported outcomes for open approaches of 64.4 % with excellent or good outcome. The mini-open thoracic XLIF approach avoids the approach morbidity of thoracotomy while using techniques familiar to the minimally invasive spine surgeon, offering direct visualization of the ventral dura, and achieving improved patient outcomes. However, the chest cavity has to be entered (either extrapleural or transpleural) to perform this procedure, exposing the patient to increased risk and making the procedure more technically demanding.

Thoracic spinal fusion is recommended in the case of thoracic disc disease when instability occurs. The resection of rib head, as well as surrounding costovertebral ligaments which span the disc space, can lead to instability. Also, more extensive resection of vertebral bone required in some surgeries may add to this problem. The closer the surgery is to the thoracolumbar junction, the more likely the patient will experience instability and back pain. Lateral cages can be used and are compatible with thoracoscopic or lateral tube technique. The use of these cages as stand-alone fusion devices remains to be determined. The more stable the segment at the time of the procedure, the more likely fusion will be successful. The use of BMP in the anterior thoracic approaches can be associated with large pleural effusions, so caution is advised [45].

As opposed to large central disc herniations or calcified disc herniations, lateral disc herniations and soft central disc herniations have been resected through posterolateral minimally invasive approaches [15, 29–31]. Chi et al. describe a transpedicular approach using a tubular retractor [15, 29–31]. The pedicle is cannulated as a visual landmark, and the hemilamina, medial facet, and pedicle are removed to provide adequate exposure. The disc is then incised laterally without any retraction on the dura and a cavity is formed. The herniated disc material is then pushed anteriorly into the defect without manipulating the spinal cord. Due to lack of direct visualization, posterolateral approaches are only recommended for lateral discs and central disc that do not exhibit calcification. Surgeons attempting to use lateral tube technology may be faced with limited views and working space which present challenges to their comfort level. Bayonetted instruments used in lateral tube technique approaches require additional skills to successfully perform the procedure. The surgeon is urged to learn from cadaver courses and slowly adopt these newer techniques with easier procedures to avoid complications. Once the disc is removed from the posterolateral transpedicular approach, the fascia and skin are closed without need for a drain. Mean operative time of 3 h and the average hospital stay were similar to the operative time and hospital stay in the open transpedicular approach. The estimated blood loss was decreased at 177 mL vs 337 mL and the incision length was 3–5 cm vs 7–10 cm. The Prolo score change at 1 year for the minimally invasive approach was higher than for the open approach (6.2 vs 2.0, $p = 0.05$) at 1 year suggesting that the patients undergoing the less invasive surgery recovered more quickly. Possible complications include spinal cord injury, postoperative neuralgia, CSF leak, and postsurgical kyphosis [31].

Isaacs et al. describe a pedicle-sparing, minimally invasive, microendoscopic transfacet approach [30]. A K-wire is inserted 3 cm off midline and docked on the transverse process caudal to the disc of interest. Using fluoroscopy, the K-wire is guided to the junction of the transverse process and rib head. The tubular retractor system is then inserted after sequential dilation. The endoscope is inserted and residual muscle is removed. The medial transverse process and lateral third of the facet complex are drilled away, exposing the lateral aspect of the spinal canal. The disc is incised laterally, and a cavity is formed in the disc space and adjacent vertebral bodies to push the herniated disc fragment anteriorly with a curette or Woodson elevator, away from the spinal cord. Perez-Cruet et al. reported a series of thoracic herniation resected via tubular retractor in seven patients [46]. Mean operative time was 1.8 h per level, estimated blood loss was 113 mL per level, and most patients were discharged from the hospital within 24 h. There were no intraoperative or postoperative complications, and all patients had resolution of myelopathy and radiculopathy with the exception of one patient with persistent back pain. Khoo et al. describe a minimally invasive extracavity approach for thoracic discectomy and interbody fusion by use of a posterolaterally placed tubular retraction system [43]. The proximal rib, transverse process, facet, and lamina are removed to provide a more lateral view of the spine. Discectomy is performed in the standard fashion, and an interbody cage is placed to minimize risk of delayed postoperative kyphosis and axial pain. The Isaacs et al., Khoo et al., and Perez-Cruet et al. studies show that minimally invasive posterolateral approaches for treatment of thoracic herniated discs are technically feasible and safe and avoid the approach-related morbidity of open posterolateral and lateral approaches [30, 43, 46].

Conclusion

Thoracic disc herniation is a rare and challenging clinical entity that has driven spine surgeons to develop a multitude of techniques to safely remove the disc herniation and minimize morbidity related to the approach. For patients with symptomatic thoracic herniated discs, the application of minimally invasive techniques has resulted in improved outcomes and resolution of pain while decreasing complications. Minimally invasive thoracic spine surgery has benefited from the tools and techniques developed from minimally invasive lumbar spine surgery. Today's spine surgeon must become proficient with these minimally invasive tools and techniques for both posterolateral and transthoracic approaches to effectively and safely treat thoracic disc herniations.

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Lumbar Herniated Nucleus Pulposus

25

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Introduction

Lumbar discectomy is the most commonly performed spine surgery in the United States, with over 300,000 discectomies performed annually [1]. Two percent of people will experience a symptomatic herniation in their lifetime with most symptomatic lumbar disc herniations affecting individuals between the ages of 30 and 50 years. Stress, lower income, manual labor, and cigarette smoking have been reported to increase the risk of herniation [2]. Although the incidence of symptomatic herniation is quite high, the majority of cases are managed nonoperatively with a treatment regimen that includes activity modification, physical therapy, anti-inflammatory medications, and epidural steroid injections. The incidence of sciatica requiring surgery is estimated to be less than 0.5 % of the general population. Ninety percent involves the L4/L5 or L5/S1 levels [2].

Open hemilaminectomy to treat symptomatic disc herniation was first performed by Mixter and Barr in 1934 [3]. Significant refinement of this surgical procedure ensued, and the traditional version of lumbar discectomy was pioneered by Yasargil and Caspar independently in 1977 [4, 5]. They described an open posterior approach with significant muscular dissection. Their surgical technique has been further refined, and a "mini-open" approach is now possible which represents the most common version of discectomy performed today. In 1997, Foley and Smith developed a mode of discectomy utilizing a series of transmuscular dilators and tubular retractors which was thought to be less invasive, with theoretically less muscle damage, decreased postoperative pain, and more rapid recovery. Their version of the procedure was performed using an endoscope or operative microscope [6]. The advent of such a system spawned a movement toward "minimally invasive discectomy" [MIS].

In contrast to a traditional open approach, minimally invasive discectomy aims to avoid muscle trauma by limiting the exposure to only the area of pathology. The use of tubular retractors theoretically decreases the amount of muscle injury/ischemia caused by self-retaining retractors. Placement of retractors still occurs through known muscular and neurovascular planes. Limiting muscular dissection, especially at the insertion of the multifidus muscle on the spinous processes, is a hallmark characteristic of the MIS approach.

This chapter will discuss the pathophysiology of lumbar disc herniation, clinical diagnosis, the role of nonsurgical treatment, and finally surgical management of symptomatic lumbar disc herniations.

Pathophysiology

The intervertebral discs are composed of two primary structures: the nucleus pulposus and annulus fibrosis. There is no direct blood supply to the discs, but they are supplied by nutrient diffusion, primarily from the vascular supply on the vertebral end plates and the periphery of the discs [7].

The nucleus pulposus is a gelatinous material that contains type II collagen fibrils, proteoglycan aggrecans, and water. Its unique chemical composition allows it to function as an effective "shock absorber." The hydrophilic chains attached to the proteoglycan aggrecan molecules transmit mechanical force into electrostatic potential with axial loading.

The nucleus pulposus is encased by the annulus fibrosis, a ringlike structure consisting primarily of type I collagen. It is characterized by high tensile strength. Its function is to contain the nucleus pulposus as it absorbs mechanical loads. Structural deterioration of the annulus is thought to begin in early adult life. In autopsy specimens, dehydration of both

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the annulus and pulposus is noted [8]. Even in asymptomatic individuals, early degenerative radiographic changes can be apparent on MRI [9]. This degenerative process results in microscopic annular fissuring which may then propagate to a full annular tear and disc herniation. These annular fissures are thought to be a medium for ingrowth of nerves and vessels which may account for a component of axial pain associated with degenerative disc disease [8].

It is theorized that LDH causing radicular pain involves a component of mechanical compression of the involved nerve root as well as chemical irritation from local inflammatory mediators. It has been suggested that large, sequestered, uncontained disc herniations have a higher propensity to spontaneously resolve on MRI than contained herniations [10]. It is thought that material in the nucleus pulposus is capable of inducing a local inflammatory response, a theory that has been demonstrated in numerous animal studies [11, 12]. Intraoperative sampling around the irritated nerve root has demonstrated a number of inflammatory mediators including matrix metalloproteinases, nitric oxide, and numerous prostaglandins [13]. Nerve conduction velocities were measured in pigs that had nucleus pulposus material injected into the epidural space. Retroperitoneal fat was used as a control. These injections were performed in groups with and without mechanical compression. Interestingly, nucleus pulposus material caused abnormalities in conduction velocities independent of mechanical factors [14]. It follows that an important component of pain generation during LDH results from chemical irritation and may be addressed with removal of the nucleus pulposus material or administration of an anti-inflammatory agent.

Classification

Classification of lumbar disc herniation (LDH) is determined by the continuity of the herniated material with the remaining disc, the geometry of the herniation, the position of the herniation compared to the posterior longitudinal ligament (PLL), and the spinal level where the herniation occurred.

When herniated disc material is completely surrounded by annulus fibers, it is referred to as "contained." When the annulus is completely violated, disc material escapes into the peridural space. This is referred to as an "uncontained" herniation. In this space, the disc material becomes covered in fibrous covering known as a "capsule." If an uncontained herniation is beneath the PLL, it may be called "subligamentous." If bordered only by peridural capsule, it is referred to as "submembranous" [2].

If the herniation has a base wider than the displaced material, it is called a "protrusion." This is in contradistinction to a disc "bulge" in which no true violation of the annulus has occurred. If the herniated material is wider in dimension than the remaining connection to the disc, it is called an "extrusion." If the entire connection from the parent disc is lost, the herniated material can be referred to as a "sequestration" [2].

The herniation is also characterized by the spinal level at which it occurred. Ninety percent of LDH occur at either the L4/5 or L5/S1 levels. There is a propensity for higher lumbar levels to be involved in the elderly population [15]. Disc material may displace caudal or cephalad within the spinal canal. This phenomenon is known as disc "migration."

LDHs are also classified based on their position around the circumference of the annulus. Central herniations occur behind, or more rarely, though the PLL. Paracentral (or posterolateral) herniations occur adjacent to the weaker lateral border of the PLL and represent the most common type, with lateral (foraminal) and far-lateral (extra-foraminal) being less common.

Paracentral herniations tend to compress the traversing nerve root at the level of the herniation. Thus, a L5–S1 paracentral LDH will most likely compress the S1 nerve root. The herniated material usually compresses the lateral margin, or shoulder, of the nerve root but may also be located in the axilla, between the medial border of the root and the dural sac. Lateral and far-lateral LDH affect the exiting nerve root; thus, a far-lateral L5–S1 LDH will compress the L5 nerve root as it exits the foramen.

Diagnosis and Clinical Exam

As with all patients presenting with suspected spinal pathology, a thorough history and physical exam are imperative. The most common complaint is pain and/or paresthesias radiating down the leg. The distribution may follow a classic dermatomal distribution but often does not. Bilateral leg pain, although less common than unilateral leg pain with LDH, can be the result of a large posterior central herniation. Patients may also describe a history of chronic axial back pain with sudden relief but new onset of radicular pain. This pattern is thought to result from an acute herniation event with transference of pressure of the pulposus from the innervated exterior annulus to the nerve root itself. Patients may also describe difficulty with positions where the lumbar spine is flexed, such as sitting or driving. Leg pain is often exacerbated by coughing or sneezing. Gait alteration may occur, either from antalgia or true muscular weakness in the extremity. In very rare circumstances, patients may describe changes in bowel or bladder patterns, such as urinary retention, and although very uncommon, cauda equina syndrome can result from LDH [16]. Constitutional symptoms should be addressed as these may indicate other causes of radicular pain such as tumor or infection (see Table 25.1) [17].

A physical exam begins with inspection of the lumbar spine, in particular for any scars which may indicate

Table 25.1 Differential diagnosis of radicular-type pain [17]

Type of pain	Differential diagnosis
Intraspinal compression/ irritation at level of root	Spinal stenosis, osteomyelitis, discitis, neoplasm, epidural fibrosis (scar)
Intraspinal compression/ irritation proximal to level of root	Conus and cauda lesions such as neurofibroma or ependymoma
Systemic disorders resulting in nerve root dysfunction	Idiopathic neuropathy, diabetes, alcoholism, chemotherapy agents, herpes zoster
Extraspinal sources	Distal pelvis or leg neoplasm, osteoarthritis of hip or knee, sacroiliac joint disease, peripheral vascular disease

Table 25.2 Motor and sensory innervations of lumbar nerves

Nerve root	Strength	Sensory	Reflex
L2, L3	Iliopsoas, hamstrings, quadriceps	Anteromedial upper thigh	None
L4	Quadriceps, *tibialis anterior*	Medial ankle	Quadriceps
L5	Extensor hallucis longus	Dorsum of foot	Posterior tibial (very difficult to illicit)
S1	Peroneals, *gastrocsoleus*	Lateral ankle/ foot	Achilles

previous surgery. Patients may have spasm and tenderness of the paraspinal muscles. Range of motion is generally limited by pain. A thorough strength and sensory exam is critical to detect any weakness (see Table 25.2). Subtle weakness in S1 (gastrocsoleus) may be elicited with an extinction test. In this, the patient is asked to perform single-leg toe raises with their uninvolved extremity. A significant decrease in the number performed with the involved extremity can indicate weakness. Loss of reflexes or asymmetric reflexes may also indicate pathology. An examination of gait should be also performed. While patients frequently walk with an antalgic gait, particular attention should be focused on normal heel-toe strike. A marching, flat-foot strike or toe drag may indicate tibialis anterior weakness. If there is any history of urinary retention, the perineal region should be assessed for sensory changes that may indicate a cauda equina syndrome. Special tests such a straight leg raise (SLR), or femoral nerve stretch for suspected high lumbar herniations, may also be useful. In a recent meta-analysis, SLR demonstrated a sensitivity of 0.92 and specificity of 0.28. The crossed SLR test had a sensitivity of 0.28 and specificity of 0.90 [18].

Imaging

Imaging for all patients with suspected lumbar disc herniations should begin with plain upright radiographs. Findings suggestive of a lumbar disc herniation may include loss of disc height or loss of normal lumbar lordosis. Performing the radiographs in the upright position is an important assessment of segmental stability. If operative treatment is being considered, a flexion upright lateral image may also be considered to evaluate for any underlying dynamic instability.

The gold standard for diagnosis of LDH is MRI including both T1- and T2-weighted sequences. Contrast is not necessary; however, it may be useful in patients with a history of previous spine surgery or in cases of recurrent disc herniation. Disc material is avascular and does not usually enhance with administration of gadolinium contrast, helping to delineate it from scar which has a vascular supply and does enhance. CT myelogram is still a useful adjunct in patients unable to obtain an MRI.

Advanced imaging should be obtained in all patients with detectable weakness on exam, symptoms suspicious for cauda equina, or suspected tumor or infection. MRI or CT myelogram should also be obtained in all patients considering surgical intervention, who have persistent symptoms recalcitrant to nonoperative management.

Nonoperative Management

Nonoperative treatment for LDH includes activity modification, physical therapy, anti-inflammatory medications, and epidural steroid injections. A recent meta-analysis comparing nonoperative treatment regimens found that groups receiving physical therapy including stabilization exercises had a more favorable outcome than groups not receiving any therapy [19]. While no literature is currently available comparing home exercises versus supervised exercises in patients prior to surgery, another meta-analysis of post-discectomy therapy regimens found no long-term difference in supervised training sessions compared to a home program [20].

Epidural steroid injections represent an increasingly popular treatment option, with the perceived impression that there is a cost savings when compared to operative treatment, although with no significant data demonstrating a change in the natural history of LDH or the ultimate need for surgery. In 2007, an estimated $175 million was spent by Medicare annually for lumbar epidural procedures [21]. In our opinion, there has been a disproportionate increase in the number of spinal epidurals over the last 5 years, for the treatment of LDH, with little data to substantiate this rapid rise. Contraindications for injections include active infection, coagulopathy, and spinal malignancy. There are three main routes for administration of an epidural injection: interlaminar, transforaminal, and caudal. For radicular pain typical of LDH, the transforaminal approach is recommended as this targets the nerve root directly. Given that a significant component of radicular pain caused by LDH is thought to derive

from chemical irritation of the nerve root, presumably caused by foreign nucleus pulposus, administration of epidural steroid is thought to combat this local inflammatory response.

Long-term results of epidural steroid injections are mixed. In one study, 55 patients with MRI evidence of nerve root compression were randomized to receive selective transforaminal nerve root injection with either bupivacaine and betamethasone or bupivacaine alone [22]. Seventy-one percent of patients who received the combination of steroid and anesthetic avoided surgery at a follow-up of 28 months compared to only 33 % receiving bupivacaine alone.

In a later randomized controlled trial, 160 patients with radicular pain were randomized to receive transforaminal injection with either methylprednisolone and bupivacaine or saline alone. At 2 weeks postinjection, pain scores and clinical exam favored the steroid/anesthetic combination [23]. At 4 weeks, however, there was no statistical difference between the two groups. At 3- and 6-month time points, a slight trend favored the saline group. At final follow-up of 1 year, there was again no difference.

Epidural steroid injections are not without risk. A postinjection flare in leg or back pain can occur. Although rare, catastrophic complications are possible and include epidural abscess, subsequent meningitis, nerve root damage, epidural hematoma, and spinal cord trauma [24]. In late 2012, 137 cases of fungal meningitis after epidural steroid injection were reported. These infections resulted in 10 deaths. Cultures were positive for the fungus *Exserohilum rostratum*. The contaminated batches of methylprednisolone were eventually traced back to a single facility in Framingham, Massachusetts [25]. Paraplegia from attempted epidural injection has also been reported [26].

Subgroup analysis of the Spine Patient Outcomes Research Trial (SPORT) demonstrated no difference in 4-year final outcome measures (pain, physical function, Oswestry Disability Index) between groups that received epidural steroid injections and those that did not. This same observation remained consistent in both operative and nonoperative treatment arms. However, a significant difference was noted in group crossover in patients who received injections. Crossover from surgical to the nonsurgical group was 41 % in patients receiving epidural steroid injections and only 12 % in those who did not receive an injection [27]. Thus, while it appears that epidural steroid injections do not seem to affect the final outcome of operative and nonoperative treatment for LDH, these injections may help patients avoid a surgical procedure by alleviating pain in the acute symptomatic phase.

Ultimately, both physical therapy and epidural steroid injections represent viable nonoperative treatment options for the management of LDH. As the natural history of LDH is overall favorable, both can be of benefit during the acute symptomatic phase. Given the high rate of patient crossover in SPORT, however, further studies are needed to establish the true value of epidural steroids in the treatment of LDH. An informed conversation must occur with the patient regarding the risks and expected benefits of both physical therapy and epidural steroid injections. The need for patients to communicate any neurologic deterioration, or increasing pain and dysfunction during these treatments, must be emphasized.

Operative Management

For many years, Weber's classic study served as the best comparison between operative and nonoperative management of LDH [28]. It included 126 patients at a single center randomized to receive discectomy or conservative treatment. Outcomes favored discectomy after 1 year; however, a statistically significant difference was lost after 4 years. At final follow-up at 10 years, outcomes between surgical and nonsurgical groups were identical. Although it served an important role in determining the natural history of LDH, Weber's study was plagued by selection bias and lack of validated outcome measures.

SPORT was a multicenter, prospective randomized controlled trial designed to combat selection bias and small sample size that limited previous studies. Its purpose was to evaluate surgical and nonsurgical outcomes of intervertebral disc herniation, degenerative spondylolisthesis, and lumbar spinal stenosis [29]. Developing a randomized controlled trial (RCT) to determine the outcome difference between nonoperative and surgical treatment of LDH is difficult. Patients must remain in control of their treatment options. Furthermore, in a truly randomized study, a sham surgery would be required. This is obviously not feasible, as it would subject the patient to unnecessary surgical and anesthesia risk. Additionally, surgical RCTs are prone to bias from surgeon technique and protocol. The SPORT study was designed as a large, multicenter study to lessen the impact of selection bias. It included two main arms, a prospective observational cohort and a RCT cohort. In the randomized arm, patients were assigned to a surgical or nonsurgical group. In the RCT arm, patients were permitted to cross over between groups. While permitting for patient preference and avoiding ethical conflict, the ability to cross over between groups predisposed the SPORT study to significant bias as patient's may never receive intended treatment. A crossover rate of 50 % would effectively nullify any randomization. Surgery consisted of a standard open discectomy. Minimally invasive techniques were not used. Nonoperative treatment was patient-specific and was recommended to include physical therapy, patient education, and possibly anti-inflammatory medications.

To combat crossover bias, the SPORT trial included two different methodologies for analyzing outcomes: "as-treated"

and "intent-to-treat." As-treated analysis evaluated outcomes based on the treatment ultimately received. In contrast, intent-to-treat analysis was performed by recording the outcome of the patient based on their initial treatment group assignment rather than by the treatment actually performed. Intent-to-treat analysis holds the idea of randomization paramount and measures outcomes based on assignment of a treatment policy rather than the treatment itself. The intent-to-treat analysis helps lessen the effect of uncontrolled variables such as physician-patient discussions, which can lead to biased treatment decisions [30].

Outcomes of the intervertebral disc herniation segment of the SPORT trial were performed using a number of standardized forms (Medical Outcomes Study 36-Item Short Form and Oswestry Disability Index). At 4 years, both surgical and nonsurgical groups in the randomized arm demonstrated significant improvement. Crossover from nonoperative to surgery was 24 %. Crossover from surgery to nonoperative was 19 %. In both groups, the as-treated analysis significantly favored surgery at both 2- and 4-year time points. Interestingly, outcomes of the intent-to-treat analysis also favored surgery at all time points; however, these were not statistically significant. The mixing of treatments due to crossover is expected to create a bias toward the null hypothesis (i.e., no difference between surgical and nonsurgical groups) in the intent-to-treat analysis [31]. When compared to the large treatment effect favoring surgery in the as-treated analysis, it seems that the intent-to-treat analysis may underestimate the treatment effect of surgery [32]. It follows that there may be a trend for improved outcomes with surgical intervention, a conclusion which is supported by midterm 4-year outcomes of the SPORT trials. However long-term results (>10 years) are not currently available.

Minimally Invasive Techniques

The development of modern imaging equipment brought with it advancement in discectomy technique. A "mini-open" approach minimizing soft tissue dissection has become the standard of care for surgical management of LDH. In an effort to further reduce soft tissue trauma and speed patient recovery, a system of tubular retractors placed under fluoroscopic guidance was developed in the mid 1990s by Foley and Smith [6]. They utilized an operative microscope in lieu of loupe magnification. This method of microdiscectomy theoretically causes less muscle denervation of the multifidus and subsequently less pain.

In discectomy, complications include inadequate decompression of the nerve root, nerve root damage, dural tear, and even wrong level surgery. The potential for increased complication rate, cost of specialized equipment, and need for additional training have been barriers for the widespread adoption of minimally invasive techniques.

In the late 1980s and early 1990s, percutaneous techniques for discectomy were developed. Efforts in this field began with injections of enzymes such as chymopapain into the intervertebral disc at the level of the herniation. Known as chemonucleolysis, the mechanism of action was thought to involve the digestion of the nucleus pulposus resulting in decreased tension on the annular fibers and withdrawal of the neurocompressive etiology back into the annular confines [31]. Chemonucleolysis is reported to have good or excellent results in 50–75 % of patients with 5-year follow-up; however, this technique also carries the risk of anaphylaxis [31, 33]. Automated percutaneous nucleotomy was a similar nonselective technique involving insertion of a mechanical device into the nucleus pulposus at the herniated level. The goals of disc debulking and involution into the annulus were similar [34]. While this technique did not carry the risk of anaphylaxis, nerve root trauma and bowel perforation were listed complications. The success rate of automated percutaneous nucleotomy was similar to chemonucleolysis [35]. Laser disc decompression was also developed at this time and involved a more gradual involution of disc material but carried with it a risk of thermal damage to the nerve root [34]. These percutaneous techniques have been largely abandoned in favor of open techniques given their failure to prove better outcomes and higher risk of complications.

Development of more advanced endoscopic equipment allowed for these technologies to be applied to spine surgery, in particular lumbar discectomy. These techniques involve insertion of an endoscopic camera through foraminal or extraforaminal space into the disc space without the use of a tubular retraction system [34]. These techniques permitted visualization and removal of the herniated fragment. Complications have been similar to open discectomy and include infection, nerve root damage, and dural tear [36]. A retroperitoneal approach has also been developed but carries the risk of bowel perforation or trauma to major vascular structures [34]. Results of endoscopic procedures are generally more favorable than percutaneous techniques with success rates reported from 75 to 98 % [37, 38]. One drawback of all endoscopic procedures is their inability to address disc pathology in cases of significant disc migration, especially in the cephalad or caudal direction. Due to the need for specialized equipment, endoscopic techniques are generally not considered cost-effective unless performed on a routine basis [39]. Endoscopic discectomy has failed to have widespread popularity as it offers no advantage over traditional mini-open discectomy or tubular MIS discectomy, with no data demonstrating superior outcomes, and yet a significantly increased "fiddle-factor" and expense. For thoracic disc herniation, endoscopic techniques hold more promise as morbidity associated with open dissection and discectomy is

high [40], although the advent and popularity of lateral access has significantly diminished morbidity traditionally associated with thoracic surgery.

With the advent of the tubular retractor system, an open, less invasive, technique with minimal soft tissue dissection became possible. This retraction system defines the modern version of the most commonly performed minimally invasive lumbar discectomy performed in the United States [1]. A tubular retraction system can be used with an operative microscope or endoscopic equipment (microendoscopic discectomy), as popularized by Fessler et al. [41]. Using an endoscope through a tubular retraction system may provide improved visualization beyond the confines of the retractor construct, especially when using a 30° endoscope [41]. These techniques allow for improved visualization and the potential to address complicated pathologies such as cephalad or caudal disc migration. Additional proposed benefits of MIS microdiscectomy include potential lower rate of surgical site infections, shorter hospital stay, and faster postoperative recovery [42]. Potential drawbacks include limited exposure compared to open techniques, limited ability to extend approach, and steep learning curve [42].

A timely meta-analysis of randomized controlled trials comparing minimally invasive discectomy and open discectomy was recently performed [42]. In their thorough analysis, Dasenbrock et al. identified 13 randomized control trials comparing MIS discectomy to mini-open discectomy. Exclusion criteria included recurrent disc herniations, follow-up less than a year, and utilization of MIS techniques without tubular retractors, leaving six trials in the meta-analysis. This left a final total of 837 patients, 388 randomized to MIS and 449 randomized to open. All studies compared "mini-open" discectomy (OD) to minimally invasive discectomy (MIS) with a tubular retractor system. Mean follow-up was at least 24 months for all studies. They examined outcome measures including visual analog scale (VAS) pain scores, operative time, total complications, incidental durotomy, and reoperation for reherniation.

Their group found no significant difference in VAS leg pain relief between groups randomized to open versus minimally invasive procedures in either short- or long-term follow-up [42]. Pooled preoperative VAS scores were 6.9 and 7.2 for minimally invasive and open groups, respectively. In both groups, there was a statistically significant decrease in postoperative VAS scores, however not significant intergroup difference. Pooled VAS scores reached 1.6 postoperatively for both groups [42]. However, analysis of complications between the minimally invasive and open cohorts demonstrated a difference. In the minimally invasive group, there was a statistically significant increase in the number of incidental durotomies (5.67 % in MIS and 2.09 % in OD) [42]. Five cases of persistent CSF leakage were reported. Suture repair of durotomy with a tubular retractor is difficult. Fibrin glue or specially designed clip devices can be used for closure. While most incidental durotomies are asymptomatic, they can lead to spinal headache, pseudomeningocele formation, or development of a CSF fistula which has the potential to result in meningitis [43]. The difference in total number of complications including incidental durotomies, surgical site infections, nerve root injury, and reoperation for recurrence of herniation was not statistically significant between the MIS and open groups (6.96 and 3.56 %, respectively) [42]. Recurrence of post-discectomy reherniation has been estimated to be anywhere from 3.5 to 20 % [1]. In Dasenbrock's analysis, the difference between reherniation in MIS and OD was not significant (8.50 and 5.35 %, respectively) [42]. This analysis did not discuss results such as length of hospital stay, time to return to work, and intraoperative blood loss. A definitive study on these topics has yet to be conducted and would represent a valuable area of research.

Conclusion

In conclusion, LDH is a common pathology that will affect a significant portion of the population. The natural history of LDH is favorable, and excellent results are often obtained with conservative management. Physical therapy and epidural steroids represent a viable treatment option; however, they are not effective in all patients.

Surgical treatment is recommended in patients with progressive weakness and suspicion for cauda equina syndrome and also in patients with persistent leg pain that is refractory to nonoperative treatment. Recent data, notably the large-scale SPORT trials, suggest that patients managed with discectomy may have a more favorable outcome when compared to conservative treatment. A "mini-open" technique is the most common modality of discectomy performed; however, minimally invasive approaches have similar overall excellent outcomes. The use of a tubular retractor system typifies the modern minimally invasive approach. A number of randomized controlled trials comparing open discectomy to minimally invasive microdiscectomy have been performed. A pooled analysis of these trials demonstrates that both techniques seem to be equally effective at relieving pain and have comparable reherniation rates. Overall complication rates are similar between open and minimally invasive approaches; however, the number of incidental durotomies is higher with minimally invasive approaches. Minimally invasive approaches offer the potential benefit of less soft tissue trauma and faster recovery; however, they can be technically demanding. Excellent results can be obtained with either a minimally invasive or open approach, and current evidence supports operative treatment for more rapid improvement in patients with persistent symptoms. Surgeon preference and surgeon training

largely drive the choice of "mini-open" versus minimally invasive discectomy, as both techniques reproducibly relieve leg pain with a similar complication profile.

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Lumbar Spinal Stenosis

26

Thomas D. Cha, Justin M. Dazley, and Safdar N. Khan

Introduction

As the population ages, lumbar spinal stenosis (LSS) is becoming a more frequent problem requiring medical attention and is the most frequent diagnosis in elderly patients undergoing spinal fusion [1]. Longer patient life expectancy and sustained interest in maintaining an active lifestyle make treatment of LSS important for any individual providing spinal care. LSS manifests clinically with diminished walking tolerance accompanied by bilateral buttock and leg pain with or without back pain. Neurologic impairment may include pain, paresthesias, or weakness alone or in combination. Chronic LSS may present with muscle weakness and foot drop. Collectively, this constellation of symptoms is termed neurogenic claudication. The etiology of LSS may be congenital, iatrogenic, traumatic, or degenerative, and this chapter will focus primarily on the latter. Anatomically, compression of neural elements from bone and/or soft tissue takes place in various regions of the spinal segment including centrally, in the subarticular or lateral recess, or the neural foramen.

Conservative measures are generally indicated as the first-line treatment and include oral analgesics, anti-inflammatories, activity modification, and physical therapy. Additionally various methods of injection therapy such as epidural or selective nerve root may be implemented however with variable results [2, 3]. Surgical treatment is reserved for patients who have exhausted all conservative measures and continue to be disabled by the symptoms. Traditional surgical options for LSS have included laminectomy, foraminotomy, or fenestration laminotomy with the primary goal of decompressing the neural elements. In cases where back pain is a predominant symptom and can be attributed to degenerative spondylolisthesis (DS) or a progressive degenerative scoliosis, a fusion procedure may be indicated to address associated dynamic compressive pathology or spinal instability.

Over the past several decades, the surgical treatment of LSS has trended toward less invasive techniques. Embrace of the surgical microscope and the development and experience with tubular retractors assisted in the progression of minimally invasive techniques from spinous process osteotomies allowing muscular attachments to remain undisturbed [4] to a unilateral approach facilitating bilateral decompression [5].

Traditional open techniques, while effective, inflict greater damage to the spinal musculature than muscle-splitting approaches [6]. Additionally, decreased intraoperative blood loss and a shorter hospital stay without compromising the quality or extent of bony decompression [7] have been shown with minimally invasive surgery (MIS) [8, 9]. A variety of procedures and techniques intended to treat LSS in a minimally invasive fashion have been described.

Indications

Regardless whether open or MIS procedures are employed, surgical candidates should exhibit neurogenic claudication and have completed a trial of conservative treatment. The desirable characteristics of MIS treatment include decreased blood loss, smaller incisions, and shorter length of stay in the hospital. While these features are desirable for patients in general, they are particularly important for elderly patients or those with serious comorbidities or chronic diseases with little hope for optimization for surgical intervention [10].

Determining which patients are appropriate for MIS may be nearly as important as the performance of the procedure itself.

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Lumbar spinal stenosis and spondylosis are major causes of morbidity among the elderly. While surgical decompression may be an effective treatment for these patients, many elderly patients are not considered candidates for surgery based on age or comorbidities. In an effort to address or minimize the surgical insult in this group of patients, Rosen et al. found minimally invasive decompression for symptomatic LSS in patients over 75 years of age to be safe and effective [11]. Spine surgery has not been spared the challenges which have come with the obesity epidemic taking place in North America. Increased surgical time, blood loss, perioperative surgical site infection (SSI), as well as diabetes and other comorbidities may be expected in these individuals. MIS provides for reduced soft tissue damage, important in obese patients. The smaller approach helps to minimize infections and wound healing disorders. Additionally, deeper regions of wounds can be clearly visualized with the aid of tubular retractors [12].

Although the efficacy and safety of MIS for LSS has been documented in the elderly population, certain considerations should be made in younger patients. These individuals may have less degeneration in their motion segments, as well as more lax ligamentous structures, including the facet capsules. In a cadaveric biomechanical study with finite element analysis, Ivanov et al. studied the effects of limited decompression on stresses of the remaining bone and showed that there were significant increases in stress at the pars and inferior facet. These effects were greatest in extension and rotation to the contralateral side, and the authors concluded that the surgeon should be aware of the possibilities of stress fractures in this patient group [13].

The neurogenic claudicatory symptoms of LSS can effectively be addressed through decompression of the affected neural elements. To this end, procedures may either exert their effects through indirect or direct decompression. An example of a MIS technique of indirect decompression is the interspinous process device (IPD). IPDs are indicated in patients over 50 years of age, with moderate cases of LSS, allowing them to walk short distances, and who have failed conservative treatment. Relief of symptoms when flexing the lumbar spine is a prerequisite for the use of these techniques [14, 15]. Similarly radiographic evidence of distraction of the spinous processes of interest should be observed [14]. These devices have shown variable results in patients with spondylolisthesis, but in general, they should be used with caution in these instances and limited to cases of no greater than Meyerding grade I [16, 17]. Furthermore, the spinous process of S1 generally does not provide adequate bone stock to distract the L5–S1 segment, generally limiting the use of IPD's to the L4–5 level or caudal. Indirect decompressive techniques also include interbody fusion procedures where the vertebral body listheses may be reduced and neural foramen may be effectively enlarged as a result of reduction and interbody distraction.

Direct decompression for LSS has traditionally been accomplished through a decompressive open laminectomy, first described in MIS for LSS, and can be achieved through the use of a mini-open incision or with the use of a tubular retractor. The procedure may be performed with or without the use of an operating microscope or endoscope. In keeping with MIS philosophy of muscle preservation, a muscle-splitting approach is preferable. In cases of unilateral radicular symptoms, decompression is typically performed from the ipsilateral side, although a contralateral approach may facilitate foraminal decompression while undercutting the facets. In cases of bilateral radicular symptoms, a unilateral approach with bilateral decompression has been shown to be safe and effective [8]. Although Asgarzadie et al. reported acceptable results for the treatment of central, lateral recess and foraminal disease, other authors [18] have observed limitations to the extent of lateral recess decompression achieved from the unilateral microendoscopic technique. Furthermore, patients with arachnoiditis, tumor, infection, high-grade spondylolisthesis, or pseudomeningocele are generally not candidates for this sublaminar microendoscopic approach. Likewise, patients who have had prior surgery at the level of interest require caution due to the presence of adhesions. If revision cases are attempted, they should be performed by surgeons thoroughly experienced with the technique in primary settings [8]. Minimally invasive techniques have overall been successfully employed treating central and lateral recess stenosis; however, foraminal stenosis can be difficult to access through these techniques into a relatively confined space bordered by the cephalad and caudal pedicles and the dural sac medially. This notwithstanding, Yoshimoto et al. recently described the successful treatment of foraminal stenosis with a minimally invasive technique [19], indicating further advancements in treating this condition, without fusion, may be on the horizon. In cases of neural foramen or subarticular recess stenosis from facet cysts, Deinsberger et al. demonstrated successful treatment by direct decompression through MIS techniques [20].

Although decompression of the compressed neural elements remains the priority of either minimally invasive or open surgical treatment of LSS, care must be taken to maintain spinal stability. Decompression alone without fusion should be contemplated with caution for patients with spondylolisthesis or coronal or sagittal plane deformities [21]. In fact, Yamada et al. cautioned against the use of decompressive foraminotomy alone in deformities with Cobb angles measuring as little as 3° in the coronal plane [8, 21].

Outcomes

Most spine surgeons care for patients with LSS, and likewise, most are familiar with open techniques for treating this disorder. Establishing benefits and shortcomings of MIS

when compared to open techniques will be a focus of this section. Additionally, demonstration of safety and efficacy for new procedures will be reviewed.

Defining outcomes for MIS for LSS is difficult due to a lack of level I studies addressing this question and prospective studies frequently not randomizing patients or containing a control group. Furthermore, although open decompressive laminectomy is generally considered the standard with which to compare the results of MIS, there is considerable variability in technique in the open approaches (i.e., the frequency and extent with which medial facetectomy or foraminotomy is performed). Within the current literature evaluating MIS, patient cohorts are often heterogeneous with regard to demographics, procedures performed, or diagnoses. Another difficulty in interpreting the literature on MIS is the outcome parameter to be measured. For example, when examining interventions for DS, changes in preoperative to postoperative scores on patient outcome instruments such as the Oswestry Disability Index (ODI) or Short Form 36 (SF-36) may be used. Alternatively, radiographic parameters such as progression of slip may define success. Finally as evidence from the Spine Patient Outcomes Research Trial (SPORT) has shown, the time at which outcomes are measured can have a great impact evaluating the benefits and value of decompressive spinal surgery. Within MIS literature, there is a spectrum of time points at which outcome data is gathered; this may be as short as weeks [22, 23] or, more typically, midterm results. Most MIS techniques have been described within the past two to three decades, some much more recently, and procedures continue to be developed currently. As a result of the innovation in this field, long-term data tends to be less common.

Nearly 100 years after the first description of open laminectomy, Young et al. described bilateral decompression of the thecal sac from a unilateral approach in 1988 [24]. Many of these early MIS techniques still included bilateral dissection of paraspinous muscles and were plagued by complications, over 20 % in Young's initial series, including a 6 % incidence of dural tears. Nevertheless, patients responded favorably clinically, and no patients developed instability or required revision to traditional laminectomy. By the end of the 1990s, endoscopic techniques had been introduced, yet they also experienced a high rate of incidental durotomy [25]. Although enthusiasm for the endoscopic technique waned in general, orthopedic surgeons continued the practice, perhaps at an advantage by familiarity with arthroscopic procedures [25]. Use of an operating microscope proved very important in the evolution of the MIS, and with the addition of tubular retractor systems in early 2000 [7, 26, 27], these techniques became much more prevalent in the field of spine surgery.

Fessler first demonstrated the feasibility of bilateral decompression from a unilateral approach in a cadaver model and showed adequate decompression and complication rates independent of approach [7]. In Palmer's early experience treating LSS with decompression through tubular retractors [26], he prospectively followed 135 patients, measuring visual analog scale (VAS), the Oswestry Disability Index (ODI), and the Short Form-36 (SF-36). Follow-up data was collected in 129 of 135 patients. Improvement was seen on the VAS (scores 7–2), ODI (scores 57–16), and SF-36 scales (bodily pain scores 20–60). Patient satisfaction with results was 94 % at a minimum follow-up of 1 year. Complications included one superficial wound infection, one case of discitis, three durotomies, and three cases of excessive bleeding (>100 ml). There were five reoperations for recurrent disc herniations and one for recurrent spinal stenosis contralateral to the index site. Of note, the rate of dural tears had decreased to less than three percent, from over 6 % in early studies. Unfortunately, patients were not randomized, and there was no control group. Palmer also demonstrated the feasibility for performing bilateral laminar decompression from a unilateral approach in the setting of LSS with DS [26]. Other authors have shown favorable results for microendoscopic posterior decompression for LSS but have observed a tendency toward medial encroachment of the facet complex as observed on postoperative axial imaging. These authors found a 2 % incidence of postoperative instability after this procedure. Interestingly, the trends of medial facet encroachment and instability occurred earlier in the course of the study, implying there may be a learning curve associated with this phenomenon [28]. A large retrospective case series of 374 patients reported by Costa et al. demonstrated 87.9 % clinically significant improvement in VAS and Prolo scores with a 0.08 % rate of postsurgical instability demonstrated in radiographs [29].

A major benefit of minimally invasive techniques is their preservation of soft tissue through muscle-splitting approaches. This can be quantified by postoperative measurement of inflammatory markers as well as markers of muscle necrosis such as creatine kinase and aldolase. Kim et al. studied the tissue damage inflicted by open and mini-open lumbar fusions by measuring creatine kinase, aldolase, proinflammatory cytokines (IL-6, IL-8), and anti-inflammatory cytokines (IL-10, IL-1 receptor antagonist) with ELISA techniques. Values were checked preoperatively and 1, 3, 7, and 14 days after operation. Serum creatine kinase and most of the inflammatory cytokines were significantly high in the control group on postoperative days 1 and 3 but returned to normal levels by postoperative day 7. The authors concluded that mini-open lumbar fusion may significantly contribute to the reduction of muscle injury and systemic inflammatory reactions during the acute postoperative period [6].

In addition to minimizing soft tissue trauma intraoperatively, MIS is an excellent alternative to open surgery in elderly patients or those with chronic illnesses [11]. Fifty

patients over the age of 75 who underwent minimally invasive lumbar spinal surgery were reviewed by Rosen et al. who noted statistically significant improvements in VAS, ODI, and SF-36 scores. This study was not randomized, there was no control group, and follow-up averaged only 10 months. However, it is one of the few studies that focus on the outcome of MIS in this elderly population—a group which is frequently referenced as one which would benefit from minimally invasive techniques.

Providing results from somewhat longer follow-up, Asgarzadie retrospectively reviewed patients undergoing MIS utilizing a tubular retractor system [8]. Compared to a historical control of 32 patients undergoing open laminectomy, 48 patients undergoing MIS left the hospital sooner (36 h vs. 94 h) and maintained patient satisfaction and improvement in ODI and SF-36 at an average of 38 months' follow-up. Also, no cases of instability were noted; other authors have shown slightly higher recurrence rates requiring reoperation, but no higher than that for open treatment of LSS [30]. In a prospective randomized study, 41 patients were randomly assigned for minimally invasive microendoscopic decompression or conventional open laminectomy by the same surgeon. With a mean follow-up of 18 months, 90 % of the patients treated with MIS decompression had satisfactory symptom relief and compared to the open group had a shorter hospital stay, mean blood loss, and lower VAS scores for back pain [31].

A little over a decade ago, interspinous process devices (IPD) were introduced as a minimally invasive method for treating LSS in patients who were poor surgical candidates and whose symptoms abated with forward flexion [14, 15]. The biomechanical rationale behind these devices is fairly intuitive. By distracting the spinous processes, flexion is achieved through the stenotic motion segment presumably widening the space available for the neural elements and resultant symptom relief similarly achieved with leaning over a shopping cart (i.e., the shopping cart sign). Goyal et al. performed a biomechanical study to evaluate if the distraction achieved with IPDs results in radiographic increase in the spinal canal and neuroforamen, as well as whether the devices stabilized the motion segment. The authors found that canal area was minimally altered and foramen height, width, and area increased in extension and were statistically significant as compared to specimens without devices in place. Furthermore, there was no device subsidence or migration after cyclic loading [32].

In a 2005 multicenter, prospective, controlled, randomized study of 100 patients undergoing placement of the X-STOP IPD, Zucherman et al. [33] showed significant improvement in neurogenic claudication symptoms at all-time points. Zurich Claudication Questionnaire (ZCQ) values were assessed at all follow-up visits, and at 2-year follow-up, those who were treated with IPDs were 45 % improved from preoperatively as compared to those who were treated nonoperatively. Of note, in this and many studies looking at the efficacy of IPDs, the control group is composed of patients treated conservatively rather than those undergoing traditional decompressive laminectomy. Only 6 % of patients in Zucherman's study arm had undergone decompressive surgery at 2 years, whereas 26 % in the control had undergone surgical decompression. A recent retrospective review of 46 patients undergoing IPD implantation at a mean follow-up of 34 months showed a rather high revision rate of 30.4 % with most cases requiring revision within a year [34]. Therefore, the role of IPDs is still being defined in the spectrum of surgical treatment options for LSS.

Recently, entirely percutaneous procedures performed under fluoroscopic guidance, dubbed "MILD," percutaneous remodeling of ligamentum flavum and lamina (PRLL), have been described utilizing epidurograms to assess the adequacy of decompression. Although preliminary data showed improvement in symptoms [23, 35], the follow-up period was only weeks in these studies, and other investigators have shown an unacceptably high failure rate of this procedure [22]. With the dearth of supporting evidence, this procedure does not currently have a place in the surgical treatment of lumbar spinal stenosis.

Outcomes in Cases of Spinal Instability

Spinal instability frequently is associated with and can contribute to LSS. This instability typically takes place in the form of degenerative spondylolisthesis (DS). Although an arthrodesis is generally performed for LSS with DS, there may still be a role for stability-preserving decompression alone in this condition. The primary concern in performing decompression alone in LSS for DS is the additional iatrogenic instability and hastening of slip progression by disrupting the existing anatomy, including inter-/supraspinous ligaments and the facet complexes. Sasai et al. investigated risk of progression of spondylolisthesis after minimally invasive decompression without fusion in 23 patients with DS and 25 patients with LSS without DS. The average follow-up in this study was 46 months. No patient in either group required fusion procedures or other additional surgery. Clinical improvement in the form of The Neurogenic Claudication Outcome Score, back pain score, and ODI had significantly improved at the last follow-up in both groups, although there were no significant differences between those with DS and LSS without DS. However, there was a trend toward inferior clinical outcome in the DS group, and there was a significantly increased slip percentage on radiographs postoperatively. The authors concluded that this less invasive procedure was not likely to result in postoperative dynamic instability at the affected level [36]. Biomechanical studies investigating instability produced by standard open laminectomy with bilateral soft tissue and bony

dissection, compared to MIS involving unilateral approach for bilateral decompression (preserving the contralateral bone and soft tissue), confirm these clinical findings. This study demonstrated less segmental motion in extension and rotation for the minimally invasive unilateral approach [37].

Contrary to purported benefits of maintained spinal stability in patients with LSS and DS treated with direct minimally invasive decompression, IPDs in this population have shown unacceptable failure rates. In their small cohort of 12 patients undergoing placement of X-STOP IPD for LSS with DS, Verhoof et al. reported failure to relieve symptoms in 58 % of individuals. Interestingly, those failing treatment with X-STOP, and undergoing open decompression and posterolateral fusion, showed no progression of slip. Nevertheless, the authors recommended against the use of IPDs in cases of LSS with DS [16]. Still other authors have reported favorable outcomes using IPDs in this these patients [38] and so seems appropriate that using IPDs in cases of DS be done on a case by case basis, with the understanding that their performance is variable (see Figs. 26.1, 26.2, and 26.3).

Although a paramedian, muscle-splitting approach is among the most common minimally invasive approaches to the posterior spine, a recent description of a midline muscle-sparing approach has been made [39]. This procedure involves limited spinous process burring from a midline approach to allow the supra/intraspinous ligaments to be split, allowing access to the interlaminar space, and performance of neural decompression. Hatta et al. demonstrated this procedure to be safe and noted a 64 % increase in the Japanese Orthopedic Association (JOA) scores from pre- to postoperative.

Complications

With any new technology, there is potential for a new set of complications as well as a learning curve that must be overcome, and minimally invasive spine surgery for the treatment of LSS is no exception [40, 41]. Initial efforts to implement minimally invasive techniques in the surgical treatment of degenerative spinal conditions were limited by visualization, and techniques such as spinous process osteotomies were used to remedy this dilemma while avoiding interruptions to muscular attachments [4]. Advances in instrumentation including tubular retractor systems and the increased use of the operating microscope and endoscope allowed improved visualization with muscle preservation via a muscle-splitting approach. The smaller operating corridors which are a fundamental tenet of MIS may present unfamiliar territory to a surgeon inexperienced in these techniques. MIS was shown to have statistically fewer complications than that of open procedures in a review of over 10,000 patients treated surgically for symptomatic LSS [42]. Complications experienced in open surgical treatment of LSS are among the most common experienced in MIS for LSS. Of note, in obese patients, a group that MIS has particular appeal, there was no increase in complications based on body mass index [12]. The complications of incidental durotomies, excessive bleeding requiring transfusion and surgical site infection, as well as pseudarthrosis and iatrogenic instability will be discussed in this section.

Because of the largely percutaneous nature of MIS, intraoperative imaging is heavily relied upon. This is a particularly critical step in identifying the correct level identified preoperatively. Becoming disoriented in this regard can prove devastating the patient and surgeon but can occur easily with MIS as illustrated by two cases in a prospective study evaluating the microendoscopic treatment of LSS [43].

Interspinous Process Device Unique Complications

One major complication of IPDs is a fracture of the spinous process (SP). Although this can happen during or after surgery, intraoperative fractures make proceeding with the procedure impossible as the fractured SP is no longer able to distract the stenotic segment. Cadaveric studies have shown that on average the force required to fracture a SP is significantly greater than the force required to implant an IPD, 317 N and 55 N, respectively [44]. However, there was an overlap between the ranges of the groups, which was correlated with bone mineral density. This may be a concerning finding if many of the patients undergoing this procedure have compromised bone mineral density [45].

Wound Problems

A prospective study using tubular retractors reported a 0.8 % rate of infection [28]. A somewhat higher incidence of 4.5 % was seen for wound hematomas or delayed healing in 222 patients studied retrospectively. More concerning was the 4.5 % rate of infection reported in this series, including one case of discitis and one case of epidural abscess [46].

Excessive Bleeding

This complication is difficult to define as there is not a standard blood loss (EBL) for any given procedure, and intraoperative blood loss for different procedures may vary dramatically. Palmer et al. considered EBL >100 cc to be excessive in the minimally invasive treatment of lumbar disc herniations and found an incidence of 2.1 % in his review of 135 patients [26].

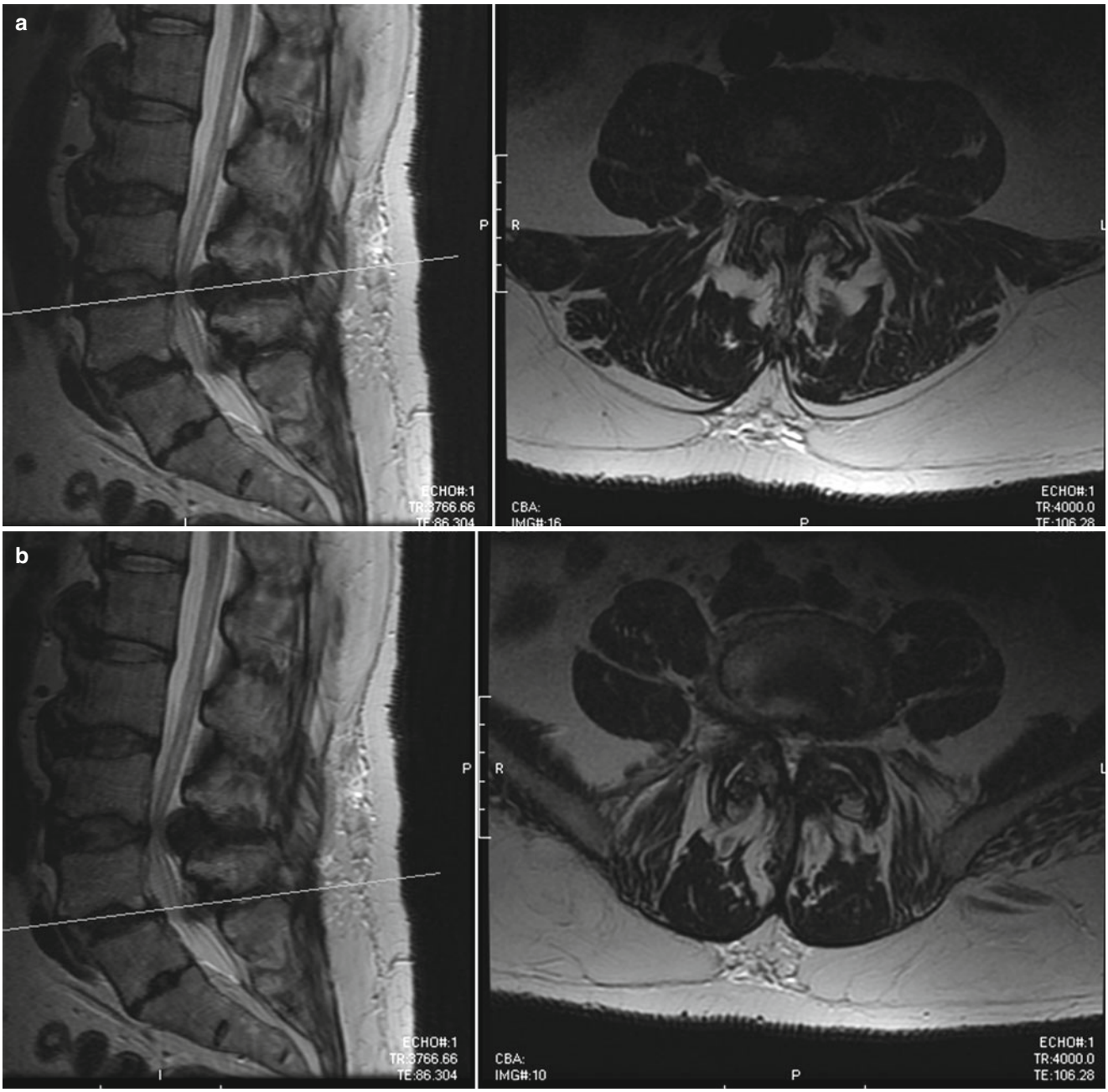

Fig. 26.1 A 66-year-old male presenting with neurogenic claudication with good relief of his symptoms upon forward flexion. His radiographic studies demonstrate a degenerative spondylolisthesis at L4–5 with advanced imaging showing concomitant spinal stenosis at (**a**) sagittal and axial image at L4–5 and (**b**) L5–S1

Recurrence

Recurrence of LSS, especially requiring reoperation, while not necessarily a complication of treatment, is an undesired outcome. Recurrence rates of LSS after surgical treatment through minimally invasive techniques have been reported to be as low as 0.8 % [26] or as high as 58 % [16]. A more moderate, yet still relatively high, rate of recurrence was seen in patients with degenerative lumbar scoliosis who underwent minimally invasive foraminotomy for foraminal stenosis [21]. These patients were shown to have recurrence of symptoms in 19.6 % of cases.

Aborting MIS

Abandoning minimally invasive efforts and converting to open techniques may not represent a complication and may not compromise a patient's outcome; however, it is an important metric and one unique to MIS. Rate of conversion to

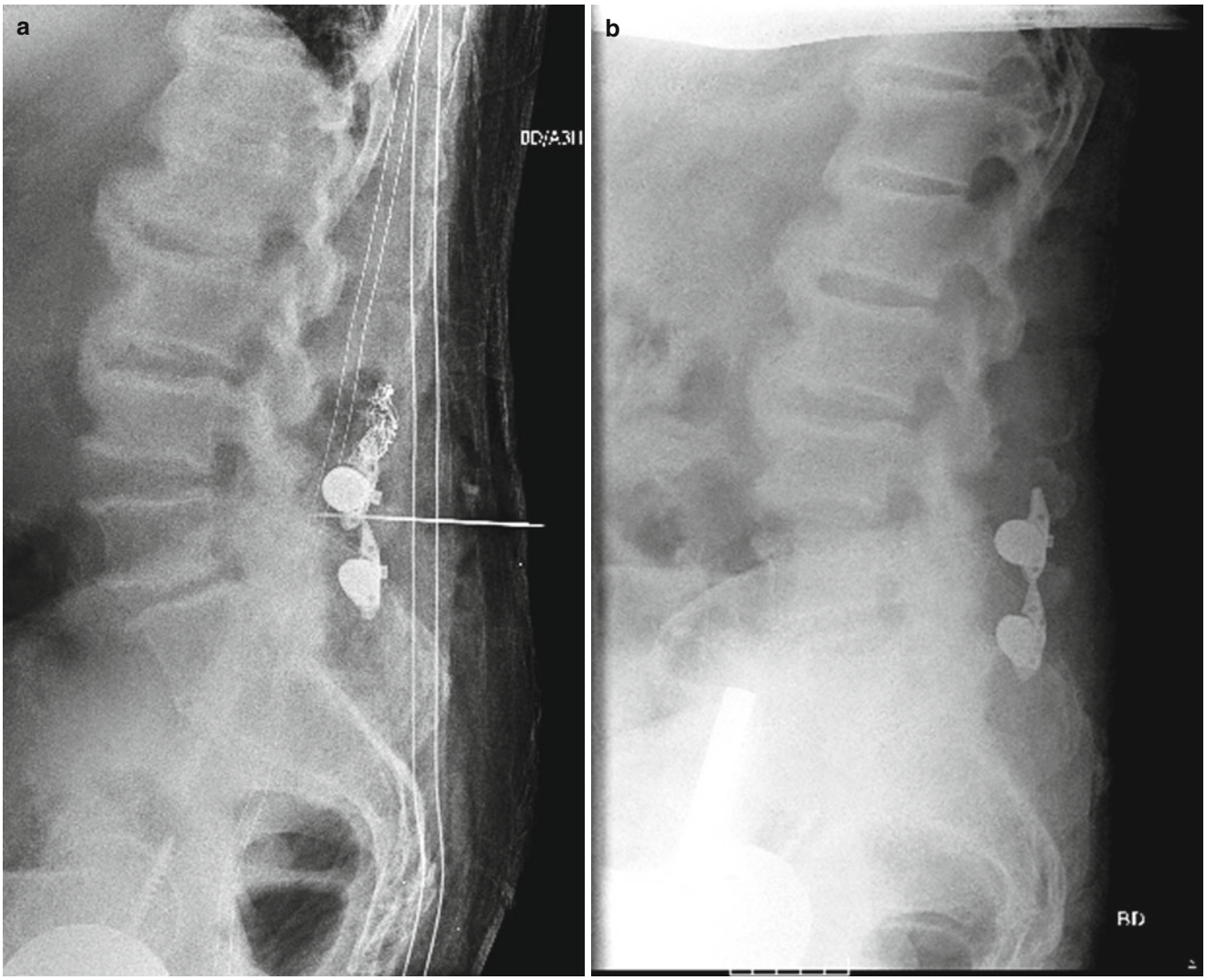

Fig. 26.2 Same patient from Fig. 26.1. Patient underwent a two-level X-STOP procedure seen on (**a**) intraoperative lateral radiograph. At two years, the patient continued to have very good relief of his symptoms with (**b**) radiographs showing maintained position of the X-STOP device

open surgery is not routinely reported in the literature. Greiner-Perth et al. reported a rate of 5 % conversion to open treatment in their prospective study of 38 individuals undergoing minimally invasive decompression for LSS [30]. It should be noted that these authors were using muscle dilators providing an 11 mm portal as opposed to portals 18 mm or larger which are more commonly used.

Iatrogenic Instability

Iatrogenic instability is a concern when employing minimally invasive techniques with their smaller operating corridors in the treatment of LSS. A clinical situation particularly concerning for development of iatrogenic instability is the surgical treatment of a facet cyst. However, Deinsberger et al. reported no postoperative instability at an average of 35-month follow-up with minimally invasive decompression of facet cysts without fusion [20]. Of note, nearly half of these patients had degenerative spondylolisthesis preoperatively. Other authors have reported cases of instability requiring reoperation due to iatrogenic facet fracture during a tubular MIS for LSS, a facet fracture after a fall, and an unidentified DS [46]. All of the combined cases of instability resulted in an incidence of only 1.4 %, and only one of these cases required arthrodesis. Over 30 % of patients in this series had spondylolisthesis, however, no mention of whether those patients experiencing instability postoperatively had spondylolisthesis preoperatively. In patients with no DS preoperatively, Musluman et al. recently showed only one patient (1.2 %) who required fusion after bilateral microdecompression from a unilateral approach [47]. Using microendoscopic techniques for bilateral decompression for LSS, Ikuta et al. similarly observed 2.6 % patients with inferior facet fractures [40].

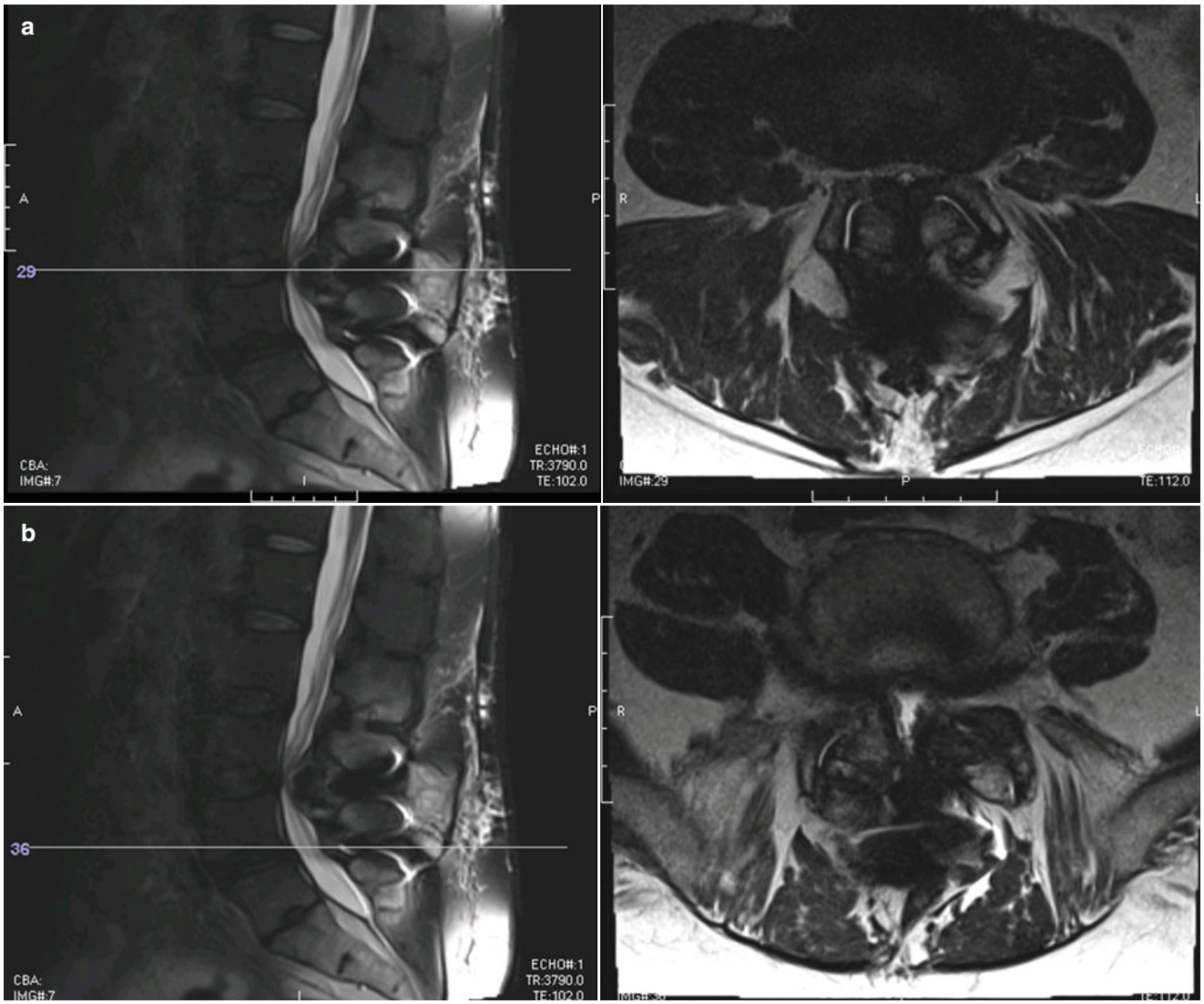

Fig. 26.3 Same patient from Fig. 26.1. Eventually patient symptoms returned to the original severity with repeat advanced imaging showing advanced spinal stenosis at the two X-STOP levels (**a**) L4–5 and (**b**) L5–S1. At three years postoperative from the index procedure, he underwent an open laminectomy along with X-STOP removal

As mentioned earlier, biomechanical investigation of stress at the bony elements after both traditional and minimally invasive decompressive techniques showed greater stress at the remaining the bony elements in the latter [13]. This was particularly the case in younger patient populations and specifically increased stress at the pars and inferior facets. Specifically evaluating progression of spondylolisthesis, Sasai et al. retrospectively reviewed patients undergoing minimally invasive decompression for LSS both with and without DS and found no difference between the groups, with no patients undergoing additional lumbar surgery at 2-year follow-up [36]. These results were not duplicated when attempting indirect decompression with the X-STOP IPD for patients with LSS due to DS. One third of patients experienced no improvement in symptoms, and three of the remaining eight patients had symptoms which recurred by 2 years. Ultimately, over half of these patients underwent revision posterolateral fusion at the previously operated level [16].

Neurologic Deficits

A retrospective review of 220 consecutive patients undergoing microscopic or microendoscopic decompression reported one foot drop lasting at least 6 months [46]. Transient neurologic deficits were also observed in 10.5 % of patients undergoing microendoscopic decompression for LSS; however, this did not appear to impact the clinical outcome of these patients at 28-month follow-up [40].

Dural Tear

When evaluating large series of minimally invasive decompression, reported rates of dural tears vary from 4.5 to 10 % [40, 43, 46].

Conclusion

Minimally invasive decompression procedures for the surgical treatment of lumbar spinal stenosis were developed in order to limit the morbidity and recovery from the traditional surgical exposure necessary relieve compression on the neural elements. Advances in retractor technology, instruments, and visualization enhancement have contributed to excellent results seen in clinical studies with midterm follow-up.

The complication profile is favorable compared to historically reported complication rates of open surgery; however, there is a clear learning curve for the individual surgeon. The role of interspinous process devices and decompression in an area of spinal instability is still to be determined.

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Minimally Invasive Spine Surgery in Lumbar Spondylolisthesis

27

Siddharth B. Joglekar and James D. Schwender

Introduction

Minimally invasive surgery (MIS) or minimal access surgical technique (MAST) is increasingly being employed in almost all areas of spine surgery. The early efforts to develop these approaches can be traced back to Wiltse who, in 1968 and 1973, described the paraspinal muscle splitting approach to the posterolateral spine through a natural cleavage plane between the multifidus and longissimus muscles [1, 2]. Wiltse mainly developed and described his approach and technique for decompression and fusion in spondylolisthesis [1]. Wiltse and Spencer also later described extended applications of this approach such as treating a far lateral disc herniation, unilateral as well as contralateral spinal canal, and subarticular decompression from the unilateral paraspinal approach and pedicle screw insertion [2]. Many of these same techniques with some modifications are being used today in the field of minimally invasive spinal surgery with the aid of specially designed instrumentation and self-retaining tubular retractor systems. The techniques as suggested by Wiltse are especially relevant in the treatment of spondylolisthesis with the use of minimal access surgical technology (MAST) [1, 2].

Isthmic and degenerative spondylolisthesis are commonly encountered lumbar spine conditions in a spine surgical practice. While this chapter focuses only on the use of MAST/MIS techniques in spondylolisthesis, it helps to review some of the generally accepted principles and issues. Degenerative spondylolisthesis usually presents in older adults with central and/or subarticular stenosis and most commonly affects the L4–5 segment. The surgical goals are primarily to decompress and fuse the unstable segment [3]. Decompression alone without fusion has been described to have good outcomes in selected cases with mild slips and no radiographic evidence of dynamic instability [4–6].

The presenting age, symptoms, and structural abnormalities for patients with isthmic spondylolisthesis can vary widely, and surgical treatment also varies accordingly. Isthmic spondylolisthesis, which most commonly affects the L5–S1 segment, usually presents with predominant back pain in the children and adolescents, whereas it presents with radiculopathy as a result of foraminal stenosis with or without back pain in the adult population. In patients with symptomatic high-grade spondylolisthesis, surgery is recommended since conservative treatment is usually unsuccessful [7]. In isthmic spondylolisthesis when decompression is required, this involves excision of the fibrocartilaginous tissue around the deficient pars area as well as partial or complete removal of the posterior elements of L5 [1]. In select cases, especially the younger patient without any radicular symptoms or neurological deficits, a fusion without decompression may be attempted [8]. In high-grade slips, reduction of the slip is considered controversial owing to its association with postoperative neurological deficits, and an in situ fusion from L4 to S1 with passive, partial, positional reduction of the slip is generally recommended [8–11]. High-grade slip correction can be considered in cases with gait, postural, or sagittal balance abnormalities [9, 12]. The highest rates of fusion have been described in case of instrumented constructs with circumferential fusion [13, 14].

The principal surgical aims of the treatment of spondylolisthesis including decompression, instrumented fusion may be performed utilizing the MAST approach by virtue of the access provided through the transsacrospinalis posterolateral approach portal. A MAST transforaminal lumbar interbody fusion (TLIF) procedure may also be completed through the same approach to improve the chances of fusion in cases with low-grade slips [15–17]. High-grade slips are generally not amenable to a TLIF

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approach and may require other methods of achieving interbody fusion and support such as a transsacral strut graft or an anterior procedure [18–20]. In such situations transdiscal L5–S1 screws may be placed in order to provide a much stiffer construct and to improve fusion rates [21]. Spondylolysis and low-grade isthmic spondylolisthesis usually respond to nonoperative treatment. Persistent pain despite a reasonable trial of nonoperative treatment for a non-healing stress reaction, spondylolysis, or low-grade spondylolisthesis may be treated with surgical repair or fusion as indicated [7, 22–25].

Advantages of MIS/MAST approach:

- Utilize anatomic intermuscular planes and minimize collateral soft tissue injury including muscle denervation and ischemia [26–32]
- Reduced bleeding [33–35]
- Reduced postoperative pain and length of stay [33–35]
- Lower infection rates up to 10-fold compared to traditional open procedures [36]
- Accelerated return to work [37]
- Reduced narcotic usage [37]

Disadvantages of MIS/MAST:

- Early learning curve [34, 38].
- Increased radiation exposure and OR time (especially early in the learning curve and with percutaneous instrumentation) [33, 34, 39]. In general with the use of biplanar fluoroscopy for intraoperative imaging, it takes 417 single-level cases for the torso and 1,471 single-level cases for the extremity in order to exceed the annual allowed radiation dose limits [39–41]. Average exposure to a patient in a single-level procedure ranges from 4.5 to 7.8 cGy compared to the threshold limit of 200 cGy for radiation-related side effects.
- Need for additional equipment and instrumentation.
- Technical complications especially early in the learning curve [35, 42].

Indications and Contraindications

The indications are similar to traditional open procedures at one or two levels in the lumbar spine for either decompression or fusion. These include progressive painful symptomatic spondylolisthesis with or without neurologic symptoms and signs in a patient unresponsive to medical management.

Contraindications include:

- Interbody fusion for high-grade slips owing to technical difficulty.
- Requirement to correct kyphosis more than 5–10°. Correction of 3–5° of kyphosis is usually possible with the TLIF procedure [43, 44]. If additional lordosis is required, we believe that the anterior approach provides better lordosis.
- Obesity. Body mass index >40. Tubular retractors greater than 8 cm reduce the degrees of freedom of the instruments possible when performing interbody fusions. Hence it is recommended that during a surgeon's initial experience with MIS fusions, an anticipated retractor length greater than 80 mm is a relative contraindication. However, with experience obesity is a relative indication for minimally invasive fusion and instrumentation rather than a contraindication. Obesity does not lead to worsening of self-reported outcome measures, operative time, length of hospital stay, or complications when compared to nonobese patients in cohorts undergoing MIS fusions [45, 46].
- Previous surgery. This is only a relative contraindication if there is need for an open approach for removal of instrumentation. The transsacrospinal approach may be easier in revision situations because less scar tissue is encountered.

Technique

Positioning and Approach

We prefer that the patient is positioned prone on a Jackson flex table (Axis table), Jackson table with a Wilson attachment, or a regular table with a Wilson frame to allow a C-arm fluoroscope to be used in a biplanar fashion. The advantage of positioning the patient prone in lumbar flexion (kyphosis) and hip flexion is to distract the interlaminar space and the disk space. This also aids in protection of the exiting nerve root during the TLIF procedure. It is important to confirm that both AP and lateral views are technically possible with the C-arm and the anatomy of the spine is well visualized prior to prepping and draping. The skin incisions are typically 2–3 cm in length and are placed 4–5 cm (two fingerbreadths) away from the midline bilaterally. It helps to insert a spinal needle or a guidewire directed towards the facet joint to be fused, confirming its position on a lateral C-arm image before marking the incisions (Fig. 27.1). The incisions are carried through the subcutaneous tissues down to the fascia which is then sharply split vertically in line with the skin incision. The first dilator is then inserted over the facet joint to be fused, and then sequential dilators are passed over it until the final dilator is inserted. The appropriate length tubular retractor system is then passed over the final dilator and fixed to the self-retaining assembly attached to the table (Fig. 27.2). Minimal distraction is applied across the blades of the retractor to avoid muscle creep, and the final position over the correct facet joint is confirmed. The rest of the procedure may be performed using bayoneted or regular instruments of the appropriate length depending on surgeon's preference.

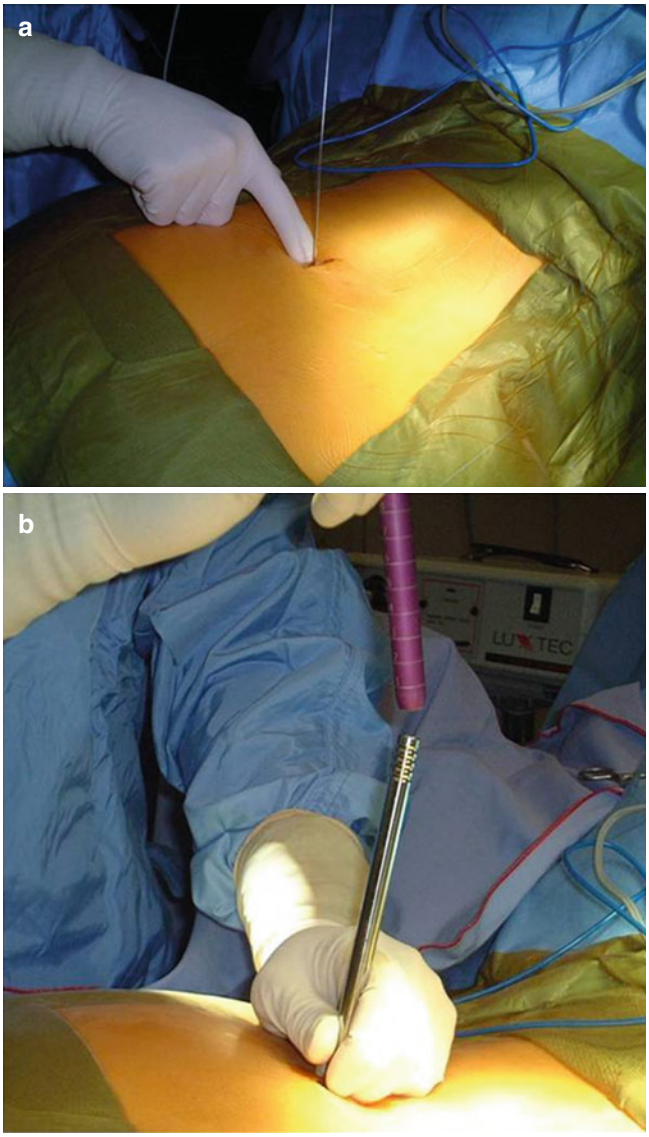

Fig. 27.1 Determination of the skin incision with the use of a K-wire and C-arm (**a**). Sequential dilation through the erector spinae muscles (**b**)

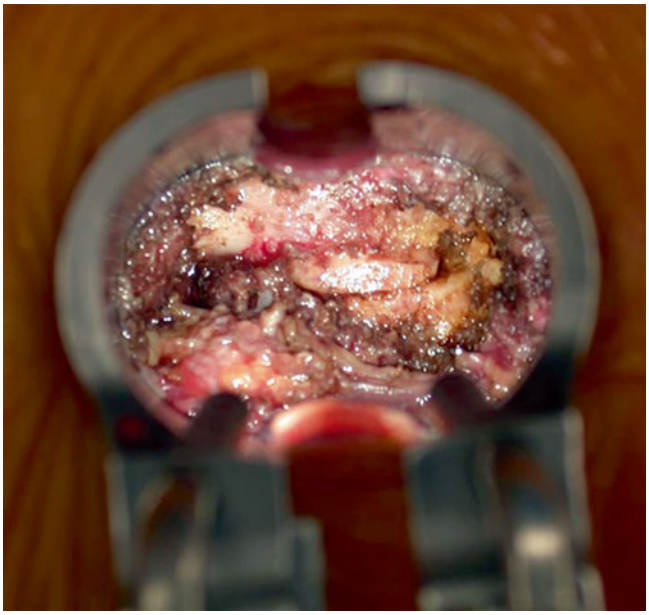

Fig. 27.2 Initial exposure of the posterior spine anatomy with the Quadrant™ Modular retractor system. Exposure of the facet joint and lamina (left). Note minimal muscle creep within the surgical field

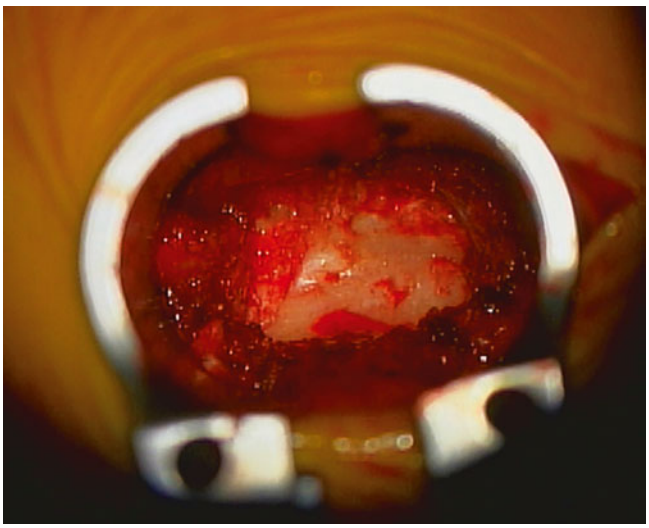

Fig. 27.3 Bilateral removal of the ligamentum flavum and "over-the-top" decompression of the contralateral lateral recess through the unilateral decompression technique

Decompression and Pedicle Screw Implantation

The pedicle screw placement may be completed at this stage since all the anatomical landmarks are clearly visible. Alternatively the pedicle screw tracts may be established initially and then the remaining procedure completed before screw placement so as to avoid obstruction of the exposure due to the screws.

On the side of the TLIF, complete resection of the inferior articular process is performed with an osteotome or high-speed burr. This bone is denuded of all the articular cartilage and soft tissue and saved as autologous bone graft. This is followed by the resection of the portion of the ipsilateral superior articular process cephalad to the pedicle. This allows for further ipsilateral decompression of central, subarticular, and foraminal stenosis. Contralateral decompression through the ipsilateral incision is possible through angulation or wanding of the retractor towards midline to the junction of the lamina and spinous process. The lamina is resected to the base of the spinous process, at which point the ligamentum flavum is resected bilaterally. An "over-the-top" decompression of the contralateral subarticular stenosis and foramen is accomplished with protection of the dura and neural elements (Fig. 27.3). Alternately, contralateral decompression can be directly performed by placing the tubular retractor bilaterally (Fig. 27.4).

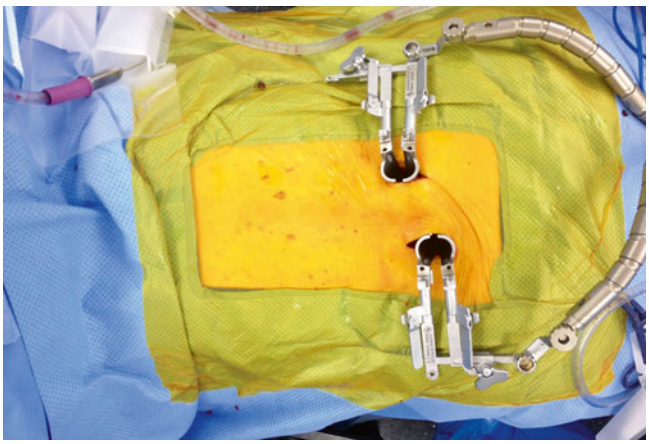

Fig. 27.4 Bilateral retractors in place. Allows for simultaneous work by co-surgeon

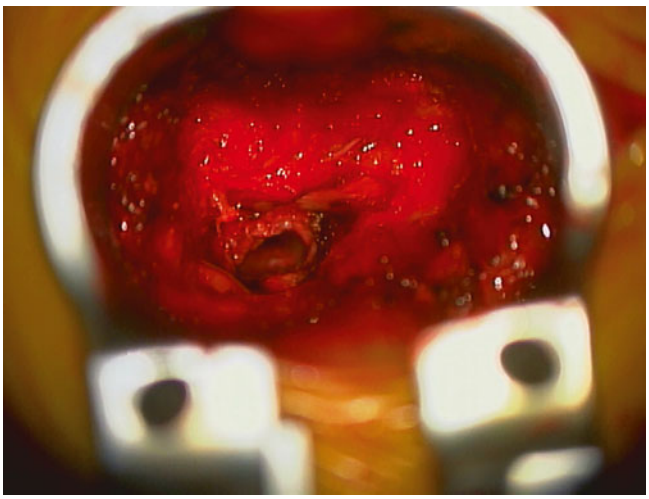

Fig. 27.5 TLIF annulotomy made lateral to the intact ligamentum flavum. This technique protects the dura and transversing nerve root and minimizes bleeding of the epidural veins

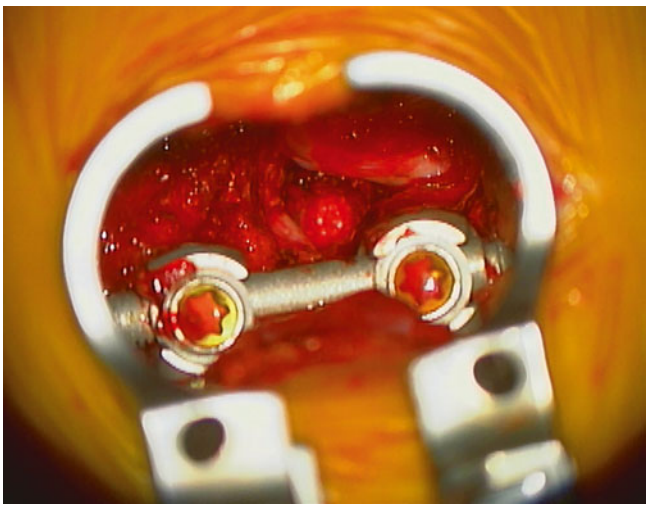

Fig. 27.6 Pedicle screw placement through the retractor system. Direct anatomic landmarks used. Minimal exposure of the supra-adjacent facet joint

Distraction and localized kyphosis via the Wilson frame or pedicle screw distraction across the interspace improves visualization of the annulus, provides better access to the interbody space, and further protects the exiting nerve root. We currently use one of two methods to accomplish this. One option is to place the patient prone on a Wilson frame then maximally lift the frame. One must remember to release the frame prior to compression across the pedicle screw construct to restore appropriate lordosis. The alternative option is to place the pedicle screw construct on the contralateral side under distraction and later change the rod for a smaller rod with compression. An Axis Jackson table may also be used to achieve these goals in a controlled fashion using the mobility provided by the table.

The annulus is exposed medial and inferior to the exiting nerve root with little or no need for neural or dural retraction. A 1 cm^2 annulotomy is made in the TLIF working portal (Fig. 27.5). The lateral to medial trajectory of the tubular retractor allows the surgeon to reach the contralateral side of the interspace to complete the subtotal discectomy, using customized instruments. In addition, resection of the ascending articular process of the facet joint, which can act as a buttress, allows instruments to be guided to the contralateral side. Structural allograft bone or cages (depending upon surgeon preference) are placed into the interspace along with autologous bone graft. If necessary, cancellous bone can be harvested from the iliac crest using a trephine technique through a 1–2 cm incision. Alternatively, graft extenders are used. Placement of the interbody cage is also based on surgeon preference but if placed anteriorly will help optimize segmental lordosis at the operative level [43, 47].

After completion of the TLIF and decompression, the pedicle screws are inserted. Standard direct visualization through the tubular retraction and periodic C-arm imaging are used to determine the starting points for the screws. A standard awl followed by a pedicle finder is used to cannulate the pedicles. The pedicle screws are then placed under direct visualization to minimize C-arm utilization (Fig. 27.6) and compression across the pedicle screw construct prior to final tightening, restoring lordosis and providing compression of the bone graft in the middle column.

On the contralateral side of the TLIF, a complete or partial hemilaminectomy, facet, and/or intertransverse fusion can also be performed easily through the same retractor as the screws are to be placed (Fig. 27.7). The advantage of using direct visualization to place the contralateral screws is reduction of C-arm utilization and the potential ability to decompress and to fuse the facet joint. The disadvantage is more tissue trauma using this mini-open technique. Alternately,

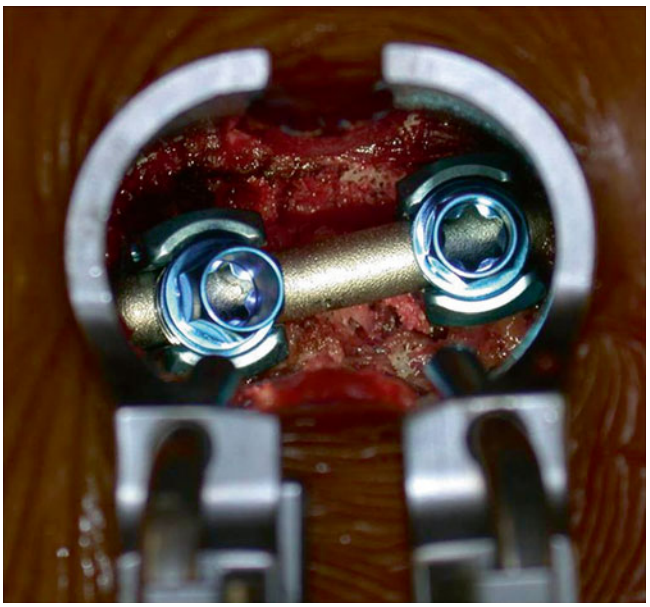

Fig. 27.7 Contralateral pedicle screw placement with bone graft of the facet joint and lamina

percutaneous screws can be placed on the contralateral side if no decompression or posterior fusion is contemplated.

Technical Pearls

- Patient positioning and good intraoperative imaging are key to success.
- The retractor once docked over the facet joint to be fused is opened only as wide as needed so as to prevent muscle creep and muscle ischemia due to retraction.
- Once the retractor is in the correct position, resist the temptation of moving the retractor often, which leads to creep of the muscle into the wound. If significant muscle creep occurs, it is best to replace the tubular retractor via re-dilation.
- Pedicle screw tracks may be easier to prepare prior to performing the decompression and facetectomy when more bony landmarks are present.
- When placing percutaneous screws, fluoroscopic images must be "perfect" AP and lateral views. Otherwise percutaneous screw placement may be aberrant.
- The treatment of an incidental duratomy should be similar to the complication treatment in an open procedure. If primary suture repair is possible, this is preferred. If you are unable to achieve a watertight repair, TISSEEL™, DuraGen™, or other dural repair products are useful. In our experience, the minimal dead space created by the less invasive procedures limits the formation of a symptomatic pseudomeningocele.
- Epidural bleeding needs to be proactively controlled. There are several ways to reduce the likelihood of problematic bleeding. The positioning of the patient on the Jackson frame with or without the Wilson attachment will reduce intra-abdominal pressure. When in the epidural space, find the bleeders before they find you and use bipolar electrocautery for coagulation of epidural vessels. Liberally use a thrombotic paste product such as Gelfoam™ paste and cottonoids. Finally, the larger more difficult to control epidurals are typically medial in the vicinity of the posterior longitudinal ligament and far laterally in the foramen. Avoid exposure of these anatomic areas unless necessary.
- In terms of procedure, start simple, such as decompressions, and work your way up in terms of technical difficulty, such as the TLIF.

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Adolescent Scoliosis

28

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and Amer F. Samdani

Introduction

Traditionally, scoliosis surgery has been associated with morbidity of large wounds, long surgeries, and large amounts of blood loss. Scoliosis surgery usually involves multisegmented instrumentation, and this fact makes MIS a more challenging goal. MIS for scoliosis became feasible with the introduction of the Harrington rod five decades ago. This device was a straight, distractible rod which had to be fixed at the proximal and distal end of a curve. It could have therefore been implanted through two short incisions. Decades later, Akbarnia et al. [1] seized on this idea and innovated growing rods as a method to control deformity in the immature spine while allowing for continued growth. On the way to achieving better curve correction with stiffer constructs, segmental instrumentation (at each vertebra) and bilateral bent rods became popular and quickly made non-segmental instrumentation obsolete for definitive fusions. Unlike in degenerative spine surgery, implants are utilized not only for stability but also intraoperatively to manipulate spinal alignment. This adds an additional layer of difficulty in adopting less invasive degenerative implants and techniques to deformity applications. Nonetheless, significant success has been achieved by a small number of surgeons in performing less invasive spinal deformity surgery.

Due to cosmetic concerns, multiple short incisions for mini-open or percutaneous screw insertion have never become popular. Therefore, surgeons who promote MIS in posterior scoliosis surgery often utilize a less invasive approach that involves starting subcutaneously. The conventional approach to the scoliotic spine involves a midline skin incision followed by a midline fascial incision and subperiosteal muscle stripping all the way to the tips of the transverse processes. This exposure facilitates identifying anatomic landmarks for screw insertion and exposes more bone surface, which may decrease the rate of nonunion. The MIS approach to the scoliotic spine usually uses a midline skin incision but continues with a Wiltse-like muscle splitting approach. This can be performed with several short or one long fascial incision on either side. The potential disadvantages include fewer anatomic orientation points which could lead to implant malpositioning, more intraoperative radiation, and difficulty preparing the fusion bed which could lead to increased risk of pseudarthrosis. The theoretical advantages of a less invasive approach in spinal deformity surgery are similar to those in other less invasive spine surgery applications: less blood loss, less muscle disruption, less pain, lower infection rates and quicker recovery. In some cases, such as in patients who are Jehovah's Witnesses, MIS for scoliosis can make surgery available to those who might otherwise forego it due to the requirement for blood transfusion in open spinal fusion.

The preservation of muscles, discs, and other soft tissue structures becomes even more critical in patients in whom motion preservation is a goal. There is a growing body of literature and experience in the fusionless treatment of spinal deformity. Almost all of these techniques utilize the principles of less invasive surgery.

Additional areas of spinal deformity surgery that have seen innovations with the goal of treating spinal deformity in a less invasive manner are anterior thoracoscopic scoliosis surgery, lateral approaches for the treatment of lumbar deformity, and techniques used to treat the growing spine. Although most surgeons in the USA prefer the posterior approach, anterior scoliosis surgery has several advantages and should be part of the deformity surgeon's armamentarium.

Since MIS in scoliosis is in its infancy, emphasis will be placed on the authors' experience. This chapter will discuss advantages and disadvantages of various applications of less invasive techniques and implants in the treatment of spinal deformity.

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Table 28.1 Less invasive posterior spinal fusion for scoliosis: comparison of techniques and perioperative outcomes from various surgeons

Series	Technique	EBL (cc)	Surgical time (minutes)	Length of hospitalization (days)
Newton et al. [2]	Thoracoscopic	470	344	6
Wimmer and Pfandlsteiner [3]	Concave open, convex transmuscular	165	175	Not reported
Durrani et al. [4]	Transmuscular	261	297	3
Miyanji et al. [5]	Wiltse	277	444	4.6
Wollowick et al. [6]	Transmuscular	Similar to open	522	Similar to open

Fusion Procedures

Posterior

True percutaneous instrumentation and fusion are technically feasible but have not gained wide acceptance due to inferior cosmetic outcome compared to a long midline incision. Therefore, the majority of minimally invasive posterior techniques used for patients with scoliosis currently are performed through one to three long midline skin incisions combined with some type of muscle splitting technique in contrast to conventional muscle stripping techniques (Table 28.1).

Wimmer and Pfandlsteiner [3] reported on 49 patients with scoliosis who underwent a less invasive hybrid instrumentation and fusion. The patients ranged in age from 16 to 29 years and carried a diagnosis of neuromuscular or idiopathic scoliosis. Patients had a conventional exposure on the concave side using up to three midline skin incisions. Once correction was achieved on the concave side after seating the first rod, transmuscular screw and rod instrumentation was performed on the convex side with the use of dilatators and fluoroscopic assistance (Fig. 28.1). The authors reported an average surgical time of 175 min, an estimated blood loss (EBL) of 165 ml, and an average coronal curve correction of 75 %. In addition, the authors observed an average of 2° lost correction at 27 months and a fusion rate of 95 %. There was no infection and no neurologic complication. Although some important parameters like the preoperative flexibility index were not provided by the authors, their results seem to be equivalent or superior when compared to the literature of conventional open posterior procedures. By contrast, a recent report on EBL on posterior fusion surgery for AIS reported an average EBL of 807 (±608) cc, 238 (±78) minutes of operating time, and 57 (±15) % Cobb angle correction in the hands of experienced adolescent idiopathic scoliosis (AIS) surgeons [2].

One of the most significant concerns that has prevented widespread adoption of MIS techniques in scoliosis surgery is the ability to obtain bony fusion. Open techniques allow for meticulous preparation of the fusion bed and placement of copious amounts of bone graft in the areas where the surgeon wants it to remain. MIS techniques do not allow for direct visualization of the fusion bed either during preparation or during grafting. This issue is less of a concern in children, as the pediatric spine often fuses unintentionally solely as a result of muscle disruption during spine exposure [7]. Betz et al. [8] reported a prospective, randomized trial of patients with AIS undergoing a posterior fusion. The subjects were randomized intraoperatively into one of two groups: 1) allograft, or 2) no bone graft (the local autograft being discarded). There was only one pseudarthrosis in that series and that was in the allograft group. However, it can be hypothesized that the subperiosteal exposure that was used for both groups significantly attributed to osseous fusion. In growing rod spine treatment of pediatric spinal deformity, the process of muscle disruption seems to contribute to unintended fusion. Bess et al. reported that growing rods placed submuscularly (as opposed to extramuscular but subcutaneous) had a lower complication rate including wound complications but that they often place rods subcutaneously to avoid autofusion [9].

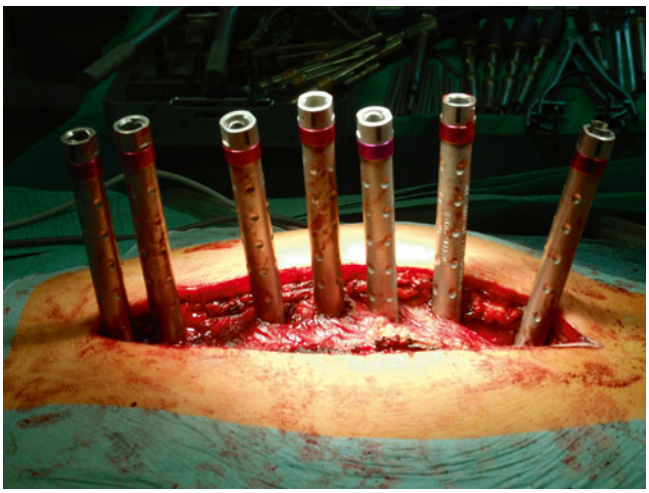

Fig. 28.1 Hybrid open/MIS technique: after instrumentation and correction via an open procedure on one side (not visible in this image), transmuscular tubes are placed for screw and rod insertion on the opposite side (Photo courtesy of Prof. Dr. Cornelius Wimmer, Schön Klinik Vogtareuth, Germany)

Durrani et al. [4] have reported on a transmuscular technique used in 30 pediatric patients with a variety of diagnoses. The average blood loss was 261.5 cc, and the average duration of surgery was 4 h and 57 min. The average length

of hospitalization was 3 days. Postoperative CT scans obtained at 6 months post-op confirmed that none of the patients in the series had pseudarthroses. However, long-term follow-up of these patients to at least 5 years will provide better insight into the pseudarthrosis rate.

The three skin incisions used in the technique described by Durrani et al. [4] are placed over the proximal and distal ends of the planned construct and at the apex of the deformity. The lengths are planned in such a way as to allow mobilization of the incisions to access each level from one of the incisions. The pedicles are instrumented over guidewires placed through Jamshidi needles inserted through the muscle under fluoroscopic guidance. This technique results in shorter skin incisions but precludes the use of bilateral guidewires, reduction tabs, or derotation devices at all levels at the same time. The inferior levels accessible from an incision must be instrumented and then allowed to remain under the skin while addressing the proximal levels accessible by mobilizing that incision.

Wollowick et al. [6] presented a retrospective matched comparison of 15 standard and 7 MIS procedures in which pedicle screw accuracy was confirmed by CT scan. They found no difference in pedicle screw accuracy or in curve correction. In contrast to Durrani et al. [4] and Miyanji et al. [5], they found no difference in length of stay or blood loss. They described their technique as utilizing three short longitudinal midline skin incisions. Pedicle screws were placed transmuscularly via a freehand technique.

Miyanji et al. [5] have also championed MIS surgery for the treatment of AIS and advocate the use of three longitudinal midline skin incisions with a bilateral Wiltse approach to the transverse processes and lateral facets. In a prospective comparison with open techniques, they showed longer operative times with the MIS approach but lower blood loss and hospitalization. The average length of operative time was reported as 444 min and blood loss as 277 cc. These promising less invasive techniques are possible with newer and stiffer metallurgy like cobalt-chrome. If long-term studies can confirm these short-term results, this hybrid technique may have the potential to represent an additional alternative to traditional bilateral open procedures, at least for flexible curves that would not require wide releases or posterior, single-column osteotomies.

A major downside of all MIS techniques is the longer radiation time and its direct effect on the patient and the surgeon. Future research must focus on less radiation dosage fluoroscopy, low-radiation navigation, and/or a freehand pedicle screw insertion technique for MIS procedures.

Authors' Preferred Technique

In contrast to the authors of the previously discussed series, the authors of this chapter prefer to use a single skin incision with transmuscular instrumentation (Fig. 28.2a). A single skin incision precludes the need to mobilize the skin to access various levels at different times, thus allowing all inserters to remain in place bilaterally throughout the case. We feel that this allows for better direct vertebral body derotation. The skin is incised in the midline but the fascia remains intact. Under anteroposterior (AP) fluoroscopic guidance, the pedicles are entered with a Jamshidi needle (Fig. 28.2b). The stylette is removed and a guidewire is inserted and advanced, preferably under lateral fluoroscopic guidance. Once all bilateral guidewires are in place, the pedicles are tapped with a cannulated tap (Fig. 28.2c). Prior to placing the screws, a small nasal speculum is used to access the facet joint to allow decortication with a high-speed burr (Fig. 28.2d). A cannulated screw (Viper System, DePuy Spine, Inc., Raynham, MA) with an extended slotted inserter is placed over the guidewire. The Viper System is used because of the longitudinal slot which facilitates the spine correction maneuvers. The tapping and screw insertion should be performed under lateral image intensification to insure that the guidewire is not advanced while the threads are advancing. Once the screw is in place, the guidewire is removed but the extended inserter is left affixed to the screw. At this point the reduction is performed as described by Rodriguez-Olaverri et al. [10]. Two straight rods are placed into the slotted inserters on the convex side of the spine dorsal to the skin. The rods are then pulled as far apart as possible within the screw inserters, thereby reducing the scoliosis curvature (Fig. 28.2e). With the spine held in this position, the concave rod is passed submuscularly. If screws are placed at each level, passing the rod is relatively uncomplicated. The rod should be precontoured to the desired sagittal alignment. The rod is secured with set screws. The spinal alignment may be further adjusted through compression and distraction between the screw extensions. The two convex temporary rods are removed. Direct vertebral rotation maneuvers are performed at this stage in a manner similar to open procedures. Next, a submuscular rod is passed on the convex side. The fusion bed is prepared bilaterally with a hemicylindrical rasp with curved handle that is passed submuscularly along the spinous processes and lamina. Bone grafting is performed by passing a tube of mesh-encased bone graft (MagniFuse, Medtronic, Memphis, TN) along the spinous processes with a vaginal packing forceps. Our postoperative pain management protocol includes regularly scheduled muscle relaxants at doses higher than what we typically use for open procedures. The higher dose of muscle relaxants may be explained by a technique that involves dilation in the muscle belly and therefore muscle pulling and stretching rather than the traditional more destructive method of detachment of muscles from their spinal origins and insertions.

Case Example

The following case demonstrates the utility of this technique. The patient is a 19-year-old overweight male with Asperger's syndrome and progressive scoliosis. He is also a Jehovah's Witness. He has a left thoracic and right thoracolumbar prominence measuring 10° and 20°, respectively, on Adams' forward

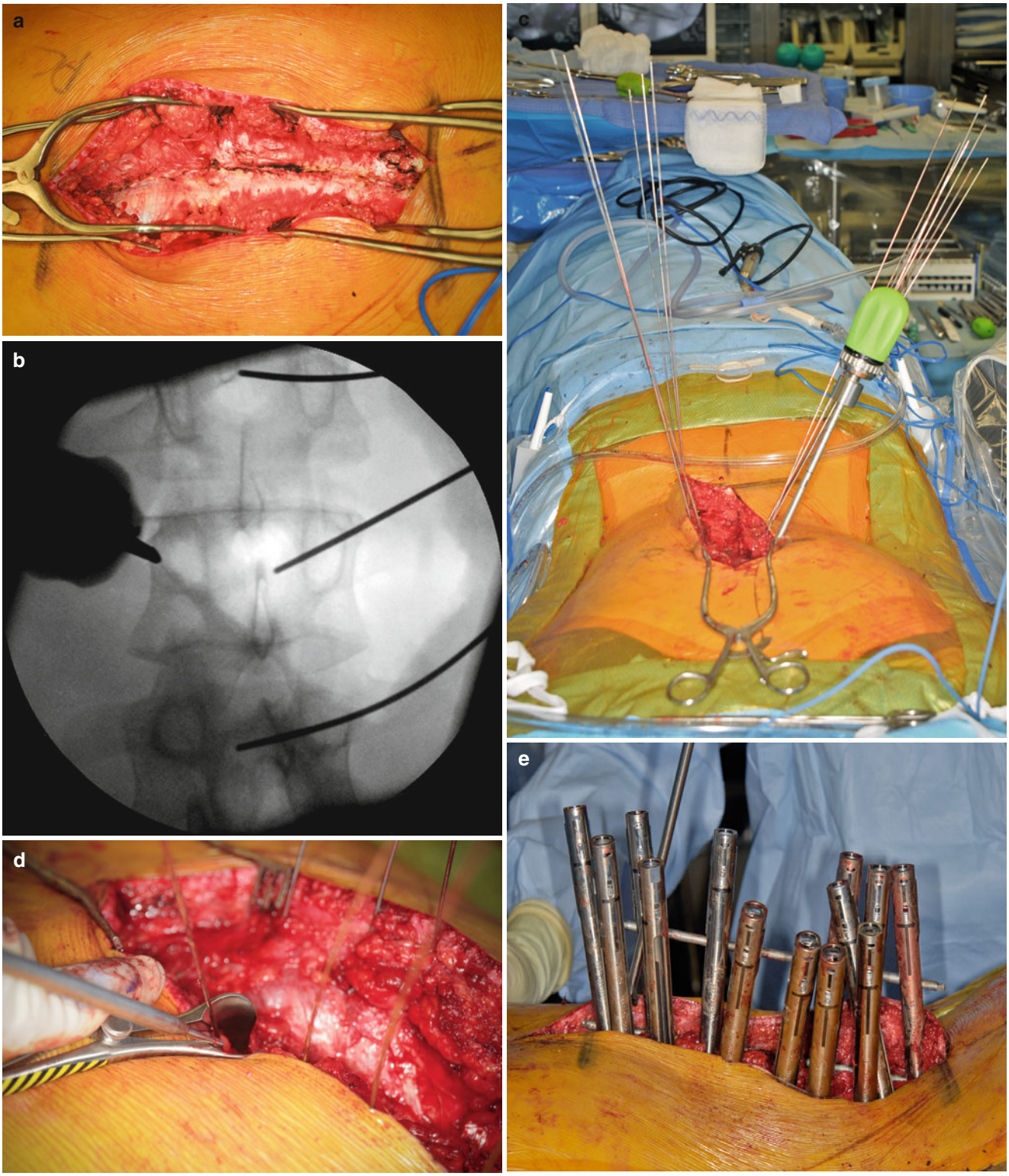

Fig. 28.2 The authors' preferred technique for minimally invasive posterior spinal fusion. (**a**) Midline skin incision with preserved muscle attachments. (**b**) Fluoroscopy view of pedicle targeting; (**c**) guidewires in position and a cannulated tap utilized to prepare pedicles for screw placement; (**d**) use of nasal speculum to access facet joint for bone graft bed preparation; (**e**) two-rod Piza-Vallespir reduction technique

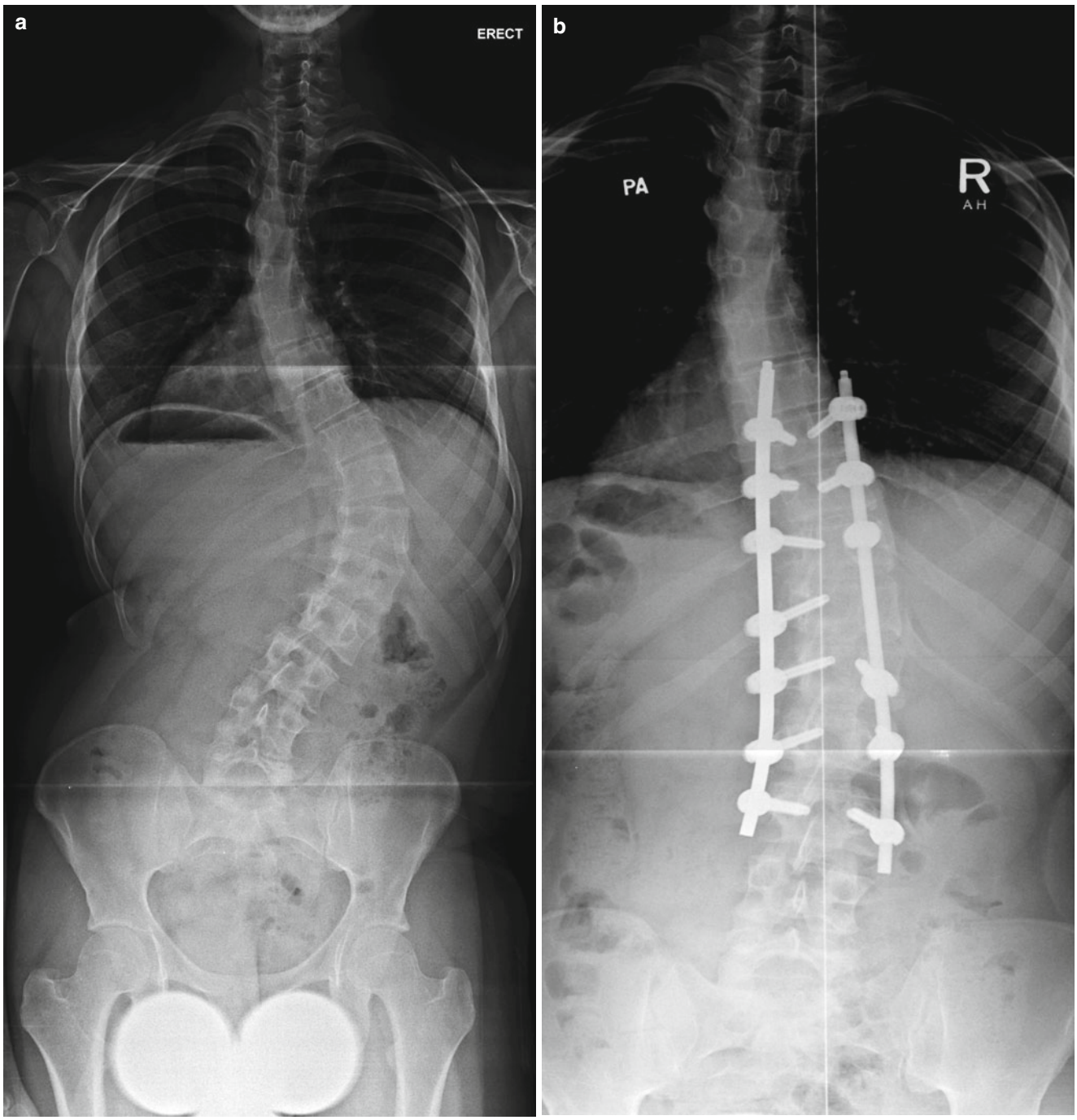

Fig. 28.3 Case example of less invasive posterior spinal fusion. (**a**) Standing preoperative PA demonstrating a thoracolumbar scoliosis. (**b**) Standing postoperative PA revealing correction of the deformity and excellent overall alignment

bend test. His right shoulder is elevated 3 cm. He has no neurologic deficits in his lower extremities. Preoperative imaging revealed a 60° thoracolumbar curve that reduced to 44° on side bending and a 40° thoracic curve that reduced to 25° (Fig. 28.3a). After appropriate preoperative counseling, he underwent a less invasive instrumented posterior spinal fusion from T9 to L3 without complication (Fig. 28.3b).

Anterior

In contrast to posterior surgery, anterior surgery can in fact be performed with a true MIS approach, which usually requires only three or four half-inch skin incisions that will be used as thoracoscopic working portals or a mini-open lumbar retroperitoneal approach.

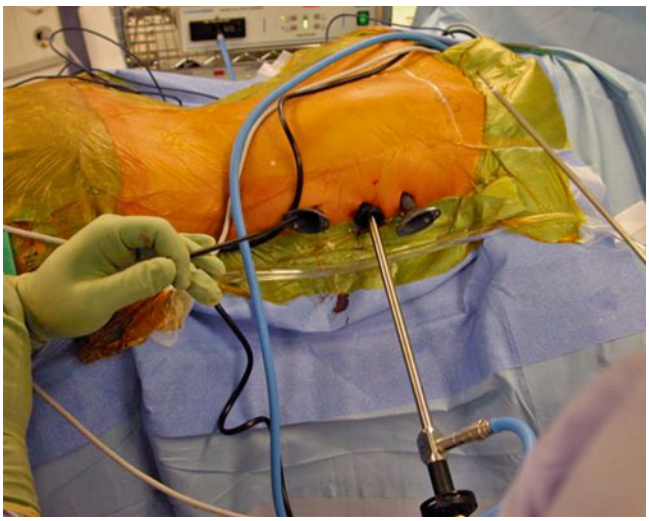

Fig. 28.4 Picture showing portal location and feasibility of prone thoracoscopic anterior release (Photo courtesy of Daniel J. Sucato, MD)

Dwyer et al. [11] in 1969 initially described the anterior approach to the scoliotic spine, and only few years later, Zielke et al. [12] published the results of 26 patients who underwent an instrumented ventral derotation spondylodesis. It is therefore somewhat surprising that despite the feasibility and theoretical superiority of thoracoscopic surgery over conventional thoracotomy, it took almost three decades for the first papers to be published on thoracoscopic scoliosis surgery. Anterior scoliosis surgery broadly encompasses any anterior discectomy (release) with or without instrumentation.

Anterior Release

Traditionally, the most popular surgical procedure for thoracic scoliotic curves exceeding 80° was open anterior release followed by posterior spinal instrumented fusion. Due to the high morbidity of thoracotomy and the more powerful correction forces of newer posterior instrumentations as well as the increasing popularity of posterior osteotomies, anterior releases have fallen out of favor. However, video-assisted thoracoscopic surgery (VATS) made minimally invasive anterior releases feasible. Anterior thoracoscopic releases can also be performed in the prone position (Fig. 28.4). Prone thoracoscopic anterior release provides two significant advantages over open or thoracoscopic anterior release performed in the lateral decubitus position: (1) posterior surgery can be performed simultaneously and (2) ipsilateral lung deflation is not required due to the effect of gravity pulling the lung anterior.

In 2000, King et al. [13] reported on a series of 27 pediatric cases in which they performed concomitant prone thoracoscopic anterior releases in addition to posterior fusion. They reported that the procedure precluded the need for single lung ventilation since gravity drew the lungs off of the spine. Furthermore, time under anesthesia was reduced by avoiding repositioning and redraping. The anterior procedure released an average of 3.3 discs and took an average of 129 min. In the same year, Lieberman et al. [14] reported similar feasibility in a series of 15 adult patients. Also in 2000, Böhm and El Saghir [15] published their results of 60 patients with either idiopathic or neuromuscular scoliosis with a mean age of 19 years (range 8–56) at surgery. On average, 3.4 segments were mobilized via anterior thoracoscopic release in the prone position. The average preoperative Cobb angle of 72° (range, 44–121) was corrected to 18° (range, −3 to 39) postoperatively. In addition, all patients with hypokyphosis could be corrected. The average axial correction was 80 %. There were no neurologic deficits or wound infections. Two patients required revision surgery, one because of a hemothorax and another due to a misplaced pedicle screw.

Sucato et al. [16] presented their data of 13 patients who had thoracoscopic anterior release in the prone position followed by posterior spinal fusion and instrumentation (TAR-PSFI) compared to 83 patients without anterior release prior to posterior spinal fusion and instrumentation (PSFI). Patients with TAR-PSFI were observed to have a more rapid decline of pulmonary function in the first three postoperative weeks but recovered significantly and were better compared to patients with PSFI at 1-year follow-up. If a thoracoplasty was added to the procedure, postoperative pulmonary function was equivalent irrespective of whether or not TAR was performed [15].

Anterior Instrumentation and Fusion

Anterior spinal fusion for the treatment of scoliosis avoids the painful and destructive effects of posterior muscular detachment. Betz et al. [17] published a retrospective comparative study of matched AIS patients treated with anterior or posterior spinal fusions. They found that anterior fusions had equivalent correction of the Cobb angle in the coronal plane and more improvement in the thoracic hypokyphosis. Furthermore, the anterior fusions were an average of 2.5 levels shorter than the posterior fusions [17]. Anterior scoliosis surgery became even less invasive with the advent of thoracoscopic anterior fusions. In 2001, Picetti et al. [18] reported their results of 50 patients who were treated with thoracoscopic instrumented spinal fusion for scoliosis. Wong et al. [19] published their results of patients undergoing VATS compared to patients who received posterior all-hook instrumentation and fusion. The authors reported on 31 patients with AIS after an average follow-up of 44 months. VATS was found to be able to decrease blood loss but also to increase surgical time and ICU days. No differences were found with respect to analgesic requirement or hospital stay. There were no complications in the PSF group and two in the VATS group. One patient had a prolonged pneumothorax

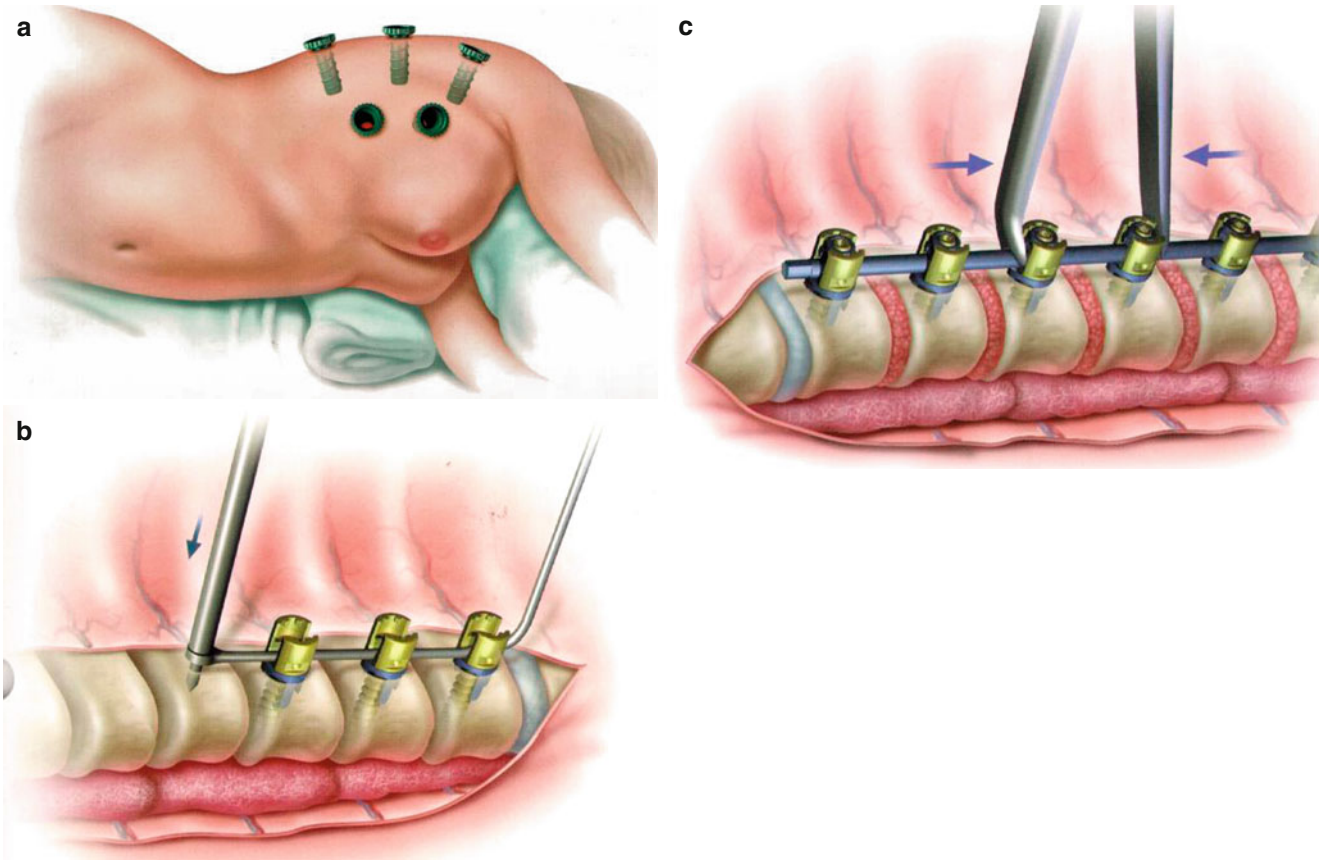

Fig. 28.5 (**a**) Working portals for thoracoscopically assisted anterior scoliosis correction. (**b**) Bicortical screws are placed after intervertebral discs have been resected. (**c**) Disc spaces are packed with bone graft and correction is achieved via compression (Drawings from DePuy Synthes Spine, used with permission)

and the second patient suffered injury to the long thoracic nerve resulting in scapular winging, which had only partially resolved at final follow-up. Coronal curve correction at final follow-up was 67 % for patients with PSF and 62 % for patients with VATS. However, this difference was not found to be significant. Both groups were found to have a loss of correction over time. No differences were identified with respect to sagittal curve behavior postoperatively. A major downside of patients undergoing VATS was the requirement to wear a hard brace for 3 months postoperatively. On the other hand, anterior instrumentation was able to save an average of 3.5 fused segments.

Lonner et al. [20] compared the results of pulmonary function tests at a minimum follow-up of 24 months after various anterior stand-alone procedures in 131 patients with AIS. Sixty-eight patients had an open thoracotomy and 44 patients had a video-assisted thoracoscopic instrumentation for Lenke type 1 curvature (single thoracic curve). In addition, 19 patients had thoracoabdominal surgery for a Lenke type 5 curvature (lumbar/thoracolumbar curve). The authors reported significantly better pulmonary function in favor of the thoracoscopic group. The open thoracotomy group experienced significant declines from preoperative to 2 years postoperative in mean absolute FEV1 (forced expiratory volume in 1 s) and FVC (forced vital capacity). In contrast, the thoracoscopic group demonstrated either slight or statistically significant improvements in mean absolute FEV1, FVC, and TLC (total lung capacity). No differences with respect to FEV1, FVC, or TLC were observed in patients who had thoracoabdominal surgery.

In summary, thoracoscopically assisted surgery in the treatment of idiopathic scoliosis is a viable alternative to conventional thoracotomy and can also be used for anterior releases as an adjunct to posterior spinal fusion of severe scoliotic curves. However, despite several advantages, thoracoscopic scoliosis surgery has still not achieved wide acceptance, perhaps because of the higher nonunion rate (4–5 %) reported in all series, difficulty and length of time needed to do the discectomies, and the reported anterior screw impingement on the aorta. In addition, the continuous improvement of posterior techniques (e.g., thoracic pedicle screws, the use of segmental osteotomies, direct vertebral rotation) that are more familiar to spine surgeons is responsible for the inability of anterior surgery, even if performed minimally invasively, to achieve gold standard status (Fig. 28.5).

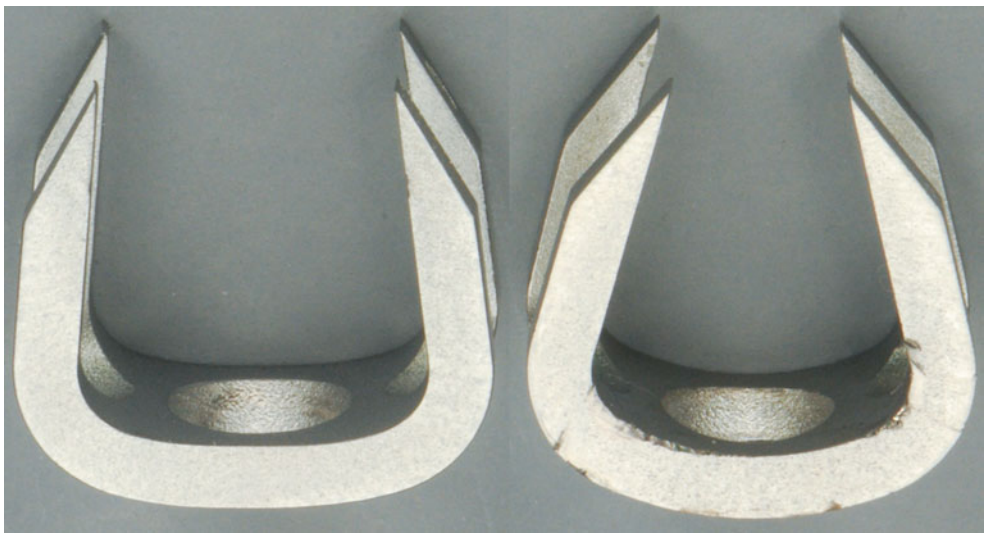

Fig. 28.6 A four-prong nitinol staple in the undeployed position near 0 °C and in the deployed position at room temperature

Fusionless Treatment of Scoliosis

The previous sections of this chapter addressed less invasive methods of performing spinal fusions for the treatment of spinal deformity. While these treatments may be less disruptive to soft tissues, they still lead to the same functional limitations of decreased flexibility as open procedures. Furthermore, patients with scoliosis fusion have significant risk of reoperation for pain and degeneration due to stresses imparted to the few remaining mobile segments adjacent to a long fusion. Several surgeons are innovating surgical methods to control spinal deformity without fusion.

Vertebral Body Stapling

A relatively new procedure is vertebral body stapling (VBS). Although this kind of unilateral epiphysiodesis was initially described in the 1950s [21, 22], it fell out of favor due to its significant complication rate. Newer metallurgy and refined indications have led to a revival of this technique. Modern staples made of nitinol, a shape memory alloy, have two or four prongs that are straight when cooled and crimp down when warming up to body temperature (Fig. 28.6). Implantation in the thoracic spine is usually thoracoscopically assisted; in the lumbar spine it is through a direct or extreme lateral retroperitoneal approach. The goal of treatment is curve control by inhibiting growth on the convex side of a curve while letting the uninstrumented concave side grow unimpeded.

Justification for Treating Immature Patients with Scoliosis

The natural history of curve progression in idiopathic scoliosis is dependent on the patient's skeletal maturity, curve pattern, and curve severity [23]. Patients with significant growth potential and large initial curves are 74 % more likely to progress without treatment [24–26]. Dimeglio et al. [27] have shown that patients who have moderate size curves (30°–40°) who have not had their pubertal growth spurt have an almost 100 % chance of progression to 50° or more. Patients with curves between 50° and 75° at maturity, particularly thoracic curves, will progress an average of 29.4° in adulthood [28]. Therefore, prevention of curve progression beyond 50° would be most prudent.

The current standard of care for immature patients with AIS is a cervicothoracolumbosacral orthosis (CTLSO) or a thoracolumbosacral orthosis (TLSO). These braces are used to control progression of curves measuring 20°–40°; however, 18–50 % of these curves will progress in spite of bracing [24–26, 29–33].

Previous Investigations of Vertebral Body Stapling

Convex vertebral body/hemiepiphyseal stapling theoretically affords immediate and possibly reversible cessation of anterior physeal growth [34, 35]. Stapling across physes of long bones is an accepted and predictable method of treating limb malalignment in young children [36, 37]. In 1949, Blount and Clarke [36] were the first to report lower extremity angular correction with hemiepiphyseal stapling. Animal studies using a rat tail model confirm the ability to modulate vertebral growth plates with skeletal fixation devices [38, 39]. Nachlas and Borden [22] performed vertebral interbody stapling across the physeal end plates and discs in a canine scoliosis model. Many dogs exhibited correction while others exhibited arrest of their curve progression. In 1954, Smith et al. [21] presented their early human results of three cases. The report

was preliminary but indicated that vertebral growth was arrested on the stapled side of the vertebrae. In all three patients, there was no curve progression within the stapled region of the spine.

There are several animal studies supporting the use of stapling for scoliosis correction while preserving motion [21, 40, 41]. In a bovine study evaluating biomechanics of the shape memory alloy staple, Puttlitz et al. [42] have shown that the staples were able to achieve reduction in axial rotation and lateral bending motion. Motion in the adjacent segment was preserved. Wall et al. [41] have applied the principle of spinal hemiepiphysiodesis, using an endoscopic approach in a porcine model. Results show that the curve progression can be halted and possible correction can be achieved.

The concept of stapling the anterior spinal growth plates seems sound; however, general orthopaedic staples manufactured from traditional metals (e.g., stainless steel and titanium) may be prone to dislodge in the spine. Recently, the US Food and Drug Administration cleared nitinol staples for orthopaedic implantation in the hand, foot, long bones, and spine (on a single vertebra not spanning the disc space) (Fig. 28.6). Nitinol is a biocompatible shape memory alloy of approximately 50 % nickel and 50 % titanium. It is currently best known for its use in cardiovascular stents [43–46]. The unique properties of nitinol include its superelasticity and shape memory. Using the shape memory property, a staple can be designed with a "preferred" shape that is exhibited above a "transition" temperature. Below the transition temperature, the staple is malleable and can be deformed into a variety of shapes without permanently yielding the material. Nitinol staples are typically designed with a preferred "C" or closed (convergent) shape. Before implantation, the staples are cooled, to extend working time, and the tines deformed until parallel. After implantation, the staples warm to the transition temperature (just below body temperature) and revert to the preferred, convergent orientation) (Fig. 28.6). The shape transformation induces compression between the tines and significantly increases the pullout force necessary to move the staple. Nitinol changes shape in response to temperature through crystalline phase changes. The result is redistribution of the crystal lattice thus generating a change in the physical geometric orientation. The metal's properties above the transition temperature are similar to titanium. The transition temperature is controlled by the alloying ratio (Ni vs. Ti) and heat treatment [47]. Injury to surrounding tissues during transformation was not reported in animal [47] or human experience with cervical spine fusions [48–50]. Nitinol has a very low susceptibility to corrosion and has been used successfully in orthodontic appliances [47] for years and more recently in cardiovascular applications [43–46].

Indications for Vertebral Body Stapling

As this is a growth-modulating procedure, the authors recommend VBS for patients who have not yet undergone their pubertal growth spurt [51]. We prefer to utilize Sanders' hand x-ray grading to determine if remaining growth is adequate to benefit from growth modulation with VBS [52]. Based on our early results with the technique, only patients with moderate curves (thoracic <35°, lumbar <45°) should be considered for the procedure [51]. We also feel that the curve must be flexible, bending to less than 20°, to consider VBS. The skeletal maturity and spinal deformity magnitude of patients best indicated for this procedure resemble those of patients for whom brace treatment is also a viable option. Thorough education of the patient and family of all options and alternatives is imperative (as it is in all interventions). As long-term results as well as backup plans for long-term complications (e.g., overcorrection, staple dislodgement) have yet to be published, families should take this into consideration when selecting VBS.

Surgical Technique

General anesthesia is utilized and a double lumen endotracheal tube is used to collapse the convex lung. Patients are positioned on a non-flexed table in the lateral decubitus position with the convex side of the scoliosis in the up position. Proper patient positioning and portal placement are confirmed with fluoroscopic imaging. All vertebrae in the Cobb angle are stapled. For thoracic curves, a thoracoscopic-assisted approach is preferred. The first portal is made in the fifth to seventh intercostal interspaces along the anterolateral chest line. Additional portals are made in the posterior axillary line for insertion of the staples. Fluoroscopic imaging is used to confirm the levels to be stapled. A staple trial is used to determine the correct staple size (4–14 mm) (Fig. 28.7) and to create pilot holes (Fig. 28.8). Staples are cooled over a basin of ice, prior to being placed into the pilot holes (Fig. 28.9). Once inserted and the position confirmed by fluoroscopy, final seating is completed with a tamp. Typically, two single staples or one double staple is placed laterally, spanning each disc space of the measured Cobb angle. In most cases, the parietal pleura does not need to be excised and the segmental vessels can be preserved. On occasion, it is necessary to make a small incision parallel to the segmental vessels to allow movement of the vessel away from the staple prong. If there is significant hypokyphosis (kyphosis < 10°) at the apex of the thoracic curve, the staples are placed more anteriorly on the vertebral body, or a third staple is placed along the anterolateral aspect of the vertebral body. Proper staple positioning is confirmed by fluoroscopic images. If a staple is not in the desired position, it is pulled out with a removal instrument and

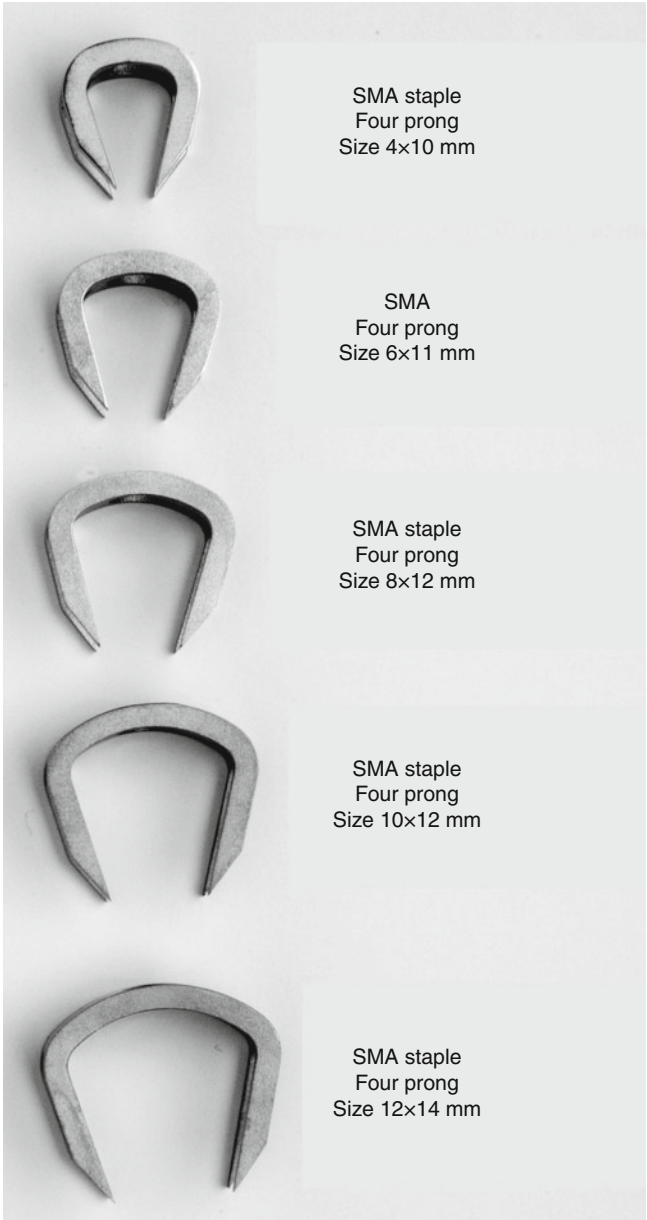

Fig. 28.7 The various sizes of proportional nitinol vertebral staples

repositioned. The incisions are closed and a chest tube placed to allow drainage of any effusions and to prevent pneumothorax.

Postoperative Protocol

Patients wear a custom, non-correcting thoracolumbosacral orthosis (TLSO) full time for 4 weeks to allow the staples to stabilize. After brace removal, there are no restrictions on physical activity. Patients are seen postoperatively at 1 and 2 months for wound inspection and then at 6-month intervals. Standing posteroanterior and lateral radiographs from the cervicothoracic junction to the sacrum are obtained at each 6-month visit.

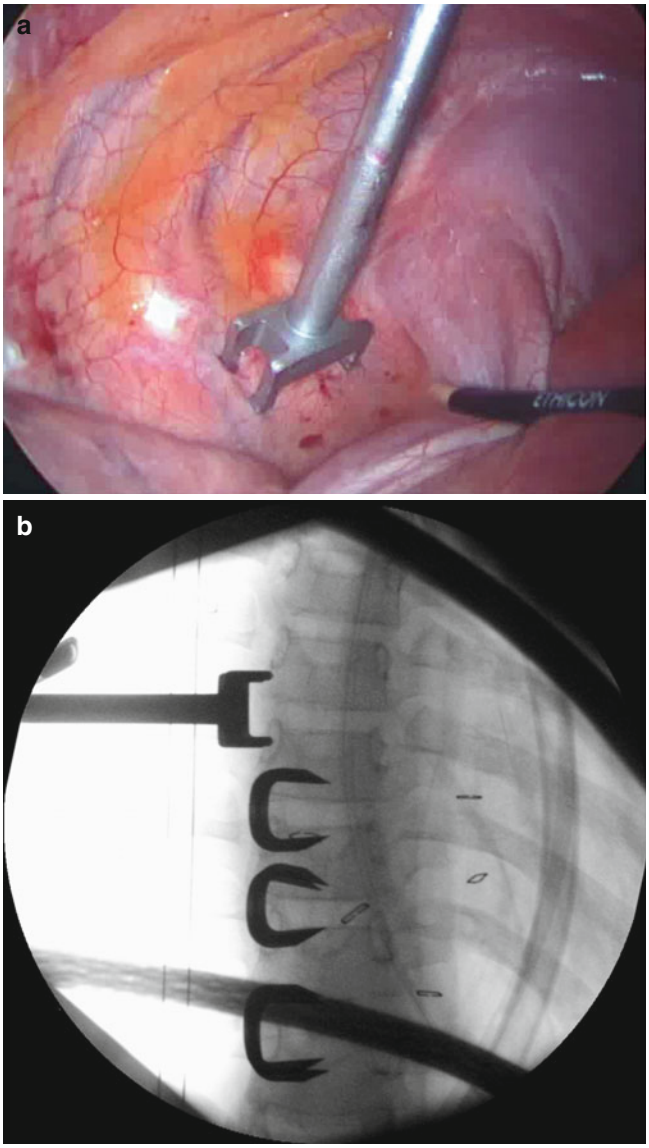

Fig. 28.8 A four-pronged trial positioned against the lateral spine as seen via (**a**) thoracoscopy and (**b**) PA fluoroscopy

Results

We have reported our results in 39 patients, in whom 87 % of curves demonstrated coronal stability at a minimum 1-year follow-up [53]. More recently, we published our series with a minimum 2-year follow-up and demonstrated coronal stability of approximately 78 % [51]. When matched to patients from a Scandinavian registry treated with bracing with similar curve size and age, stapling compared favorably in lumbar and thoracic curves between 25° and 34° [54]. The two treatments were equivalent in lumbar curves between 35° and 44°. Bracing was superior for curves between 35° and 44° (Table 28.2). The initial correction of the deformity as measured on the first erect x-ray correlates with the success rate of the procedure. For those curves where the initial postoperative Cobb angle measured 20° or less, the need for a fusion and/or progression to 50° or more was

avoided 71 % of the time [51]. We feel that an important means to obtain good immediate correction of scoliosis is through careful positioning on the OR table. Lastly, the use of staples does not preclude future surgery; if the curve progresses >50°, fusion becomes necessary. The procedure can be performed with excellent correction of deformity. However, the superiority of VBS compared to the natural history or brace treatment has yet to be evaluated in a randomized study. Limitations of VBS include the potential risk of staple dislocation and overcorrection as well as general surgical risks like bleeding and infection.

Case Example

A 12-year-old male had moderate idiopathic scoliosis with a 25° right thoracic curve and a 33° left lumbar curve (Fig. 28.10a). He was skeletally immature as evidenced by his open triradiate cartilages. According to recent work by Dimeglio et al. [27], he has a 100 % risk of progression to a magnitude requiring fusion (50°). He underwent right thoracoscopically assisted VBS and left mini-open retroperitoneal VBS. His curves measured 10° thoracic and 5° lumbar on his first erect radiograph after surgery. At 2 years after surgery, his thoracic curve continues to remain at 11° and his lumbar curve at 10° (Fig. 28.10b). His triradiate cartilages are now closed and he is Risser 2. An untreated male with similar maturity and curve magnitude has a 0 % chance of progression to fusion according to the data from Dimeglio, et al. [27]. VBS prevented this young man from requiring a spinal fusion.

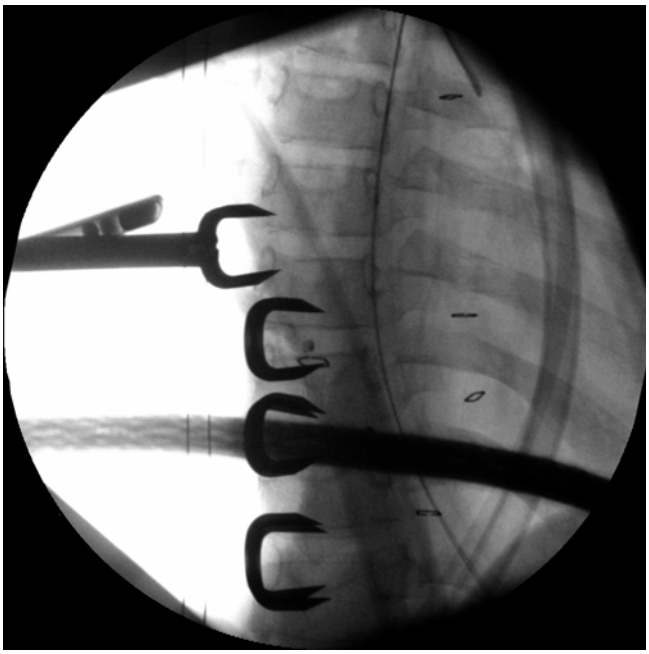

Fig. 28.9 A fluoroscopic image of the staple being inserted in the starting holes created by the trial

Vertebral Tethering

Due to the poor outcomes of vertebral stapling for thoracic curves larger than 35°, anterior vertebral tethering is another potential fusionless option that is being developed. Based on the extensive animal work done on this technology [55, 56], we have used this in skeletally immature idiopathic patients with curve sizes deemed too high for intervertebral body stapling (>35° in the thoracic spine). The technique is very similar to placing instrumentation for an anterior instrumented fusion. The procedure can be performed either through a mini thoracotomy or thoracoscopically. Vertebral body screws are placed on the convexity of a thoracic curve, and a flexible tether (Dynesys, Zimmer, Inc., Warsaw, IN) is tensioned into the screws thus reducing the curvature (Fig. 28.11). Patients are placed into a flex foam brace postoperatively for 3–6 months. We have performed this procedure on 15 patients and early results appear promising without any major complications. Longer-term follow-up is needed to better understand the utility and indications for this technique.

Table 28.2 Results of a retrospective comparison of vertebral body stapling to a Scandinavian brace registry in the treatment of idiopathic scoliosis [54]

	No change/improvement (%)	Progression (%)	*P* value (Fisher's exact test)
Thoracic curves 25°–34°			
VBS (*N*=26)	81	19	0.16
Bracing (*N*=36)	61	39	
Thoracic curves 35°–44°			
VBS (*N*=11)	18	82	0.19
Bracing (*N*=12)	50	50	
Lumbar curves 25°–34°			
VBS (*N*=15)	80	20	1.0
Bracing (*N*=16)	81	19	
Lumbar curves 35°–44°			
VBS (*N*=5)	60	40	0.43
Bracing (*N*=2)	0	100	

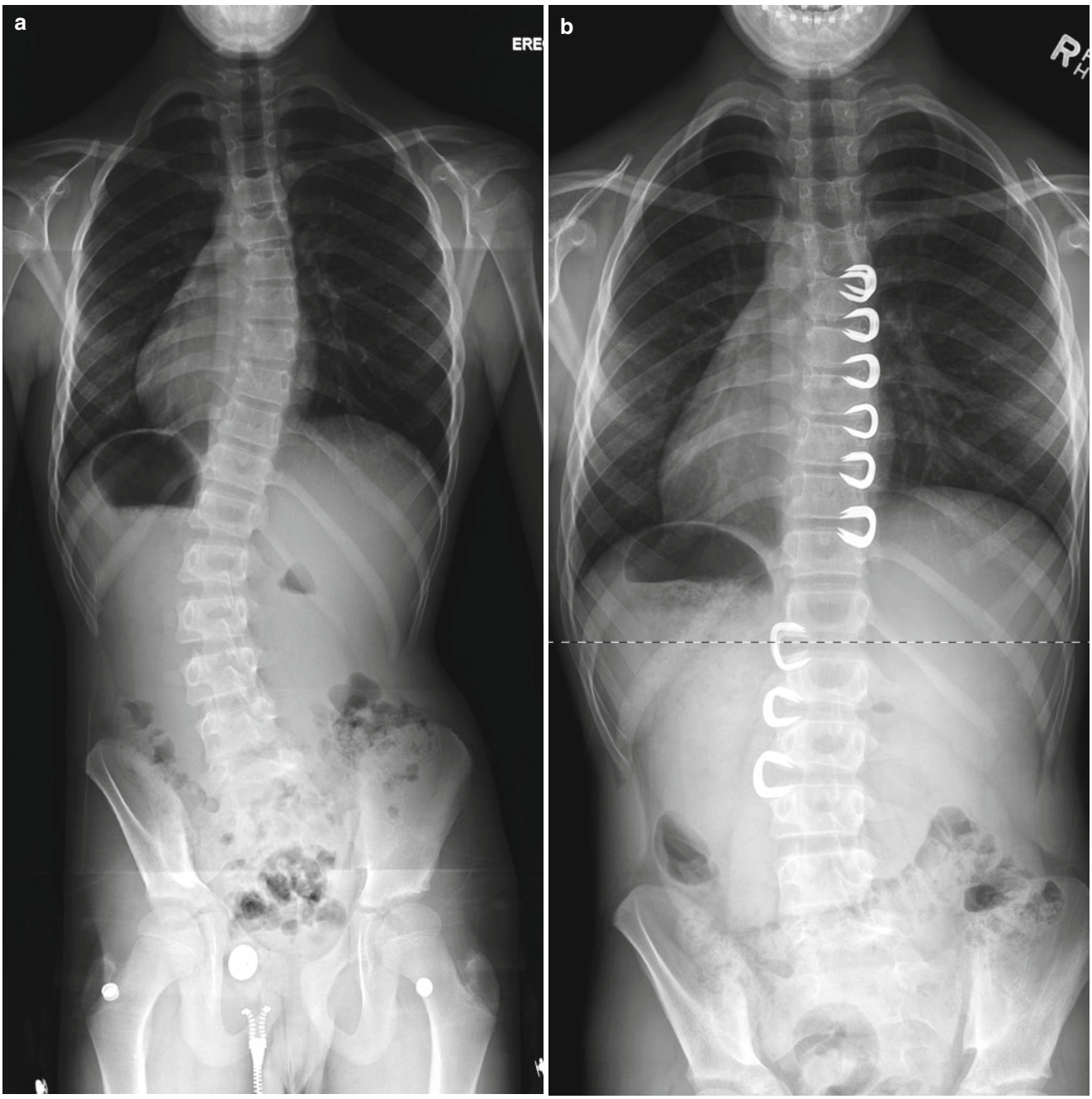

Fig. 28.10 (**a**) Standing preoperative PA and (**b**) 2-year postoperative standing PA of a skeletally immature male who underwent vertebral body stapling for moderate idiopathic scoliosis

Summary

Although the adoption of MIS techniques to the treatment of spinal deformity is in its infancy, pioneering advances to the field are emerging. Surgeons are applying principles of minimizing soft tissue disruption to existing procedures such as posterior spinal fusions with promising results. Several surgeons are also adapting the principles of preservation of structural anatomy and motion in innovative ways as evidenced by emerging interest in thoracoscopic vertebral body stapling and vertebral tethering.

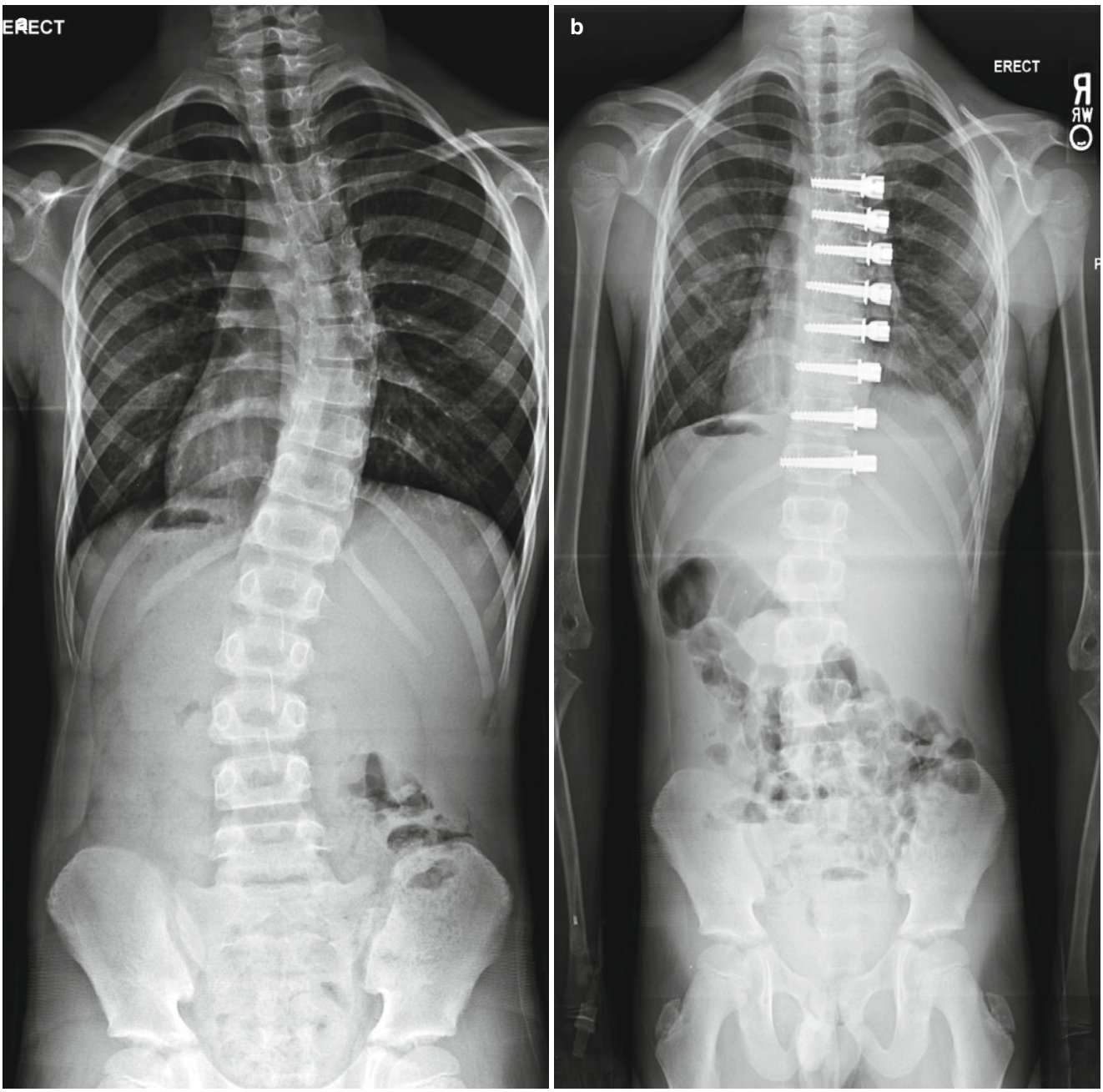

Fig. 28.11 (**a**) Standing preoperative PA and (**b**) 2-year postoperative standing PA of a skeletally immature male who underwent vertebral tethering for moderate idiopathic scoliosis

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Adult Scoliosis

29

Steven M. Presciutti, Isaac L. Moss,
and Frank M. Phillips

Introduction

Historically, scoliosis was thought of too simply as an abnormal lateral curvature of the spine. However, through a better understanding of biomechanics and spinal anatomy, along with better imaging techniques, it has been recognized that in addition to the coronal imbalance that there is also often both a sagittal imbalance and a malrotation of the spine, which are both integral components of the deformity. Scoliosis, therefore, represents a complex three-dimensional deformity that affects the spine in the coronal, sagittal, and axial planes.

Scoliosis is diagnosed in adult patients when it occurs or becomes relevant after skeletal maturity with a Cobb angle of more than 10° in the coronal plain [1]. Scoliosis can be present since childhood or adolescence and become progressive and/or symptomatic in adult life secondary to degeneration of the idiopathic curve (IS). Scoliosis may also appear "de novo" in adult life without any precedence in earlier life. This latter type is termed degenerative scoliosis (DS).

Degenerative adult scoliosis, specifically in the lumbar spine, is characterized by a common pathologic morphology and mechanism (Fig. 29.1). In de novo scoliosis, the intervertebral disc and/or the facet joints degenerate asymmetrically. This leads to an asymmetric loading of the spinal segment, which in turn leads to an asymmetric deformity (i.e., scoliosis and/or kyphosis). A vicious cycle is then created, with the deformity again triggering further asymmetric degeneration and inducing more asymmetric loading [2]. This process typically occurs in a setting of postmenopausal females or older men who have some degree of osteopenia [3]. The potential for asymmetric bony deformation and collapse in the weak osteoporotic vertebra is increased and can contribute to further curve progression. The accompanied degeneration of intervertebral discs, facet joints, and joint capsules usually results in some form of uni- or multisegmental instability. There may be not only a spondylolisthesis but also translational dislocations in either the coronal plain alone or three dimensionally, expressing itself as a rotational dislocation [4]. This deformity frequently results in the development of spinal stenosis with symptoms consistent with radiculopathy and/or neurogenic claudication.

Patients with IS have fundamentally different curves. These IS curves generally have a more severe rotational deformity. When surgery is indicated, these patients frequently require longer fusions that include the thoracic spine in order to achieve adequate deformity correction. DS typically has less of this rotational deformity but more frequently has rotary subluxation and varying degrees of spinal stenosis.

Nonoperative care is usually the first-line treatment for patients with adult scoliosis. However, when these measures fail and patients are sufficiently symptomatic, surgical intervention is indicated. Recently, minimally invasive surgical options, as an alternative to the traditional open surgical approaches, have been explored. The application of minimally invasive surgery for adult scoliosis is best appreciated in the context of the history of surgical techniques for scoliosis.

Early in the twentieth century, spinal arthrodesis for scoliosis involved a noninstrumented posterior approach, with prolonged bed rest postoperatively for as long as 1 year. In addition, these early results were marred by poor deformity correction and high rates of pseudarthrosis [5, 6]. Harrington [7] revolutionized spine surgery in the late 1950s with the advent of internal spinal fixation using a single stainless steel rod anchored by a single proximal sublaminar and a single

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distal supralaminar fixation hook. This technique was improved by Luque's [8] approach of segmental fixation with sublaminar wires and two longitudinal rods and again later with the development of segmental hook fixation [9]. These methods resulted in further improvements in coronal-plane correction and more physiologic sagittal-plane contour.

The anterior approach to the spine was simultaneously being refined by Hodgson and Stock [10] in the context of spinal tuberculosis. Involved segments were resected and rib strut grafts were used to restore alignment and achieve arthrodesis. The anterior approach was continually improved upon in the context of scoliosis and strides were made in instrumentation by Dwyer et al. [11], Zielke and Berthet [12], Millis et al. [13], and Brodner et al. [14].

As these various techniques evolved and have since often been combined, surgical correction of scoliosis has improved over the past century and now provides reliable radiographic correction of deformity in both the coronal and sagittal planes. However, both traditional approaches, open posterior alone and open anterior/posterior, carry with them a very significant perioperative risk profile. Overall complication risk for open posterior surgery to address adult scoliosis is estimated between 25 and 80 %. These include excessive blood loss, infection, neurologic injury, and various minor and major

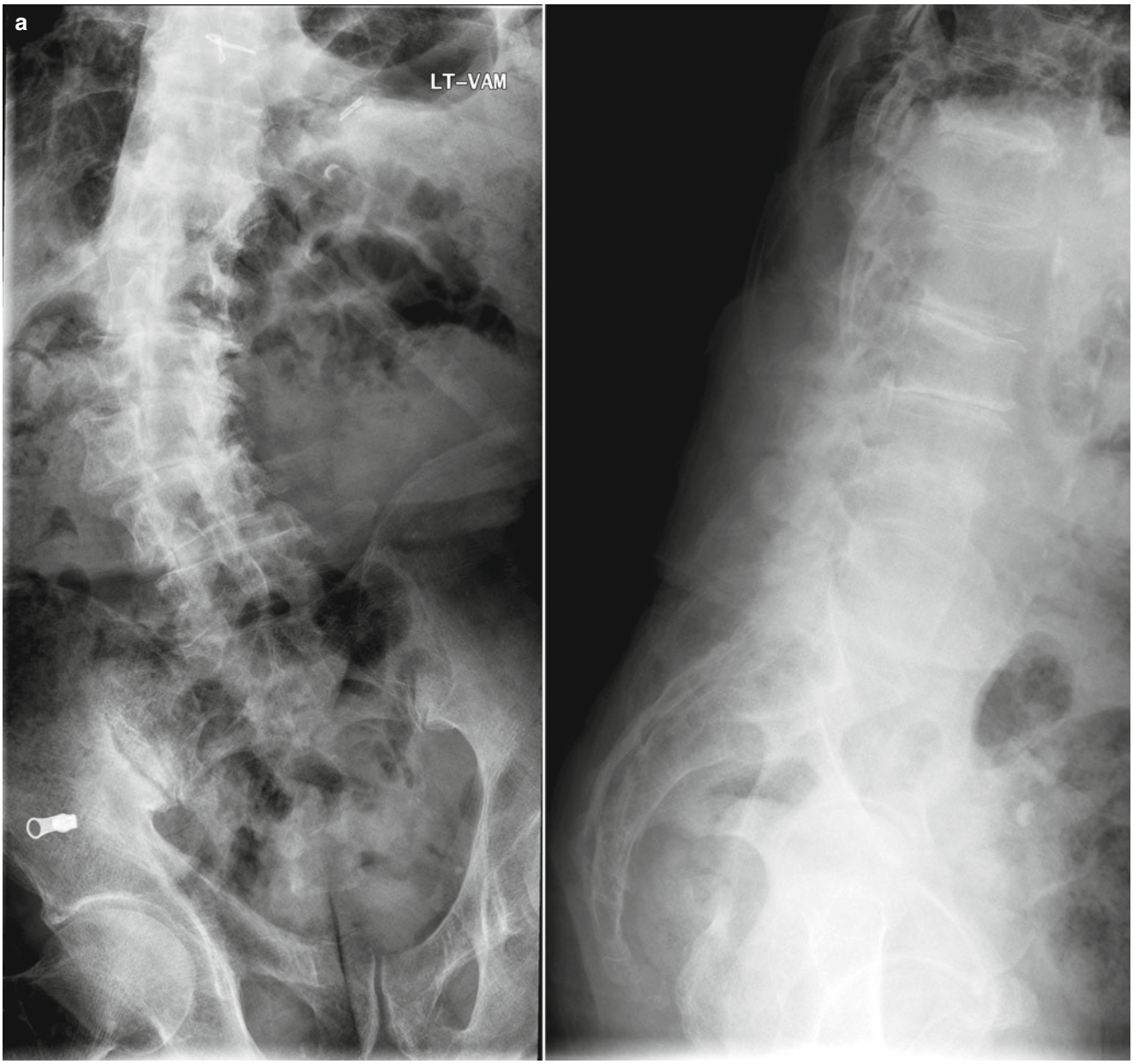


Fig. 29.1 AP and lateral radiographs (**a**) and selected T2-weighted magnetic resonance image (**b**) demonstrating the typical features of adult scoliosis including a predominantly lumbar curve, lumbar kyphosis, significant disc and facet joint degeneration, and spinal stenosis

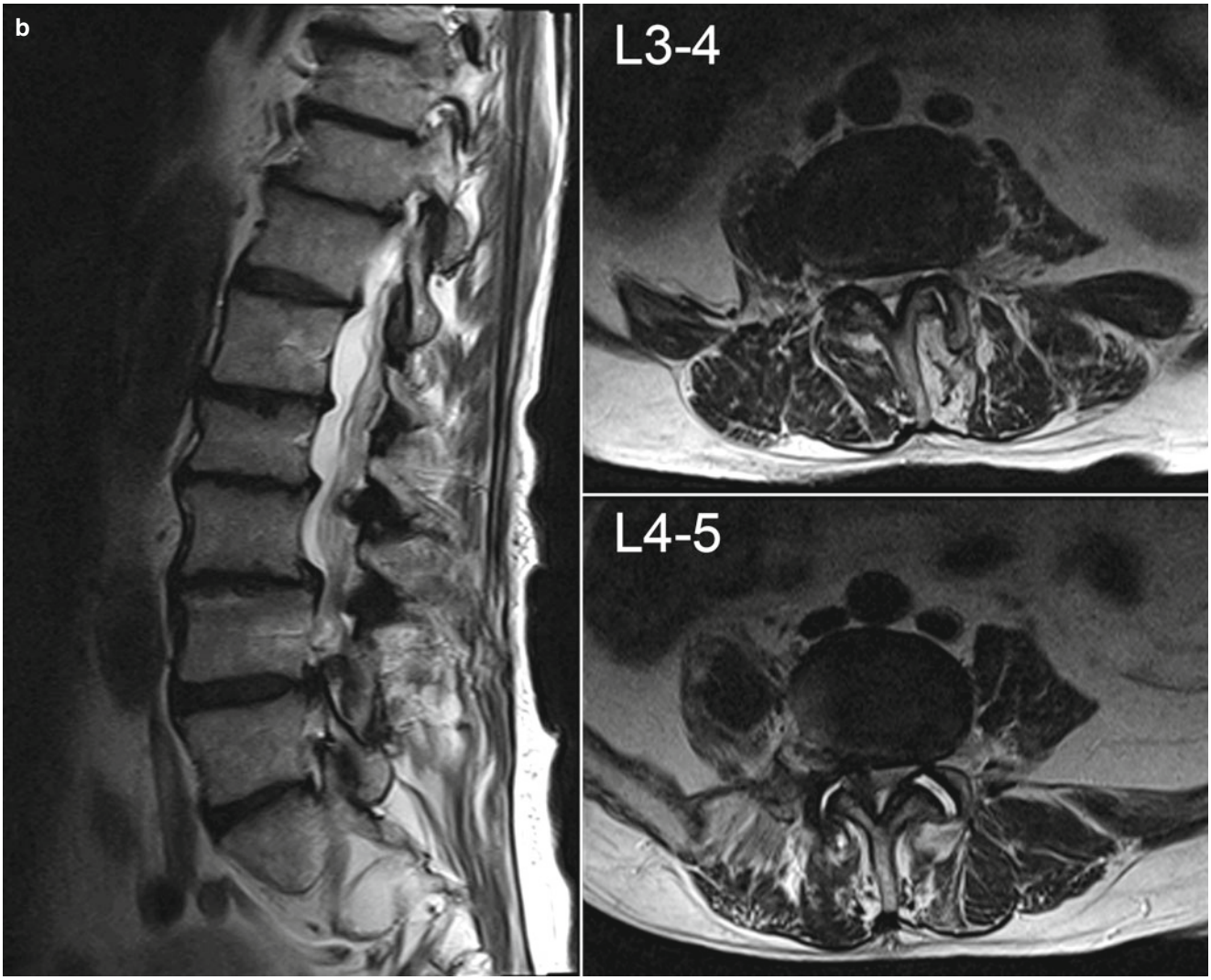


Fig. 29.1 (continued)

medical complications [15, 16]. The traditional open anterior approach is associated with up to a 40 % risk of complications including abdominal hernia, neurovascular injury, retrograde ejaculation, and ureteral or bladder injury [17].

There is thus clearly a need to try to reduce the morbidity associated with surgery in patients with adult scoliosis. This is especially important in the setting of adult deformity given that the typical elderly patient often has significant medical comorbidities. Over the past decade, less invasive surgical approaches to neural decompression and fusion have been popularized and have recently been applied to the treatment of adult deformity.

Epidemiology

Adult scoliosis is a common disorder that can have a significant and measurable impact on health-related quality of life. Patients can be significantly affected in terms of pain, function, self-image, mental health, and overall quality of life. While adult scoliosis is common, the exact prevalence is unknown. It has been widely reported in the literature to be between 1.4 and 68 %. Differences in the definition of scoliosis used and in the methods of defining cohorts and sample sizes have led to this variability. Healey and Lane [18] identified curves over 10° in more than 50 % of elderly females with back pain and osteoporosis. Schwab et al. [19] looked at healthy, adult volunteers over the age of 60 and identified a scoliosis of greater than 10° in 68 % of them.

Adult scoliosis places a significant financial burden on the US health-care system. In 2004, $3.7 billion was spent on 134,000 hospital inpatient visits for patients older than 18 years of age with discharge diagnosis of spinal deformity [20]. This represents approximately 4 % of the overall cost of spine-related health care in the country [21].

Table 29.1 SRS adult deformity classification

Primary curve types			
Single thoracic	Double major	Thoracolumbar	Primary sagittal
Double thoracic	Triple major	Lumbar "de novo"/idiopathic	
Adult spinal deformity modifiers			
Regional sagittal modifier (*include only if outside normal range as listed*)			
(PT) Proximal thoracic (T2–T5): ≥ +20°			
(MT) Main thoracic (T5–T12): ≥ +50°			
(TL) Thoracolumbar (T10–L2): ≥ +20°			
(L) Lumbar (T12–S1): ≥ −40°			
Lumbar degenerative modifier (*include only if present*)			
(DDD) decreased disc height and facet arthropathy based on x-ray include lowest level between L1 and S1			
(LIS) listhesis (rotational, lateral antero, retro) ≥3 mm include lowest level between L1 and S1			
(JCT) junctional L5–S1 curve ≥10° (intersection angle superior endplates L5 and S1)			
Global balance modifier (*include only if imbalance present*)			
(SB) sagittal C7 plumb ≥5 cm anterior or posterior to sacral promontory			
(CB) coronal C7 plumb ≥3 cm right or left of CSVL			
SRS definition of regions			
Thoracic: apex T2 to T11–12 disc			
Thoracolumbar: apex T12 to L1 disc			
Lumbar: apex L1–2 disc to L4			
Criteria for specific major curve types			
Thoracic curves			
Curve ≥40°			
Apical vertebral body lateral to C7 plumb line			
T1 rib or clavicle ≥10° in upper thoracic curves			
Thoracolumbar and lumbar curves			
Curve ≥30°			
Apical vertebral body lateral to CSVL			
Primary sagittal-plane deformity			
No major coronal curve			
One or more regional sagittal measurements (PT, MT, TL, L) outside normal range			

Adapted from Lowe et al. [26]

Classification

There have been multiple classification systems for adult scoliosis proposed over the years. Early systems, such as those proposed by the Terminology Committee of the Scoliosis Research Society (SRS) [22] in 1969 and from King and colleagues [23] in 1983, focused more on adolescent scoliosis and provided little guidance for the care of adult scoliotic curves. The Lenke system has been highly successful and widely adopted but, like its predecessors, is focused on adolescent idiopathic scoliosis and lacks the ability to really help guide treatment for the adult spinal deformity [24].

In adult scoliosis, global sagittal balance and symptomatic degenerative changes within the deformity are important determinants of both the clinical impact on the patient and the physician's treatment plan. As discussed earlier, the spinal deformity in adult scoliosis is distinct from that in the adolescent. Symptomatic degenerative changes including stenosis, spondylolisthesis, and rotational subluxation that result in neurogenic claudication and radiculopathy are common with adult scoliosis. In fact, alleviating these neurogenic symptoms while creating a stable and balanced spine is often the primary surgical goal, with correction of the actual deformity regarded as a secondary concern. Global imbalance in the coronal plane is also more common in adults as compared to adolescents. Global sagittal alignment, however, has the most significant impact on pain and function compared with the other radiographic parameters including curve location, curve magnitude, and even coronal balance [25].

The SRS has recently proposed a new classification of adult scoliotic deformity (Table 29.1; Fig. 29.2) that builds on the King/Moe and Lenke classifications by incorporating the clinical and radiographic parameters unique to adult socliosis [26]. This new classification system offers context for the establishment of a comprehensive description of adult scoliosis and is intended to provide a framework for an accurate and organized categorization of patients with

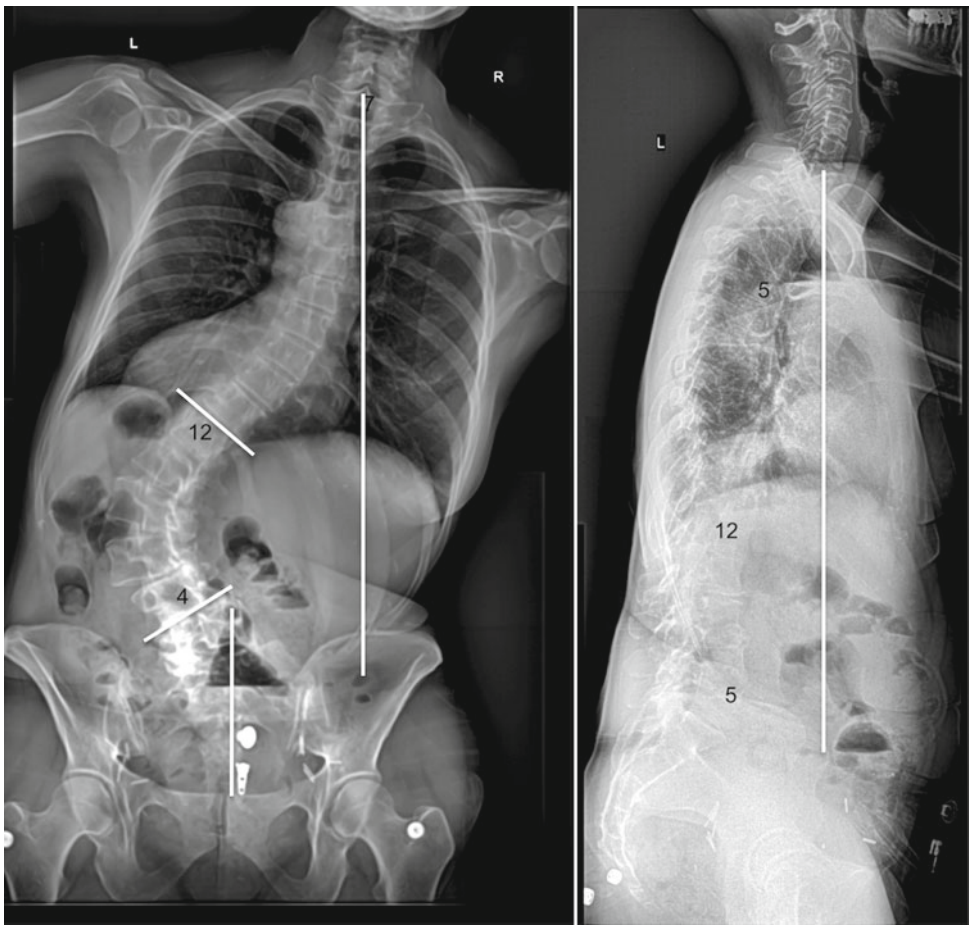


Fig. 29.2 AP and lateral x-ray case example of a 56-year-old woman with back and leg pain demonstrating application of the SRS Adult Deformity Classification: primary lumbar curve; negative PT, MT, TL, and positive L regional sagittal modifiers; + degenerative modifiers L2–S1; positive global sagittal balance; and positive right coronal imbalance

spinal deformity. As is the case with the Lenke classification used for IS, the new system divides deformities into major curve types and then uses modifier for more specific description. Due to the clinical significance of sagittal-plane deformity in adult patients, a "primary sagittal" major curve type was added.

Clinical Presentation and Evaluation

As is the case with specific curve patterns, the clinical presentation also differs between the adult with scoliosis and the adolescent with idiopathic scoliosis. It is important to understand these as they underlie the fundamental differences in the goals of treatment and the surgical strategies for these two patient populations. In the adolescent with idiopathic scoliosis, the goal of care is to prevent progression of deformity and any consequences of deformity progression. In the adult with scoliosis, however, the goal of care is to improve patient pain, disability, and function.

The most frequent clinical presentation in adult scoliosis is back pain, accounting for over 90 % of patients who present to a spine surgeon's clinic [27–29]. Back pain itself can present in a variety of patterns and types. The etiology of the patient's pain is important to decipher and determine whether it is caused by progression of the deformity, deconditioning, or neurological compromise. Pain that localizes over the convexity of the curve is often the result of muscle fatigue and/or spasm. Unbalanced, overloaded, and stressed, paravertebral back muscles may become very sore and in return will not contribute to balance the muscle play, consequently becoming part of a vicious circle. This is especially true when the lumbar curve is accompanied by the loss of lumbar lordosis [30]. In contrast, pain on the concavity of the curve may be secondary to spondylotic changes.

The second important symptom of adult degenerative scoliosis is radicular pain and claudication symptoms when standing or walking. Smith and colleagues [31] identified radicular pain in 85 % of their patients who presented to their neurosurgical practice, and nearly 10 % of patients had

neurologic symptoms including weakness. Asymmetric disc space collapse and facet hypertrophy in the concavity of the curve often result in significant neuroforaminal stenosis and radiculopathy due to exiting nerve root compression. Although pain originating on the convexity of the curve is often mechanical in nature and isolated to the back, dynamic overstretch of a nerve root may also result in radicular symptoms. As the curves are often present in the proximal lumbar spine (L2–3 or L3–4), the groin or thigh pain from L2 or L3 nerve root compression is often initially attributed to other diagnoses, especially hip osteoarthritis, before a spinal etiology is considered. An objective neurological deficit is rare, however. When present, it is typically due to a significantly compromised space in the spinal canal with a relatively acute aggravation and decompensation. Hypermobility and spondylolisthesis are often present at the caudal aspect of the curve or at the transition to the sacrum, especially in cases of stiff curves. This pathology often results in significant single- or multilevel central canal stenosis. These patients can present with both radiculopathy and neurogenic claudication symptoms [32].

Grubb and Lipscomb [33] described the symptoms of adult patients presenting with progressive idiopathic scoliosis as compared with de novo degenerative scoliosis. Those with idiopathic curves complained of mainly mechanical back pain with a minority presenting with neurogenic symptoms. Conversely, the majority of patients with degenerative scoliosis had primarily neurogenic complaints attributed to spinal stenosis. These symptoms were often, but not all accompanied by mechanical back pain. Interestingly, unlike patients with spinal stenosis without deformity, those with degenerative scoliosis often did not get relief of their leg symptoms while sitting or flexing forward. Loss of lumbar lordosis resulting in symptomatic flat back was also found to be more common in patients with degenerative curves as opposed to those with curve of idiopathic origin.

Patients with coronal-plane deformity often complain of waist asymmetry and ribs abutting the pelvis. More commonly, a progressive forward lean caused by lumbar kyphosis results in positive sagittal imbalance and has been closely linked to a decrease quality of life by Glassman et al. [30]. Patients with greater than 5 cm of anterior sagittal imbalance can experience a significant decline in function. The energy requirements of these patients to stand and ambulate are greater than for those patients who have a compensated sagittal balance. They experience the so-called flat back syndrome, characterized by back pain that progresses with duration of activity, early fatigue, and an intolerance of standing secondary to walking with compensation through their other joints. Their hip extensors and quadriceps work in eccentric contraction leading to intolerance for most activities.

Deformity progression in the adult is common and is why these patients require ongoing follow-up. Even after skeletal maturity, it has been shown that with over 40 years of follow-up that adult IS curves continue to progress in 68 % of patients [34]. Thoracic curves greater than 50° have the highest rate of progression, followed by thoracolumbar and lumbar curves. For patients with DS, important changes in the curve over time include curve size progression, loss of lumbar lordosis, and reduced flexibility within the deformity [35].

A thorough physical exam is critical. Specific to adult scoliosis, waist asymmetry, trunk shift, and the relative heights of the iliac crests should be noted. Measurement of leg lengths is also important in determining the source of pelvic obliquity, as it can be caused by either a limb-length discrepancy or a deformity between the pelvis and spine. Asking the patient to stand with the knees fully extended is helpful to elucidate a fixed sagittal-plane deformity. If the deformity resolves when the patient assumes a sitting position, then this indicates that flexion at the pelvic-femoral junction is the cause of sagittal malalignment. Similarly, the Thomas test may be used with the patient in the supine position. Recognizing such a global sagittal-plane deformity is important for surgical planning [36].

Radiographic Evaluation

Radiographic evaluation is imperative for successful surgical management of adults with scoliosis. We highly recommend full-length standing 36″ posteroanterior (PA) and lateral radiographs to adequately evaluate global balance. The patient's knees and hips should be fully extended, and leg-length discrepancy should be balanced with standing blocks. The standing lateral radiograph must include the base of the occiput and bilateral femoral heads to adequately evaluate both the sagittal balance and pelvic parameters. Degenerative changes including lateral subluxation and spondylolisthesis should also be noted, as these are very important to consider in surgical planning.

The use of flexion and extension lateral lumbar spine radiographs can be useful for determining dynamic instability or a fixed kyphotic deformity. Certainly, dynamic instability may influence the extent of surgical instrumentation and fusion. Assessment of coronal flexibility is also very helpful. Various techniques are available to assess the flexibility of both the major and minor curves. These include supine side-bending films and fulcrum-bending films, and in patients with larger- or short-radii curves, traction radiographs may give the best assessment of flexibility.

Global sagittal alignment is an extremely important parameter in adult deformity correction and has been shown to be the single most important factor affecting outcome for adults undergoing spinal deformity surgery [27]. Paying particular attention to the lumbopelvic anatomy is

Table 29.2 Measurement of spinopelvic parameters

Parameter	Normal value (degrees)	Description
Pelvic incidence (PI)	51	Angle formed by a line drawn perpendicular to the midpoint of the sacral end plate and a line drawn from this point to the center of the femoral head PI = PT + SS
Pelvic tilt (PT)	11	Angle formed by the intersection of a line drawn from the midpoint of the sacral end plate to the center of the femoral head and a vertical reference line Position-dependent parameter Describes pelvic orientation
Sacral slope (SS)	40	Angle formed by a line drawn along the sacral end plate and a horizontal reference line Position-dependent parameter Describes pelvic orientation

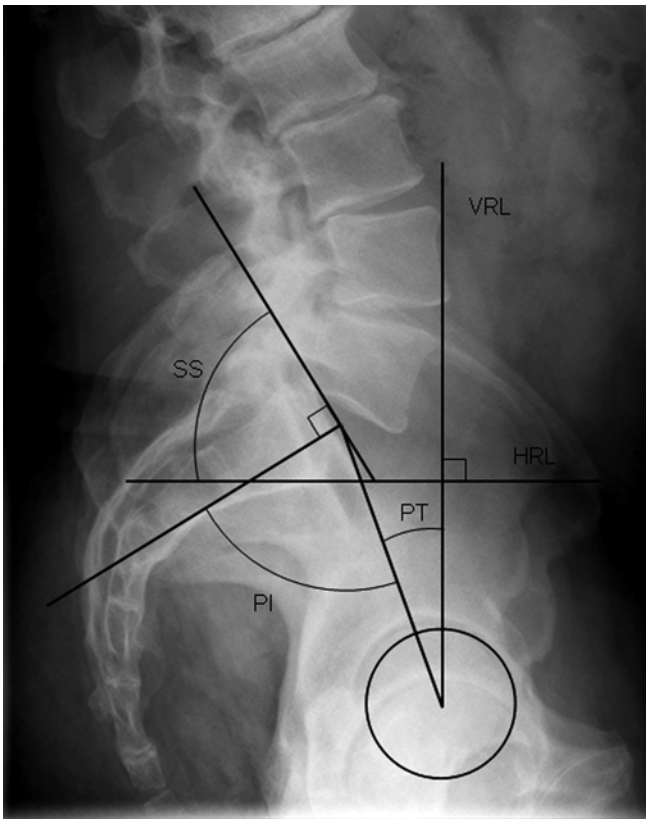


Fig. 29.3 Lateral radiograph of the lumbosacral junction and the demonstrating measurement of important spinopelvic parameters pelvic incidence (PI), pelvic tilt (PT), and sacral slope (SS). These parameters are measured in reference to the horizontal (HRL) and vertical (VRL) reference lines. See Table 29.2 for details of measurement

crucial. The most important parameters are summarized in Table 29.2 and Fig. 29.3. Since pelvic morphology is relatively static for each individual, the morphology of the pelvis can be considered the foundation on which the rest of the spine derives its sagittal orientation. Multiple parameters have been described to describe this relationship, including pelvic tilt (PT) and sacral slope (SS). These are patient position dependent, however. Radiographically, pelvic morphology is best described through measuring the pelvic incidence (PI). PI is defined as the angle from a line perpendicular to the midpoint of the sacral end plate and a line connecting this point to the center of the femoral heads. PI is an individualized posture-independent measurement of pelvic morphology [37]. This global sagittal alignment may affect the surgical decision on osteotomy type and location, as well as how and where correction is achieved along different segments of the spine.

Many of the patients with adult scoliosis present with radicular symptoms or neurogenic claudication and should therefore be evaluated with advanced imaging such as MRI and/or CT. These are very helpful in evaluating the spinal neuroanatomy, intervertebral disc pathology, and vascular anatomy of the levels to be operated. Particularly, when correlated with findings on history and physical exam, decompression of both foraminal and central canal stenosis is a critical part of a successful surgical plan. Noting the degree of central versus foraminal stenosis is important, as each may need to be addressed separately in many minimally invasive surgical strategies.

Nonoperative Care

Surgeons are generally conservative in the treatment of adult deformity because of the complication rates associated with the surgeries and the marginal bone quality endemic to this population. A commonly described prerequisite to surgical intervention is a failure of all appropriate conservative care. Nonoperative management of these patients therefore plays a large role; however, evidence of the efficacy of specific treatment regimens is lacking in this area. The current level of evidence is limited to extremely small-case reports and expert opinion. In a recent systematic review by Everett and Patel [38], the authors found that current evidence is indeterminate with level 4 evidence on the role of physical therapy,

chiropractic treatment, and bracing and level 3 evidence on the use of injections for treatment of adult scoliosis.

In general, asymptomatic patients with spinal deformities do not require formal treatment, although periodic follow-up may be required to monitor for curve progression. In symptomatic patients, it is generally recommended that they pursue a low-impact muscle-strengthening endurance program. A core-strengthening program, often under the direction of a physical therapist, may also be of benefit for both back pain and stenosis symptoms. Nonsteroidal anti-inflammatory drugs are a useful adjunct to an exercise program in patients without medical contraindications. Narcotic analgesics are often prescribed for severe pain, but their use must be carefully monitored, as there is a high incidence of dependence or abuse. Determination of bone mineral density with a DEXA scan is often indicated, and depending on the results, referral for osteopenia or osteoporosis treatment should be considered.

Epidural and/or selective nerve root injections are often considered based on clinical findings and imaging studies. Cooper et al. [39] performed a retrospective study of 61 patients with degenerative scoliosis with subjective radicular complaints. They explored the role of transforaminal fluoroscopic-guided epidural steroid injections in the treatment of radicular pain and obtained follow-up on 52 (85.2 %) of 61 included patients. They defined a successful outcome as a patient who was both satisfied with their results and experienced improvement in pain and function patient reported scores. Using these criteria, 59.6 % of patients had a successful outcome at 1 week post-injection, 55.8 % at 1 month post-injection, 37.2 % at 1 year post-injection, and 27.3 % had a successful outcome at 2-year post-injection ($p<0.01$). This data suggests that epidural injection may be helpful for short-term pain relief, but a long-lasting effect is uncommon.

Unlike adolescent scoliosis, bracing has a limited role in adult deformity. It is not likely to halt curve progression because, in adults, the mode of progression is usually not spinal growth but rather transverse instability. Also, it is generally believed that the temporary pain relief experienced with brace wear is easily outweighed by the muscle deconditioning that will result from long-term external support [40]. Weiss et al. [41] looked at a group of 29 women with an average Cobb angle of 37°, average age of 41 years, and for an average of 7.5 months. The patients were treated with a custom LSO that attempted to restore "sagittal realignment." The patients noted an immediate, but only short-term relief of pain with the brace. Also, 22 (76 %) had stopped wearing the brace at the time of follow-up, suggesting long-term compliance is limited.

Operative intervention should be offered to those patients who do not respond to the conservative measure and have ongoing pain and disability.

Operative Care

Preoperative Planning

When considering surgical correction of adult scoliosis, it is important that the surgeon has a good understanding of the patient's expectations. It is also important that the surgeon not react simply to all of the radiographic changes on imaging but to properly correlate the patient's individual symptoms with specific pathology on the radiographs.

Particular attention must also be paid to the patient's individual profile of comorbidities, as they are an important determinant of perioperative complications. Osteoporosis screening or monitoring is also recommended for those populations at risk.

Environmental and social conditions have been shown to correlate with either poor clinical outcomes or increased surgical risks. This is particularly true with the use of tobacco [42], nutritional deficiency [43], and depression [44]. Such factors should be optimized as much as possible preoperatively. It is recommended that the patient stops all tobacco products before surgery.

The risk of development of adjacent segment disease above and below fusion segments should be considered for patients undergoing any fusion procedure. The preoperative status (or health) of the segment or disc is the greatest predictor for the development of adjacent segment disease [45]. For the population with adult scoliosis, where some identifiable degenerative disease is nearly ubiquitous, this is particularly relevant. Fixed lumbar motion segments after spinal instrumentation and fusion may increase stress on unfused spinal segments and cause accelerated degeneration of the adjacent segments [46–48]. There are controversies regarding the best proximal and distal fusion level in adult long lumbar instrumented fusions.

Care consideration of which segment to include as the uppermost instrumented vertebrae (UIV) is necessary to mitigate the risk of developing junctional kyphosis. This phenomenon results from accelerated disc degeneration above the UIV or fracture of the vertebrae itself and leads to progression of global kyphosis and often, significant spinal stenosis [49]. Kim et al. [50] performed a retrospective study comparing the postoperative radiographic measurements as well as the prevalence of revision according to the three different proximal fusion levels (T9–T10, T11–T12, and L1–L2) after multilevel lumbar/lumbosacral instrumented fusion from the distal thoracic/upper lumbar spine (T9–L2) to L5 or S1. One hundred twenty-five patients were evaluated (average age 57.1 years) who underwent long (average 7.1 vertebrae) segmental posterior spinal instrumented fusion with a minimum 2-year follow-up (rage 2–19.8 years). The three groups demonstrated no significant differences in the

prevalence of proximal junctional kyphosis (group 1 51 % vs. group 2 55 % vs. group 3 36 %, $p=0.20$) and revision (group 1 24 % vs. group 2 24 % vs. group 3 26 %, $p=0.99$) at the ultimate follow-up. Subsequent proximal junctional angle and sagittal vertical axis changes between the ultimate follow-up and preoperative ($p=0.10$ and 0.46 respectively) were also not significantly different. The SRS total and all subscale outcomes scores among the 3 groups did not demonstrate significant differences ($p>0.50$). This study demonstrates that there is no one universal correct level to choose for UIV, rather individual parameters must be considered. In general, it is recommended that the uppermost instrumented vertebrae be within the coronal stable zone, have neutral rotation, have neutral sagittal alignment, and have little or no degeneration in the segment directly cranial to it [51].

The decision of whether to include the L5 or the sacrum as the distal extent of a long fusion for scoliosis is also an important consideration. Fusion to the L5 offers the theoretical benefits of preserved lumbosacral motion, shorter surgical time, and a decreased likelihood of pseudarthrosis. On the other hand, a long fusion to L5 carries the potential for accelerated symptomatic advanced L5–S1 disc degeneration. With subsequent disc degeneration, axial discomfort, radiculopathy, and loss of lumbosacral lordosis may result. Edwards et al. [52] performed a matched cohort analysis of 95 adult patients with "healthy" (grade 0 or 1 degeneration) L5–S1 discs that underwent long adult deformity fusions from the thoracic spine to either L5 or the sacrum. Correction of sagittal imbalance was superior for patients fused to the sacrum (C7 plumb line: L5, 0.9 cm; sacrum, 3.2 cm; $p=0.03$). At latest follow-up (L5, 5.2 years; sacrum, 3.7 years), 67 % of patients fused to L5 had radiographic evidence of advanced L5–S1 disc degeneration and the L5 cohort tended to have inferior sagittal balance (C7 plumb line: L5, +4.0 cm; sacrum, +1.2 cm; $p=0.06$). The sacrum cohort, however, required more surgical procedures (L5, 1.7; sacrum, 2.8; $p=0.03$) and experienced a greater frequency of major complications (L5, 22 %; sacrum, 75 %; $p=0.02$), including nonunion (L5, 4 %; sacrum, 42 %; $p=0.006$) and medical morbidity (L5, 0 %; sacrum, 33 %; $p=0.001$). SRS-24 scores reflected a similar patient assessment of outcome and function for the two cohorts (L5, 89; sacrum, 87). Typically, fusions that extend to the sacrum are indicated in the presence of spondylolisthesis or previous laminectomy at L5–S1, stenosis requiring decompression at L5–S1, severe degeneration, or an oblique takeoff of L5 to the sacrum greater than 15° [53].

Surgical Considerations

Patients with adult scoliosis present with a number of different clinical presentations and their surgical strategies typically encompass a broad range of approaches and options. Patients commonly have symptoms that result from a combination of degenerative spondylosis, progressive deformity, as well as neurologic compression. Surgical intervention must be individually tailored based on the specific pathology that is symptomatic for each patient.

Decompression alone may be indicated in patients with neurologic symptoms with relatively small degrees of scoliosis without frank instability. Kelleher et al. [54] reported on a consecutive series of 75 patients treated over 5 years. A subset of this larger group had DS, those with stenosis + DS ($n=16$) and those with stenosis + spondylolisthesis + DS ($n=12$). The preoperative and postoperative Oswestry Disability Index (ODI) after MIS laminoplasty improved from 50.7 to 31.5 % and 53 to 22 %, respectively. These outcomes compared favorably to those patients undergoing decompression for stenosis without the presence of deformity who were also included as an arm in the study and had a change in ODI from 48 to 18.7 %. The revision rate was reported to be 25 % for both deformity groups, which was higher than in those patients without deformity. In 75 % of patients requiring revision surgery, there was preoperative lateral listhesis. The authors concluded that MIS decompression alone for leg dominant symptoms is a clinically effective procedure in the majority of patients including those with degenerative spondylolisthesis or adult scoliosis.

Transfeldt et al. [55] compared the surgical outcomes of patients with DS treated with decompression alone, decompression with a limited fusion, or decompression with full-curve fusion. Not surprisingly, complication rates were highest in the full-curve fusion group at 56 % and lowest in the decompression alone group at 10 %. In addition, 37 % of the full-curve fusion group required reoperation for pseudarthrosis, instrumentation revision, seroma evacuation, or wound infection. In the decompression alone group, only 10 % were brought back to the operating room, all for repeat decompression. Patient reported outcomes demonstrated mixed results. SF-36 was improved when all three groups were combined. Oswestry Disability Index (ODI) improved in the decompression alone (20 %) and limited fusion group (22 %), but not in the full-curve fusion group. Interestingly, despite a lack of improvement in ODI, patient satisfaction with the procedure was highest in the full-curve fusion group with 75 % of patient reporting that the surgery was a success and 77 % stating they would have the procedure again. In contrast, patients with decompression alone were less satisfied with 64 and 55 % positive response to the same questions, respectively.

Complication rates for traditional open (anterior/posterior) approaches are reported in the literature to range from 25 to 80 % [14, 15]. Charosky et al. [56] recently reported on a multicenter retrospective study ($n=306$) where all the patients

were operated for either adult idiopathic or degenerative scoliosis and had no history of spinal surgery. Overall complication rate was 39 %, and 26 % of the patients were reoperated for mechanical or neurological complications.

Weistroffer et al. [57] reported complications rates in 50 patients with long fusions to the sacrum for adult scoliosis with a minimum of 5-year follow-up. Perioperative complications included nerve root deficits in six patients, four of whom recovered spontaneously; deep wound infection requiring debridement and long-term antibiotics in 12 % of patient; and approximately 25 % minor complication rate including dural tear (10 %), postoperative ileus (4 %), pleural effusion (4 %), coagulopathy, cardiac arrhythmias, and acute renal failure. Long-term complications included pseudarthrosis in 24 % (50 % in patients specifically with degenerative scoliosis), symptomatic hardware requiring implant removal in 22 % of patients, and implant loosening or fracture in 18 % of patients.

Zimmerman et al. [58] reported prospectively collected data on 35 patients aged 40 years or older undergoing primary surgery for adult scoliosis with a minimum of 2-year follow-up. Patient reported outcome data demonstrated improvement in disability and function. However, the overall complication rate was 49 %. Major complications occurred in 26 % of patients, including pulmonary embolism, retroperitoneal hematoma, pseudarthrosis, sacral fracture, and deep infection. Minor complications including transient brachial plexus or peroneal nerve injury, pneumothorax, atrial fibrillation, splenic laceration, dural tear, pleural effusion, and urinary tract infection occurred in 31 % of patients.

It is important to keep this high complication rate of open surgery in mind as the minimally invasive options highlighted below are discussed. With the introduction of endoscopic and mini-open techniques for both anterior column fusion and posterior interbody fusion/pedicle screw technology, the field of spine surgery is moving decidedly toward lessening approach-related morbidities through the use of these more minimally invasive techniques.

Anterior Approaches

Anterior lumbar interbody fusion (ALIF) has been a reliable adjunct for the treatment of adult spinal deformity. Thorough release of contracted tissues and osteophytes, preparation of the interbody space, and placement of structural graft, anterior column support is more directly achieved. ALIF allows for improved sagittal alignment and offers a larger surface area for fusion. In addition, compared to posterior procedures, ALIF results in decreased perioperative blood loss and no need for neural retraction [59]. It has also been shown that ALIF procedures have shorter operating times than posterior lumbar interbody fusions (PLIF) with or without pedicle screw instrumentation [60]. These advances have led to shorter hospitalization times and comparable fusion rates [61]. It should be noted that anterior access of the lumbar spine is not without risk. Postoperative ileus is the most common complication following the anterior approach [62]. Fortunately, this will usually resolve with medical management. Incisional hernias, either true or pseudo, can occur if closure of the abdominal wall fascia fails, or the motor nerves supplying the abdominal wall musculature is injured. Significant vascular injury has been reported to occur in between 2 and 4 % of cases [63]. Retrograde ejaculation from injury to the sympathetic hypogastric plexus has been reported to occur in as high as 45 % of cases; however, the true rate is likely between 5 and 10 % of the case using modern techniques [64]. Anterior approaches to adult scoliosis have been shown to be useful in release of a rigid deformity, improvement of sagittal alignment, and gaining effective arthrodesis of the spine. A combined anterior and posterior approach for the treatment of adult scoliosis has been advocated for improvement of lumbar lordosis and improvement of fusion rates, especially at the lumbosacral junction [65, 66]. Relative indications for a combined anterior and posterior approach to adult scoliosis include hypolordosis, large curve magnitudes, posterior-element deficiency, pseudarthrosis, and poor quality bone (particularly at the lumbosacral junction).

Combined anterior and posterior surgery in adult deformity has resulted in good clinical outcomes and radiographic corrections. Berven and colleagues [67] reported their results of combined anterior and posterior surgery in 25 adults with scoliosis and significant sagittal-plane deformity. They demonstrated effective deformity correction in both the coronal and sagittal planes with high rates of patient satisfaction. To note, however, 40 % of patients had perioperative or late complications, including wound infection, dural tears, pneumonia, and pseudarthrosis. Similar high complication rates utilizing a combined approach for adult deformity surgery have been reported in other studies [17, 68, 69].

Lateral Transpsoas Lumbar Interbody Fusion

Lateral transpsoas lumbar interbody fusion is a minimally disruptive modification of the traditional ALIF procedure that has gained popularity in recent years. As described by Ozgur et al. [70], the spine is accessed by traversing the psoas muscle overlying the intervertebral discs via a retroperitoneal approach. The procedure can be safely performed without the assistance of an access surgeon through one or two 3–4 cm incisions and does not require violation of the peritoneal cavity or manipulation of the great vessels. Hence, many of the complications typically associated with traditional ALIF surgery are avoided.

The lateral transpsoas approach allows for placement of a wide-footprint intervertebral implant that rests on the peripheral ring apophysis of the vertebral body. The interbody distraction achieved can provide significant indirect neural decompression and deformity correction and achieve interbody fusion with a relatively atraumatic surgical approach. It should be noted that lateral interbody fusion for adult scoliosis can be more complicated than that of degenerative spinal conditions due to the three-dimensional deformity inherent to the condition. The application of transpsoas lateral lumbar interbody fusion to adult lumbar DS was first reported by Phillips in 2005 [71]. Currently, lateral interbody fusion is applied as part of a minimally invasive surgical strategy in the management of adult scoliosis as an anterior-only procedure, in combination with a percutaneous posterior procedure, or in combination with more extensive open posterior procedures to achieve neural decompression and restore sagittal and coronal balance.

There are numerous important nervous and vascular structures at risk of injury when approaching the spine laterally through the retroperitoneum. As can be expected, the anatomic course of all of these structures may be altered in the setting of spinal deformity. Regev et al. [72] reported that as the vertebral body rotates toward the convexity the vessels rotate oppositely toward the concavity. The psoas covers less of the vertebral body and lies more posterior on the concavity. The superficial sensory nerves also take the same course, which is why they are more prone to injury. Again, a detailed review of preoperatively obtained magnetic resonance imaging or computed tomography scan is essential in understanding the location of the vasculature and other structures during the lateral approach.

Most surgeons recommend approaching the spine from the concavity of the deformity when performing lateral interbody fusion [73]. This provides several advantages. The concavity of the curve is the site of foraminal narrowing, bony compression, and soft tissue contracture. A more extensive release here will theoretically allow for improved deformity correction and, more importantly, restoration of foraminal height and indirect neural decompression. In addition, approaching from the concavity allows for access to more levels through fewer incisions and provides an easier approach to L4–L5 where the iliac crest typically obstructs access from the convexity. Finally, breaking the table with the concavity up will facilitate intraoperative correction of scoliosis.

Isaacs et al. [74] prospectively studied 107 patients (mean age 68 years) treated with lateral interbody fusion for DS. A mean of 4.4 levels per patient (range, 1–9) were treated. Supplemental pedicle screw fixation was used in 75.7 % of patients, 5.6 % had lateral fixation, and 18.7 % had stand-alone lateral interbody fusion. Mean operative time was 178 min (58 min/level) and blood loss 50–100 mL. Mean hospital stay was 2.9 days for single-stage combined anterior and posterior surgery. Major complications occurred in 13 patients (12.1 %): 2 (1.9 %) medical, 12 (11.2 %) surgical. Of procedures that involved only less invasive techniques (stand-alone lateral interbody fusion with or without percutaneous instrumentation), 9.0 % had one or more major complications. In those with supplemental open posterior instrumentation, 20.7 % had one or more major complication. Early reoperations were required in three patients (all for deep wound infections), all of whom had undergone open posterior instrumentation procedures. Twenty-nine patients had isolated postoperative hip flexor weakness felt to be related to passage of retractors through the psoas muscle to access the spine. By the 6-month examination, 82.1 % of those with 1 grade of weakness initially had fully resolved. Only one patient had a major weakness of the proximal muscles (<4/5) of the lower extremity (0.9 % of cases, or 0.3 % of levels approached). This improved to 4/5 by the 6-month visit.

Dakwar and colleagues [75] reported on their early outcomes of treating 25 patients with adult scoliosis (mean 62.5 years old) using the lateral interbody fusion technique. The mean total blood loss was 53 mL per level and the average length of stay in the hospital was 6.2 days. Mean follow-up was 11 months. Patients did well subjectively, with a mean improvement of 5.7 points on VAS scores and 23.7 % on the Oswestry Disability Index (ODI). Three patients (12 %) experienced transient postoperative anterior thigh numbness, ipsilateral to the side of approach. All of the patients who had follow-up for more than 6 months were found to have radiographic evidence of fusion by CT scan.

Diaz et al. [76] reported on 39 (mean age 68 years) patients who underwent lateral interbody fusion for the treatment of symptomatic DS. Four patients included additional internal fixation. Lateral interbody fusion was performed at one to four lumbar levels. Patients were followed clinically and radiographically for up to 3 years postoperatively. Mean operative time was 125 min, and blood loss was less than 50 cc. Patients were typically out of bed and ambulating on the day of surgery and were discharged next day. There were no procedural complications. Mean VAS score decreased from 9.1 preoperatively to 4.6 at 3 years. ODI score improved from 49 preoperatively to 23 at 3 years. Deformity was corrected from a mean of 18–8°, and lumbar lordosis improved from a mean of 34–41°.

Akbarnia et al. [77] also reviewed their experience of patients with DS (minimum 30°) who underwent anterior reconstruction with lateral interbody fusion followed by a formal posterior open approach. All 16 patients had minimum of 2-year follow-up with significant improvements seen in all clinical parameters, including VAS, ODI, and SRS-22 scores. They also found good deformity correction,

with an average of 45 % coronal deformity correction with lateral interbody fusion alone and nearly 70 % correction after second-stage posterior instrumentation and fusion (at 2 years follow-up). Lumbar lordosis improved from 31° preoperatively to 44° postoperatively. Coronal L4 tilt improved to 10° from 23° preoperatively. Temporary paresthesias were reported among 9 of the 16 patients. Of these, 2 of the patients had persistent symptoms at 2-year follow-up.

A prospective nonrandomized clinical study on the indirect decompressive effect of lateral interbody fusion was reported by Oliveria et al. [78] Consecutive patients ($n=21$) presenting with degenerative conditions (including DS) that also had concomitant lumbar stenosis were treated via stand-alone lateral interbody fusion. Substantial dimensional improvement was found in 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. These data suggest that it appears that interbody distraction through lateral interbody fusion is an effective mechanism for achieving indirect decompression in patients with DS who present with symptomatic stenosis. This study was limited by the short follow-up period as the imaging was obtained only 1 month postoperatively. The authors do concede that some interbody cage subsidence is likely to occur and may have a negative effect on the longevity of the indirect decompression.

While there is some variety in how lateral interbody fusion is applied to patients with adult scoliosis, the senior author uses the following treatment algorithm. After a multilevel lumbar lateral interbody fusion is performed, the patient is encouraged to mobilize out of bed with the use of a brace. If the preoperative neurogenic symptoms are resolved, postoperative sagittal and coronal alignment is acceptable on long films, and the bone quality is felt to be adequate without violation of the end plates during disc space preparation, either stand-alone interbody fusion or more commonly supplemental percutaneous screw fixation as a second-stage surgery is performed. In cases where the end plate was violated during the lateral procedure, there is residual spondylolisthesis, or poor bone quality, supplemental fixation with pedicle screws is recommended. If neurogenic symptoms persist, or further deformity correction is necessary, the patient is brought back to the operating for a direct spinal decompression and/or an open posterior fusion procedure. The second procedure is usually staged 2–3 days after the initial surgery.

AxiaLIF

As discussed above, it may be necessary to include the L5–S1 level as the distal extent of fusions for scoliosis. It has been shown that there is a relatively high rate of pseudarthrosis (and other complications) after posterior L5–S1 fusion in this setting [79, 80]. Augmentation of the lumbosacral posterior reconstruction in long constructs with anterior column support in the form of interbody fusion at L5–S1 improves biomechanical stability [81] and reduces the risk of lumbosacral pseudoarthrosis [82]. Due to anatomic consideration, it is not possible to achieve interbody fusion at L5–S1 with either a lateral transpsoas or endoscopic anterolateral approach.

Percutaneous, paracoccygeal axial fluoroscopically-guided lumbar interbody fusion (AxiaLIF, Trans1 Inc.) is a procedure developed to achieve interbody fusion between L4 and S1, through a percutaneous approach traversing the presacral space. This technique was originally described by Cragg et al. [83].

AxiaLIF utilizes the concept of axial implants that have been used previously in open spine surgery in the form of parasagittal fibular struts, keyhole interbody rods, and vertebral body replacement devices [84–86]. Axial implants are unique in that they are placed with minimal dissection of the surrounding structures. The annulus of the targeted level's disc is even left completely competent. Until the advent of the AxiaLIF approach, the use of these axial implants has been limited by the fact that an open surgical approach was required.

Aryan et al. [87] reported on their experience with 35 patients (mean age 54 years) who underwent AxiaLIF with an average follow-up of 17.5 months. Six of these patients specifically had DS. All patients underwent an AxiaLIF with cage, local bone autograft, and rhBMP. Twenty-one patients underwent AxiaLIF followed by percutaneous L5–S1 pedicle screw-rod fixation. Two patients underwent AxiaLIF followed by lateral interbody fusion and posterior instrumentation. Ten patients had a stand-alone procedure. Overall, 91 % had radiographic evidence of stable L5–S1 interbody cage placement and fusion at the last follow-up. Clinically, both VAS and ODI scores were significantly improved postoperatively. The results of the subgroup of patients with DS were not reported separately.

Although short-term follow-up shows a high fusion rate with low revisions, long-term results have yet to be determined. To date few studies have been performed specifically for patients with adult scoliosis. Some surgeons caution that with severe degeneration (i.e., bone on bone), AxiaLIF should not be used, as sufficient distraction and restoration of L5–S1 lordosis may be difficult to achieve. Also, patients with previous pelvic surgery should not undergo AxiaLIF, as the presacral corridor may be scarred down.

Posterior Approaches

Traditional surgical treatment of severe rigid adult spinal deformities has consisted of an anterior procedure

performed through either a thoracotomy or thoracoabdominal approach followed by posterior instrumentation and fusion. With the advent of new instrument techniques and increasing experience with placing segmental pedicle screws, using multiplanar osteotomies, and transforaminal lumbar interbody fusion (TLIF), many surgeons have trended away from the use of anterior surgery for the treatment of adult scoliosis. At this point, a significant portion of adult spinal scoliosis is treated via an all-posterior surgical approach, with the use of segmental pedicle screw fixation, spinal osteotomies, and transforaminal lumbar interbody fusions as needed to achieve decompression and correct deformities. Posterior fixation alone with the use of modern surgical techniques and implants has demonstrated similar correction rates to that of anterior release and posterior fusion in adolescent scoliosis [88]. It has also been shown to have similar deformity correction as combined anterior/posterior fusion for the treatment of adolescent idiopathic scoliosis curves more than 90° [89, 90].

Pedicle screws allow segmental fixation of individual vertebrae and subsequent correction in multiple planes of a scoliotic deformity [91, 92]. Pateder et al. [93] advocated using a posterior-only approach to adult lumbar DS in curves less than 70°, but this took into account extensive posterior releases through a large open approach. There is a paucity of information in the literature providing specifics addressing these same questions (posterior-alone vs. anterior-alone vs. combined circumferential fusion) for minimally invasive surgery.

Summary and Selection of Surgical Techniques

In order to adequately address a particular patient's pathology, the correct surgical technique or combination of techniques must be selected when planning surgical intervention. A case example employing some of the techniques discussed in this chapter is provided in (Fig. 29.4).

Careful consideration of the patient's symptoms and radiographs is necessary in order to ensure the highest chance of success. Silva and Lenke propose six distinct levels of operative intervention for patients with adult scoliosis ranging from decompression alone to thoracolumbar fusions with vertebral osteotomies [94].While their treatment algorithm describes traditional open surgical techniques, the principles can be applied to the minimally invasive strategies discussed in this chapter (Fig. 29.5). The presence of neurogenic symptoms due to stenosis requires a decompression, which can be achieved directly or indirectly. Direct decompression alone should only be reserved for those without significant back pain, minimal deformity, and no instability. If significant back pain, deformity, and/or instability are present, addition of a fusion is indicated. An adequate decompression can often be achieved indirectly with lateral interbody fusion while simultaneously stabilizing the spine and reducing the deformity. Lateral interbody fusion may be left as a standalone construct if neurogenic symptoms resolve, bone quality is adequate and global balance is acceptable. When these criteria are not met, posterior instrumentation with or without direct decompression should be performed. If augmented stability is the primary goal of posterior instrumentation, then it is reasonable to consider a percutaneous pedicle screw fixation. However, if further deformity correction is necessary to restore sagittal or coronal balance, then a formal open posterior fusion should be considered. When the deformity (Cobb angle <30°) and instability (<2 mm of subluxation) are moderate in severity, a limited fusion of the most significantly affected levels can be considered. However, if more extensive deformity (Cobb angle >30°) and instability (>2 mm of subluxation) are present, fusion of the entire curve is generally recommended to address back pain and reduce the rate of rapid adjacent segment degeneration and recurrent stenosis. According to Silva and Lenke's algorithm, a combined anterior and posterior fusion is generally recommended for patients with lumbar kyphosis and those at risk for failure of a posterior-only construct. These issues are both well addressed by lateral interbody fusion. In fact, the substantial release achieved during lateral interbody fusion and the use of either coronally or sagittally tapered implants may also obviate the need for traditional posterior osteotomies which are often recommended in rigid or severe scoliosis cases. When fusion to the sacrum is necessary, pedicle screw fixation with anterior interbody support is highly recommended. As the L5–S1 disc is not accessible using the lateral transpsoas interbody technique, fusion to the sacrum can be achieved by either an open or minimally invasive posterior approach with TLIF and/or iliac fixation or via presacral axial interbody fusion. If global imbalance is present, or kyphosis extends beyond the lumbar spine, the fusion should be extended into the thoracic spine. This can be achieved via lateral interbody fusion or posterior techniques.

Anand et al. [95, 96] demonstrated the utility of combining multiple minimally invasive approaches for the surgical treatment of adult scoliosis. Their 2-year follow-up was reported for adult scoliosis curves with an average Cobb angle of 22°. They used a combination of three techniques: extreme lateral interbody fusion, AxiaLIF, and percutaneous screws posteriorly. Average blood loss was 241 mL for the anterior surgery and 231 mL for the posterior portion. Coronal Cobb angles improved from 22° to 7° at their final follow-up. VAS and ODI improved from 7.05 and 53.5 to 3.03 and 25.88, respectively. The overall complication rate was 21 %, which compares favorably to historic controls. This study demonstrates how a combination of some of the abovementioned minimally invasive techniques can be effectively applied to challenging adult deformity cases.

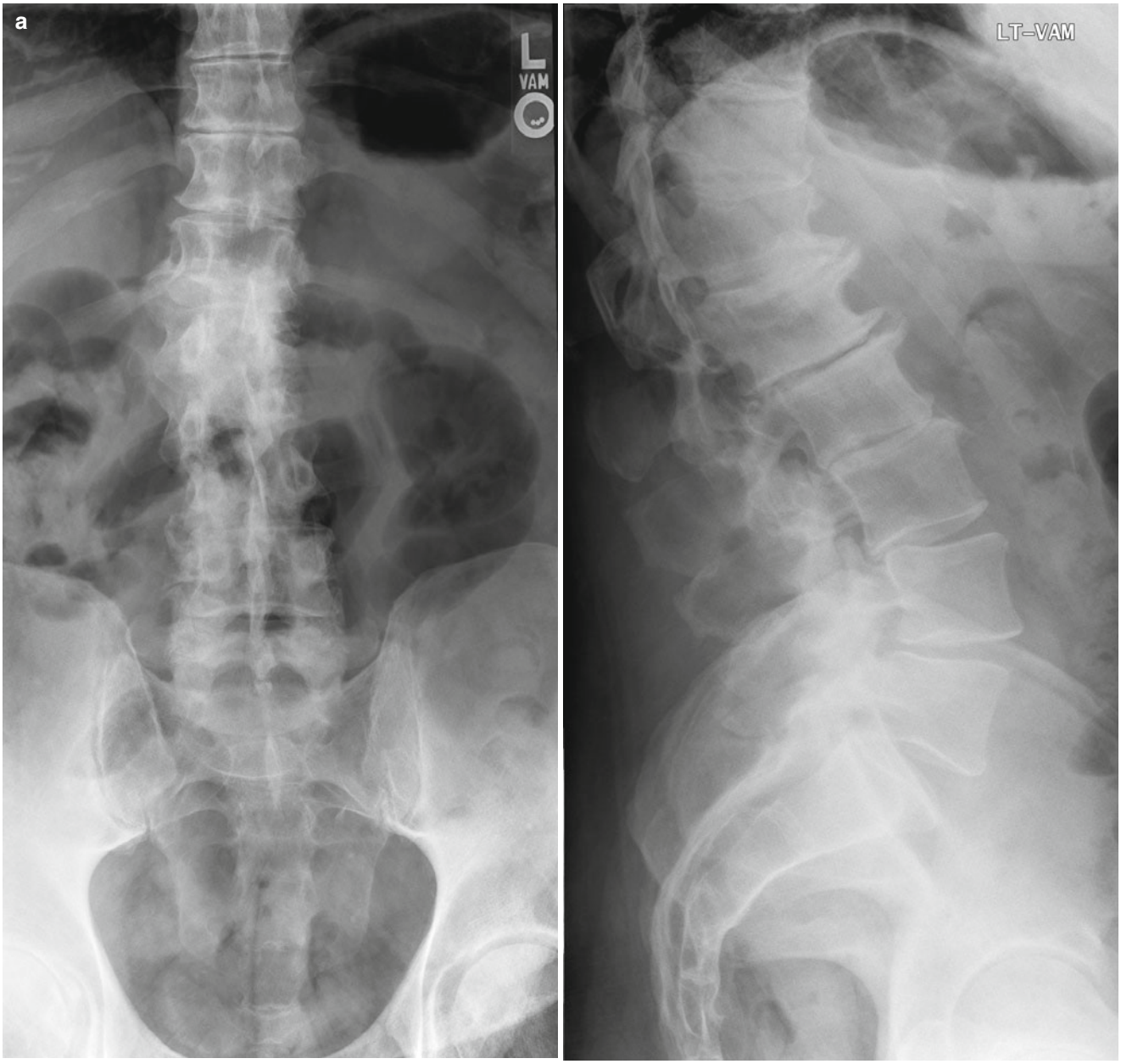


Fig. 29.4 Case example: lateral interbody fusion for kyphoscoliosis: (**a**) 63-year-old man presented with back pain, bilateral radiculopathy, and progressively kyphotic posture. He failed conservative management and elected to undergo surgical intervention. Preoperative X-rays reveal disc degeneration with lumbar scoliosis and kyphosis. (**b**) MRI revealed foraminal and lateral recess stenosis at the levels of scoliotic deformity. (**c**) X-rays after a staged T12 to L5 transpsoas lateral interbody fusion followed by percutaneous pedicle instrumentation from T11 to L5 with T11 to 12 minimally invasive posterior fusion. The indirect decompression achieved from the lateral interbody fusion relieved radicular symptoms, so no open decompression was necessary. Blood loss for the combined procedures was approximately 300 mL, and there were no major perioperative complications

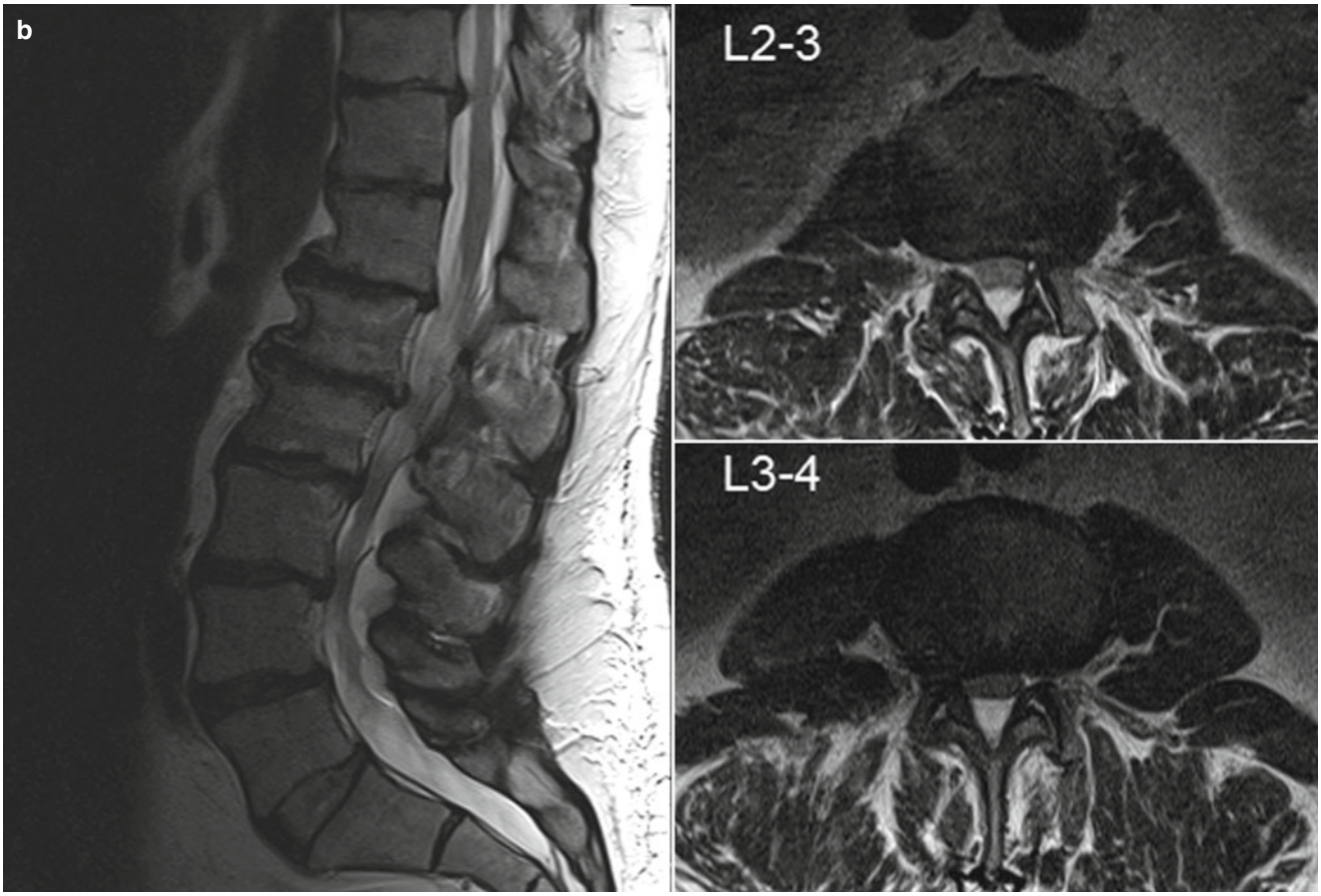
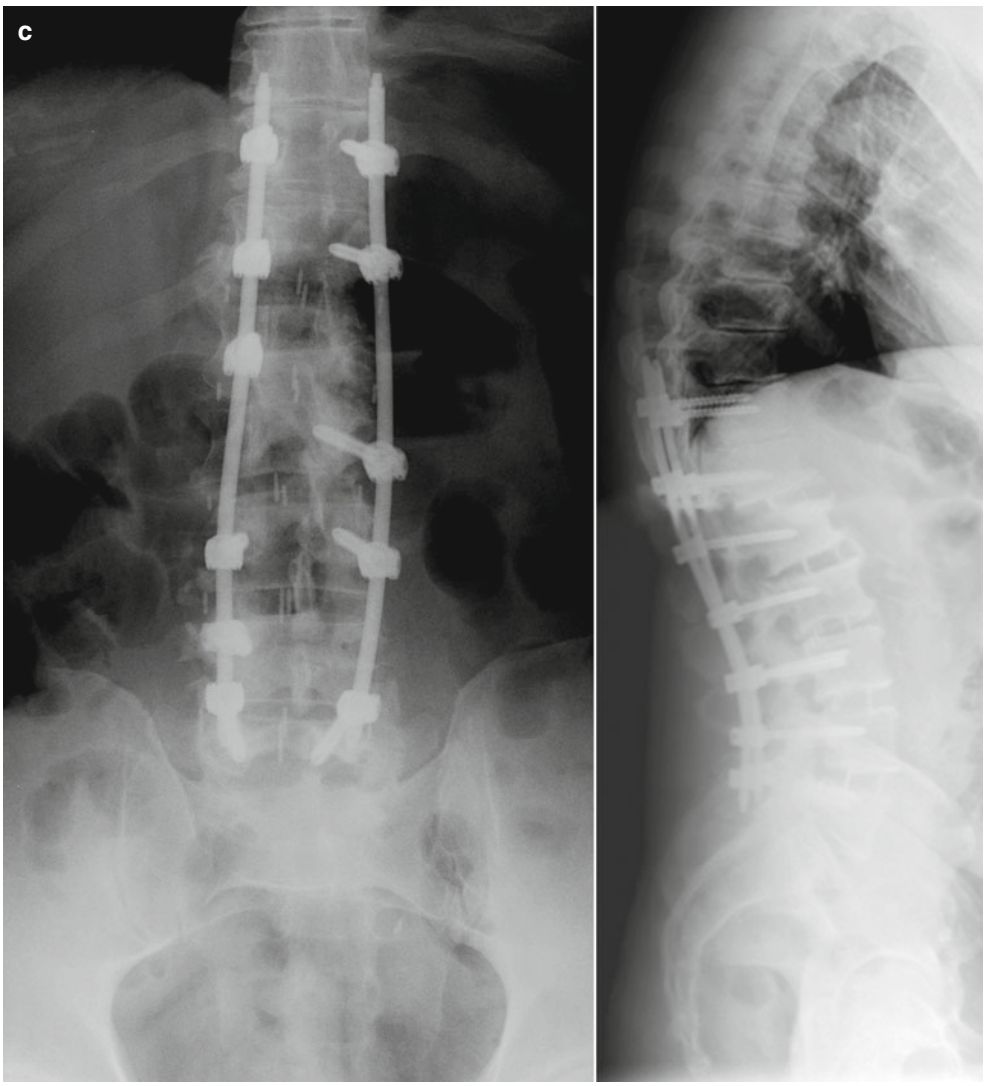


Fig. 29.4 (continued)

Fig. 29.4 (continued)



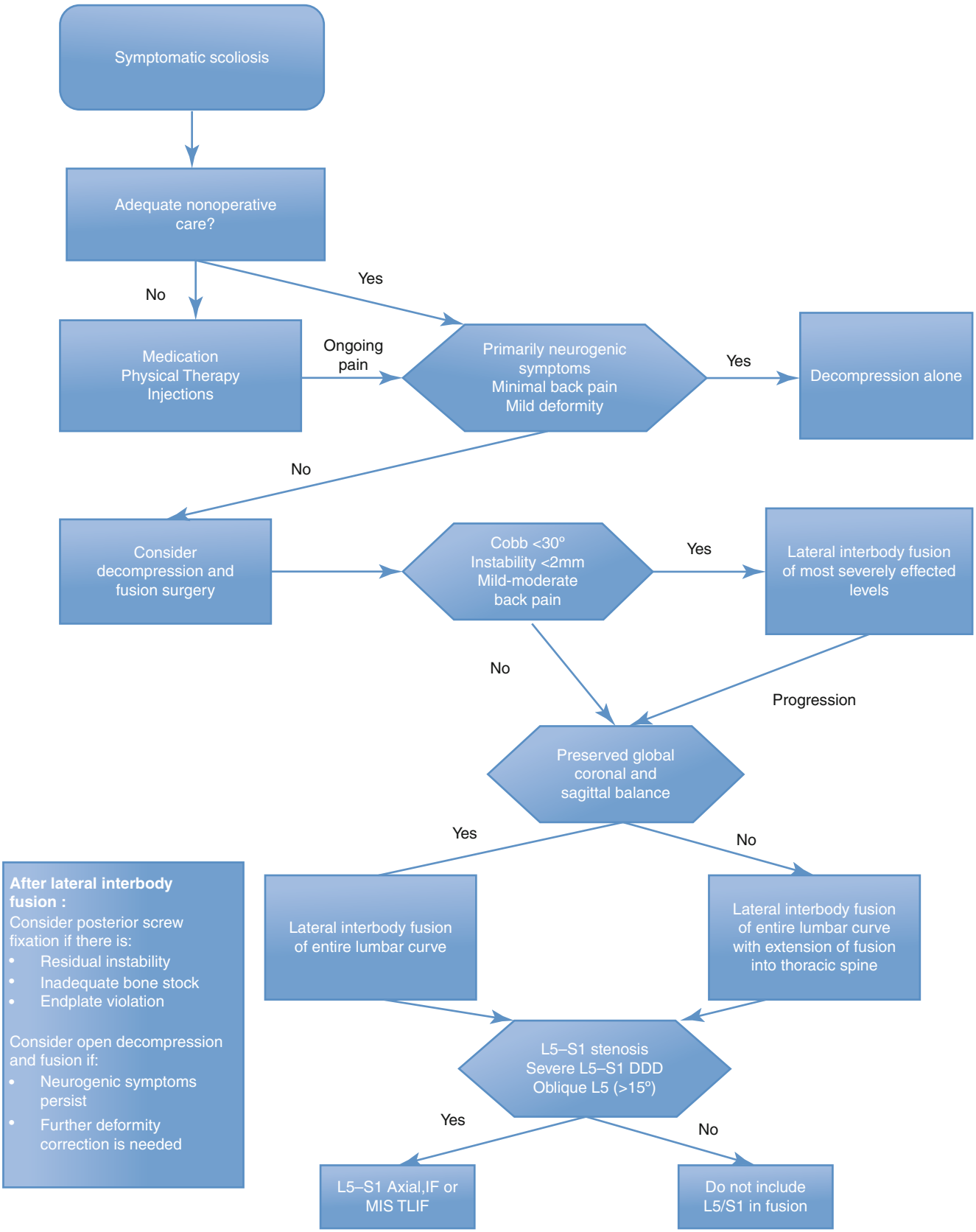


Fig. 29.5 A proposed algorithm for the treatment of adult scoliosis using the minimally invasive techniques discussed in this chapter

Conclusion

There are a variety of approaches and techniques employed in the surgical treatment of adult scoliosis. As has been demonstrated in this chapter, these techniques are in a state of constant evolution. The recent trend toward the application of minimally invasive surgical techniques to this challenging population may provide significant advantages, but leaves many unanswered questions. Much of the current literature reports result in small series of patients, and there is little that directly compares the results of minimally invasive versus those of traditional open procedures. In applying these novel techniques, it is important to remember that while minimally invasive surgery may offer reduced perioperative morbidity, these methods should only be employed if they can effectively and safely accomplish the necessary surgical goals. Depending on the characteristics of the patient's particular pathology, a combination of multiple approaches is often necessary. As these techniques continue to evolve, future studies will clarify questions such as long-term complications along with the effects of specific curve types and comorbidities. This data should also afford the development of better classification systems that will provide the surgeon with specific, validated treatment algorithms to ensure the ideal treatment for patients with adult scoliosis.

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Anterior Column Realignment (ACR): Minimally Invasive Surgery for the Treatment of Adult Sagittal Plane Deformity

30

Gregory M. Mundis Jr., Nima Kabirian, and Behrooz A. Akbarnia

Introduction

Treatment of adult spinal deformity is a complex decision-making process involving not only spine-specific parameters but also taking into account the general health of the patient in order to end up with a successful outcome. Restoration of normal sagittal plane alignment is arguably the most important surgical goal in maintenance of long-term clinical success.

Technological advancements and our rapidly growing knowledge of adult spinal deformity over the last two decades have shifted the treatment from non-operative palliative treatment to surgical approaches to improve function and quality of life. Diminished physiologic reserves and high perioperative complication rates have mandated less invasive techniques to address adult sagittal plane deformities. Regardless of technique the basics of deformity surgery must still be adhered to, i.e., decompression of neurological elements, realignment of the spine, stable fixation, and arthrodesis.

Normal Sagittal Alignment

Numerous indices have been defined and studied to guide treatment and outcome and include three broad categories: (1) regional and global sagittal curvatures, (2) pelvic parameters, and (3) sagittal spinal balance.

Bernhardt and Bridwell [1] retrospectively reviewed the lateral radiographs of the spine from 102 healthy individuals (age range: 4.6–29.8 years) with no spinal pathology and found that the mean thoracic kyphosis from T3 to T12 was 36° (standard deviation [SD]=±10°) with the apex at T6–T7 disc, and the mean lumbar lordosis from L1 to S1 was 44° (SD=±12°) with apex at L3–L4 disc. He also found the mean upper thoracolumbar junction (T10–T12) Cobb angle was 5.5° of kyphosis (SD=±4°), and the mean lower thoracolumbar junction (T12–L2) Cobb angle was of 3° of lordosis (SD=±7°). The means for sagittal alignment were different by age and sex.

Gelb et al. [2] in a similar study reviewed the sagittal alignment in 100 adult patients (mean age of 57±11 years). The mean sagittal vertical axis (SVA) was −3.2 cm (SD=±3.2). The mean upper thoracic kyphosis (T1–T5) was 14° (SD=±8°), and the mean lower thoracic kyphosis (T5–T12) was 34° (SD=±11°). Mean total lumbar lordosis from the inferior end plate of T12 to the superior end plate of S1 was −64° (SD=±11°). There was no significant difference in SVA, thoracic kyphosis, and lumbar lordosis between men and women. There was also no significant change in thoracic and thoracolumbar kyphosis related with age; however, there was a significant correlation between total lumbar lordosis and age.

Pelvic incidence (PI), pelvic tilt (PT), and sacral slope (SS) are three essential pelvic parameters to be considered in preoperative planning of the spinal sagittal plane reconstruction. The normative values for these three variables in different age groups have been studied by Schwab and Lafage et al. [3]. They used a multilinear regression analysis and developed a formula to predict the SVA and PT of the patient based on the pelvic incidence (PI), thoracic kyphosis (TK), and lumbar lordosis (LL) [4].

Pelvic incidence (PI) is a morphological constant in each person once skeletal maturity is achieved. PT and SS are positional variables that change as necessary to compensate for a positive sagittal balance.

Duval-Beaupere et al. [5] found the geometrical equation describing the relationship between these three pelvic parameters; PI=PT+SS. Berthonnaud et al. [6] suggested that parameters of the adjacent zones of spinopelvic axis (tho-

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racic, lumbar spine, and pelvis) are interdependent. These relationships essentially dictate the resultant adult sagittal alignment and compensatory mechanisms.

Pelvic tilt (which is representative of the pelvic version) and the unfused thoracic spine are two important compensatory mechanisms that counteract progressive hypolordosis of the lumbar spine and sagittal imbalance. Individuals who pathologically lose control of their sagittal alignment (loss of lumbar lordosis, focal kyphotic deformity, fracture, tumor, post-laminectomy, etc.) will experience a reciprocal amount of pelvic retroversion and PT increase to draw the cranium back over the pelvis and reduce the positive balance. Moreover, the unfused thoracic spine may lose its normal kyphosis to restore global alignment [7].

The Clinical Impact of Sagittal Malalignment

Glassman et al. [8] studied 298 operative patients, 126 with previous spine surgery, and adult spinal deformity in order to correlate these parameters with health-related quality of life outcomes. The authors found that patients with positive sagittal balance (SVA >5 cm) had worse outcomes compared to patients with a normal sagittal balance. Patients with a positive sagittal balance had worse scores in pain, function, self-image, and social function regardless of their surgical history. The authors concluded that positive sagittal balance is the most important and reliable radiographic predictor of worsened clinical health status in both groups with or without previous spine surgery.

Glassman later [9] demonstrated that worsening pain and decreasing function is correlated linearly with increasing magnitude of sagittal imbalance. All measures of health status (SF-12, SRS-22, and ODI) showed significantly poorer scores as C7 plumb line deviation increased. Also, comparison across the entire range of curve location showed that a more distal region of maximal kyphosis generated higher disability on ODI ($P<0.05$).

Classification

Several classifications have been created for adult spinal deformity. Bridwell et al. [10] described three different types of sagittal imbalance in adults. Type I consists of regional sagittal deformity (thoracic/thoracolumbar hyperkyphosis or lumbar hypolordosis), with maintained global sagittal balance (within 5 cm) with hyperextending the remaining mobile segments distal to the regional deformity. Coronal imbalance is less than 5 cm. Type II includes patients with maintained coronal balance but decompensated sagittal balance through the remaining mobile segments. Type III includes patients with global sagittal and coronal malalignment and no intact segments to compensate for the deformity.

Table 30.1 SRS-Schwab classification of adult spinal deformity [12]

Coronal curve modifiers	Sagittal modifiers	
T: *Thoracic Only* With lumbar curve <30°	PI minus LL	
	0	Within 10°
	+	Moderate 10–20°
	++	Market >20°
L: *TL/Lumber only* With thoracic curve <30°	Global alignment	
	0	SVA <4 cm
	+	SVA 4–9.5 cm
	++	SVA >9.5 cm
D: *Double curve* With T *and* TL/L curves >30°	Pelvic tilt	
N: *No major coronal deformity* All coronal curves <30°	0	PT <20°
	+	PT 20–30°
	++	PT >30°

LL lumbar lordosis, *PI* pelvic incidence, *PT* pelvic tilt, *SVA* sagittal vertical axis

Lowe et al. [11] reported and validated the SRS classification for adult spinal deformity built on King/Moe and Lenke classification systems for adolescent idiopathic scoliosis. Despite the fairly comprehensive inclusion criteria and good interobserver reliability, modifiers were not correlated with patient-reported outcomes. Furthermore, this classification did not address the sagittal plane as the primary deformity. The expansion of our knowledge of the role of the pelvis and its importance in surgical planning and patient-reported outcomes has prompted the need for a classification that builds on these principles.

The SRS-Schwab classification [12] has recently been validated. Three modifiers have been defined to guide the management of adult sagittal deformity and were shown to correlate health-related quality of life measures. This classification identifies four different curve types, three coronal and one sagittal: (1) T, thoracic (with lumbar curve <30°); (2) TL/L, thoracolumbar/lumbar (with thoracic curve <30°); (3) D, double (at least 30° deformity of T, T/L or L curves); and (4) S, sagittal (coronal deformity <30° but with moderate to severe modifiers). Three different sagittal modifiers exist to further describe the deformity: (1) lumbar lordosis minus pelvic incidence, (2) pelvic tilt, and (3) global balance (Table 30.1). Schwab et al. [7] showed that to achieve a successful outcome after surgery, radiographic outcomes should include LL within 10° of pelvic incidence, PT <25°, and SVA <50 mm.

Is "Minimally Invasive Surgery (MIS)" Worth It?

The question arises if there is a role for MIS in adult sagittal deformity. Complications of traditional open anterior- and/or posterior-based techniques for correction of adult spinal deformity have been well described. These include but not

limited to excessive blood loss, higher infection rates, vascular injury, neurological injury, instrumentation failure, as well as significant medical morbidities including pulmonary embolism, cerebrovascular accident, myocardial infarction, sepsis, and finally death. Auerbach et al. [13] reviewed the results and major complications of 3-column osteotomy in 105 consecutive patients with adult spinal deformity. Major complications occurred in 35 % of 3-column osteotomies including 38 % of PSO and 22 % of VCR. 15.2 % experienced a major medical complication and 24.8 % a major surgical complication.

Cho et al. [14] compared the outcomes and complications of primary ($n=126$) versus revision ($n=124$) adult spinal surgery. The authors reported a complication rate of 45.2 % with primary surgery and 58.2 % in revision spinal surgery. They also found that patients with primary surgery had higher initial and final scores on SRS and ODI questionnaires. Several risk factors were identified including higher body mass index, number of final instrumented levels, fusion to the sacrum, osteotomy, length of surgery, and estimated blood loss.

In a separate study in 2012, Cho et al. [15] reported on major complications of revision spinal surgery among 166 patients over 3.5 years. Estimated blood loss >2,000 mL and pedicle subtraction osteotomy (PSO) were the only two intraoperative risk factors associated with perioperative (<6 weeks) and long-term follow-up complications. Overall, complications occurred in 50 % of the patients after multilevel revision surgery for adult deformity.

Neurological complications in a series of 108 consecutive patients after lumbar PSO were reported as 11.1 % over a 10-year period by Buchowski et al. [16]. Neuromonitoring (SSEP, MEP in all, and EMG in select cases) was used but failed to note the intraoperative deficits. Neurological deficits were most commonly observed in degenerative sagittal imbalance group (16 %; 5/32), of which 2.8 % were permanent.

Patient Selection

Selection of the right patient for less invasive procedures to correct the kyphotic deformity is complex and depends on multiple factors including the region of spinal deformity, number of levels involved (focal vs. regional vs. global sagittal deformity), severity of deformity, previous surgery, and flexibility of focal kyphosis.

The transpsoas lateral lumber interbody fusion (LLIF) is best used for correction of focal or regional kyphosis at or between T12–L1 and L4–L5 discs. This technique has been infrequently used for T11–T12 or even higher thoracic levels with resection of the corresponding rib. The presence of the iliac wings precludes the access to L5–S1.

For regional kyphosis, multiple levels can be approached and treated with LLIF. Also, depending on the severity of the regional deformity, this technique can be supplemented with posterior-based osteotomies (e.g., Ponte osteotomy) at one or multiple levels to achieve the desired correction. Focal kyphosis with significant spinopelvic imbalance may require more deformity correction than can be achieved with single or multilevel LLIF. Lordotic (10°) and hyperlordotic (20° or 30°) cages are invaluable tools for this purpose. Moreover, the LLIF technique can be supplemented with a release of the anterior longitudinal ligament (ACR) or pedicle subtraction osteotomy (PSO).

Surgical planning is essential to achieve desired postoperative spinopelvic alignment. Various software platforms and measurement techniques exist to plan, and the surgeon should employ these in an attempt to achieve the desired outcomes. Ultimately, it is the surgeon's responsibility to restore sagittal alignment and spinopelvic harmony and not rely on a particular implant to do the job. The limit of sagittal deformity correction via minimally invasive techniques still remains to be defined.

Minimally Invasive Surgery in Correction of Sagittal Spinal Deformity

Initial studies of minimally invasive surgery (MIS) for management of adult spinal deformity were mainly focused on correction of coronal deformity, reducing the blood loss and hospital stay and minimizing the complications [17, 18]. The MIS literature on correction of sagittal spinal deformity through anterior, posterior, or combined MIS techniques lacks studies with large cohorts, long follow-up, or patients with significant sagittal deformity.

Previous reports either showed an unsatisfactory change in global lumbar lordosis [19–21] or reported the results of a subset of patients with mild (<5 cm) sagittal imbalance [22].

Acosta et al. reviewed a cohort of 36 patients with degenerative lumbar disease treated with minimally invasive direct lateral interbody fusion (DLIF) [20]. Despite the statistically significant correction in segmental sagittal deformity, the authors did not find further improvement of sagittal balance or lumbar lordosis.

Akbarnia et al. reported the results of lateral lumbar interbody fusion in 16 cases with advanced scoliosis (>30°) who underwent anterior reconstruction with lateral approach for interbody fusion followed by a formal posterior open approach with minimum 2-year follow-up [23]. The authors showed that the sagittal parameters on average improved by restoring more normal lordosis from 31° preoperative to 44° postoperative. Sagittal segmental alignment at the latest follow-up approached to the normal values proposed by Bernhardt and Bridwell [1] (Table 30.2).

Table 30.2 Correction of segmental sagittal alignment through lateral lumbar interbody fusion [23]

	Mean preoperative	Mean final	Normal alignment
T12–L1	−1°	+3°	+1°
L1–L2	+4.9°	−5.4°	−4°
L2–L3	−2.9°	−8.3°	−7°
L3–L4	−12.3°	−14°	−13°
L4–L5	−23.8°	−19.3°	−20°

Marchi et al. reported his results of LIF for symptomatic sagittal imbalance in eight patients with the use of lordotic cages without ALL release [24]. The mean preoperative sagittal parameters of the patients were focal lordosis of 2.3°, global lumbar lordosis of 17.7°, sagittal vertical axis (SVA) of 11.8 cm, and pelvic tilt of 35.2° which corrected to 27.1°, 39.9°, 6.2 cm, and 23.8° at the latest follow-up, respectively. Factors influencing segmental lumbar lordosis after lateral transpsoas interbody fusion were studied by Kepler et al. in 29 patients using 10° lordotic cages [25]. Mean segmental lordosis increased 3.7° at instrumented segments, increasing from 4.1° preoperatively to 7.8° postoperatively. Cage positioning (obliquity) and height were not significantly associated with change in lordosis. Anterior cage placement resulted in the largest lordosis gain (+7.4°/level), while posterior placement was prokyphotic (−1.2°/level). There were no significant associations with age, sex, or body mass index.

Le et al. also reviewed the segmental and regional correction of the sagittal plane in 35 patients who had undergone stand-alone transpsoas lateral interbody fusion with 10° lordotic cages [21]. Despite the improvement in segmental lordosis (11.1–13.6°), the global lumbar lordosis did not change significantly. The authors concluded that the use of hyperlordotic cages or transection of the ALL should be considered if significant correction of global lumbar lordosis is desired.

Uribe et al. studied the changes in lumbar segmental angles and lumbar lordosis in cadavers after LIF with or without ALL release and incremental increase in cage lordosis (10°, 20°, and 30°) [26]. Compared with baseline, the mean post-implantation increase in segmental lordosis in all levels combined was 0.9° in Intervention 1 (10° cage without ALL release), 4.1° in Intervention 2 (ALL release with 10° cage), 9.5° in Intervention 3 (ALL release with 20° cage), and 11.6° in Intervention 4 (ALL release with 30° cage). Following ALL release and placement of lordotic cages at all 4 lumbar levels, the average global lumbar lordosis increased 3.2° using 10° cages, 12.0° using 20° cages, and 20.3° using 30° cages.

Duekmedjian et al. reported their preliminary clinical experience of minimally invasive release of ALL in 7 patients for sagittal imbalance. The anterior construct stabilized posteriorly by placing pedicle screws, most commonly using a percutaneous technique [27]. The authors discovered a mean increase in global lumbar lordosis of 24°, increase in segmental lumbar lordosis of 17° per level of ALL released, and decrease in pelvic tilt of 7°. Sagittal vertical axis (SVA) decreased from 9 cm preoperatively to 4.1 cm at the latest follow-up (a 4.9 cm improvement). The authors concluded that the technique may be a feasible alternative for correction of adult sagittal deformity.

Surgical Technique: Anterior Column Realignment (ACR)

Anterior column realignment is a modification of the lateral transpsoas interbody fusion technique described in Chap. 18 with the use of specialized instruments and interbody cages for the treatment of sagittal deformity.

Standard lateral decubitus positioning with anterior/posterior and lateral fluoroscopic imaging is used to locate the disc space. Care is taken to limit excessive flexion of the operating room table to prevent excess tension on the psoas muscle and lumbar plexus. A standard lateral retroperitoneal approach is made to the disc space ensuring neuromonitoring signals indicate a safe passage. The target of the first dilator and guidewire is the posterior third of the disc space to ensure a complete release as well as facilitate the placement of the 22 mm interbody cage. Many transpsoas exposure systems and monitoring systems exist. The surgeon must be familiar with the particular characteristics of each. The author's experience is confined to the XLIF system (Nuvasive) that has instruments specifically designed for this procedure.

After sequential dilation is completed, the retractor is inserted and stabilized to the OR table with a mounting bracket. A shim or retaining pin can be used to secure its position and prevent anterior migration of the retractor. The retractor is opened enough to perform the initial discectomy and is not expanded anteriorly until this is completed. Also of note is that the retractor should be minimally expanded in the cephalad–caudad direction only enough to be on the margin of the disc space. A thorough discectomy is completed with release of the contralateral annulus and the disc space prepared for the appropriately sized implant. It is the author's experience that a 24 mm disc preparation is necessary to perform an ACR. Next, the retractor is expanded to visualize the anterior aspect of the annulus, which will appear to have a downward slope. Gentle anterior dissection is performed with a specialized curved Penfield. It is imperative to develop the plane directly anterior to the ALL in order to retract the anterior vascular structures and prevent injury. Once a plane has been developed, an anterior retractor is inserted under direct visualization and with fluoroscopy and secured to the existing retractor for stability. Fluoroscopy is used to confirm that the retractor reaches the contralateral pedicle. The retractor must be wide enough to ensure that it does not fall within the disc space after the ALL is divided.

Additional disc material is then removed from directly posterior to the ALL in order to isolate the ALL and facilitate safe division. Once the ALL is isolated and the anterior retractor is checked to be in the proper position, the ALL can be released sharply with the curved blade or with a custom curved bovie tip. A paddle distractor can be used to facilitate release of the ALL by tensioning it and as confirmation of complete release. If there is persistent tension during distraction, then the contralateral ALL or annulus must be reassessed and released as necessary. If the posterior release is incomplete, it too can act as a tether to expansion of the disc space.

Trialing is performed using standard implant sizes until a 12 mm trial can be inserted with minimal resistance. Next the ACR trials are inserted which come in lordotic angles of 20° and 30°. After the appropriate-sized implant is determined, a lateral image is imperative to identify its position in the sagittal plane. As the hyperlordotic graft is placed through the posterior blade, it is important to have this blade docked in the ideal location to ensure the graft is placed in a predictable space within the disc. The hyperlordotic, flanged cage is placed through a posterior rail to guide the interbody in the proper location within the disc space and to prevent anterior migration. The insertion of the cage will require expansion of the retractor temporarily. The positioning is confirmed in both planes under fluoroscopy. To prevent graft migration, a screw is placed through the cephalad flange into the bone adjacent to the end plate of the cephalad vertebra. This cephalad location is chosen to avoid interference with pedicle screw instrumentation.

Wound closure is performed in a standard layered fashion for the lateral approach after ensuring hemostasis is adequately achieved. The transversalis fascia is approximated with a heavier absorbable suture to prevent a hernia. The author's preferred method includes placement of a small round drain over the psoas to decrease the hematoma formation within the muscle. It is removed after the patient ambulates the following day.

Results and Outcomes

Akbarnia et al. were the first to describe the technique for ACR [28]. Our initial experience includes 17 patients from two centers who underwent anterior column realignment using a less invasive lateral interbody approach with anterior longitudinal ligament release to correct a focal kyphotic spinal deformity between 2005 and 2011 [28]. All ACR procedures were followed by posterior pedicle screw fixation (Figs. 30.1 and 30.2).

We measured three different radiographic angles by the Cobb method at four time points: (1) preoperative, (2) intraoperative immediate post ACR, (3) post posterior spinal fusion and instrumentation within 90 days follow-up, and (4) at the latest follow-up. Motion segment angle (MSA) was measured from the superior end plate of the upper end vertebra to the lower end plate of the lower vertebra. The lumbar lordosis (LL) was measured from the superior end plate of L1 to the superior end plate of S1. Also, pelvic parameters including pelvic tilt (PT), pelvic incidence (PI), and sacral slope (SS) were measured at the abovementioned events. To assess sagittal imbalance, T1 spinopelvic inclination (T1SPI) was measured per Legaye et al. to represent the angular sagittal imbalance in degrees which is not liable to calibration error as with the traditional sagittal vertical axis (SVA) measurement in millimeter [29].

There were 12 females and 5 male patients who had a mean age of 63 years (range: 35–76 years) at surgery, and mean follow-up was 24 months (range: 12–82 months). Fourteen of 17 (82 %) had previous spine surgery, and 12/17 (71 %) had previous spine fusions. Surgical indications for ACR included progressive focal sagittal plane deformity, instability and motion at the level of the focal deformity, and declining quality of life. Junctional kyphosis following a previous fusion was the most common indication for the ACR procedure. Three patients had degenerative scoliosis with sagittal plane deformity, 1 had primary thoracolumbar kyphosis, and 1 had a grade II spondylolisthesis with sagittal imbalance. ACR was performed at L1–L2 ($n=6$), L2–L3 ($n=3$), and L4–L5 ($n=8$). Twelve of seventeen patients (71 %) had screw fixation through a flanged implant designed for vertebral body fixation. A hyperlordotic cage was used in ten patients (seven patients with 30° cages and three patients with 20° cages). Fifteen patients (88 %) had posterior Smith–Petersen osteotomies at the level of the ACR. Three patients had severe sagittal malalignment (SVA >100 mm) and had a planned pedicle subtraction osteotomy in addition to ACR. It was felt that this group would have required a double PSO if ACR was unsuccessful. Mean intraoperative blood loss was 111 cc during the ACR and 1,484 cc during the posterior procedure. Five patients had a fusion performed at the lumbosacral junction at the time of ACR (three anterior lumbar interbody fusions (ALIF) and two transforaminal lumbar interbody fusions (TLIF)).

Preoperative motion segment angle (MSA) averaged 9° and improved to −19° immediately after ACR (28.1° of correction by ACR) and to −26° after posterior surgery for total correction of 37°. Lumbar lordosis improved from −16° to −38° after ACR and −45° after posterior instrumentation. Lumbar lordosis maintained at −51° at the latest follow-up ($p<0.05$). Pelvic tilt (PT) averaged 34° before ACR and improved to 24° after ACR and posterior instrumentation and maintained at 25° at the latest follow-up ($p<0.05$). Similarly, pelvic incidence (PI) averaged 60° before ACR and measured 59° after ACR and posterior instrumentation and maintained at 61° at the latest follow-up. Finally, we reviewed T1

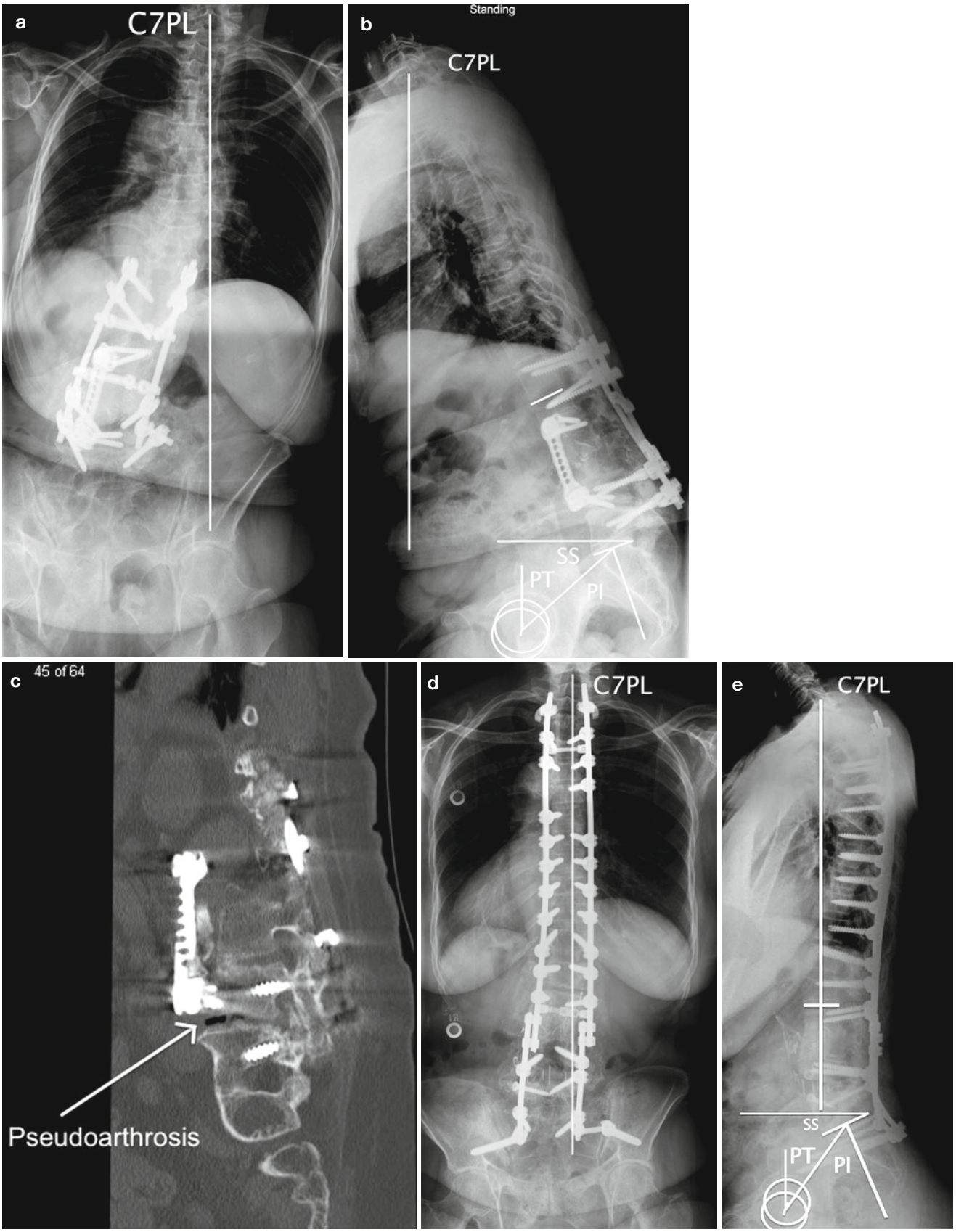


Fig. 30.1 (**a**, **b**) AP and lateral preoperative radiographs of a 76-year-old female with previous failed open anterior spinal fusion (L2–L4) and posterior spinal fusion (T12–L5) with an L4–L5 pseudarthrosis (**c**) and severe coronal (120 mm) and sagittal (+215 mm) imbalance and abnormal pelvic parameters (PI = 57°, PT = 47°, and LL = +8°). (**d**, **e**) Postoperative AP and Lat radiographs of the patient after ACR and posterior spinal fusion. Coronal and sagittal balances are within normal limits, and pelvic parameters were improved (PI = 54°, PT = 32°, and LL = −26°)

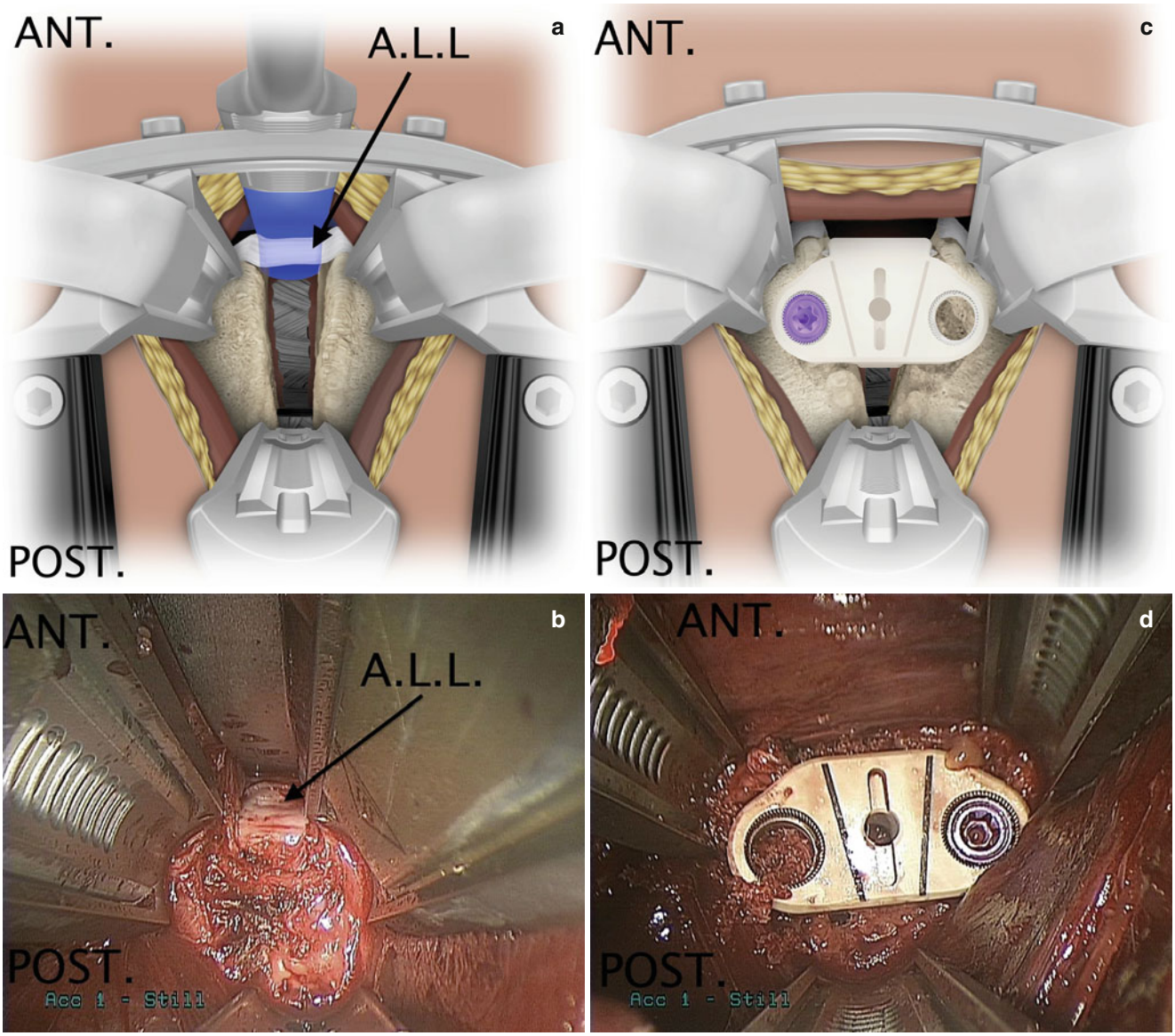


Fig. 30.2 (**a**) Schematic drawing and (**b**) intraoperative clinical photograph showing the exposed intact anterior longitudinal ligament (*ALL*). (**c**) Schematic drawing and (**d**) intraoperative clinical photograph showing the transected ALL and hyperlordotic cage in place. *ANT* anterior, *POST* posterior

spinopelvic inclination (T1SPI) and divided the results into two groups: patients with negative T1SPI and those with zero or positive T1SPI preoperatively. Those with negative T1SPI averaged −6° and improved to −0.6° after ACR and posterior instrumentation and further corrected to −2° at the latest follow-up. Those with zero or positive T1SPI averaged +5° and improved to −0.5° after ACR and posterior instrumentation and further corrected to −3° at the latest follow-up (Fig. 30.3).

Patients with previous spinal fusion had worse mean preop focal sagittal parameters compared to patients with no previous fusion (IDA = 6° vs. 2°; MSA = 10° vs. 5°; LL: −15° vs. −18°); however, the amount of correction after ACR (IDA = 26° vs. 23°; MSA = 29° vs. 26°; LL: 23° vs. 21°) and additional correction after posterior approach (IDA = 7° vs. 7°; MSA = 7° vs. 5°; LL: −8° vs. 2°) were comparable between the groups.

The average SRS-22 overall baseline score improved from 2.42 to 2.96 ($p < 0.05$) and 3.14 ($p < 0.05$) after ACR and after final follow-up, respectively. The mean visual analogue scale (VAS) decreased from 6.83 to 5.2 after ACR ($p < 0.05$) and 4.1 at the latest follow-up ($p < 0.05$).

Complications

As previously discussed, sagittal realignment surgery carries a high complication rate regardless of etiology. In our series of minimally invasive anterior column reconstruction (ACR),

we had a total of eight patients with complications (47 % of the patients in this series), four patients during or after ACR procedure (24 %), and six patients after the posterior stage (35 %). Two patients experienced complications after both ACR and posterior stage.

We categorize neurological complications as minor or major. Minor complications include transient (less than 3 months) dysesthesia or paresthesia in the ilioinguinal, iliohypogastric, genitofemoral, lateral femoral cutaneous nerve (LFCN), or anterior cutaneous nerve distributions persistent beyond 1 month after surgery. Major neurological complications were defined as persistent radiculopathy, paresthesia, and dysesthesia which continued beyond 1 month postoperatively, those requiring revision surgery, symptoms of neurogenic weakness (not approach related) isolated to a specific nerve root or persistent iliopsoas weakness beyond the first postoperative visit (1 month post-op).

Of 4 patients with complications related to ACR, 1 occurred at L1–L2 (severe radiculopathy requiring Smith–Petersen osteotomy for decompression) and 3 at L4–L5 level. When isolating complications by level of ACR, the complication rate was 38 % at L4–L5 (3/8) and 11 % among the remainder of the levels from L1–L4 (1/9).

The three complications at L4–L5 included a common iliac artery tear during a revision exposure at L4–L5 (with assistance of a vascular surgeon) for anterior plate removal. It was repaired with multiple figure of eight sutures by the exposing surgeon. The patient experienced transient lateral thigh numbness and 4/5 quadriceps weakness postoperatively, both of which resolved within 3 months from surgery.

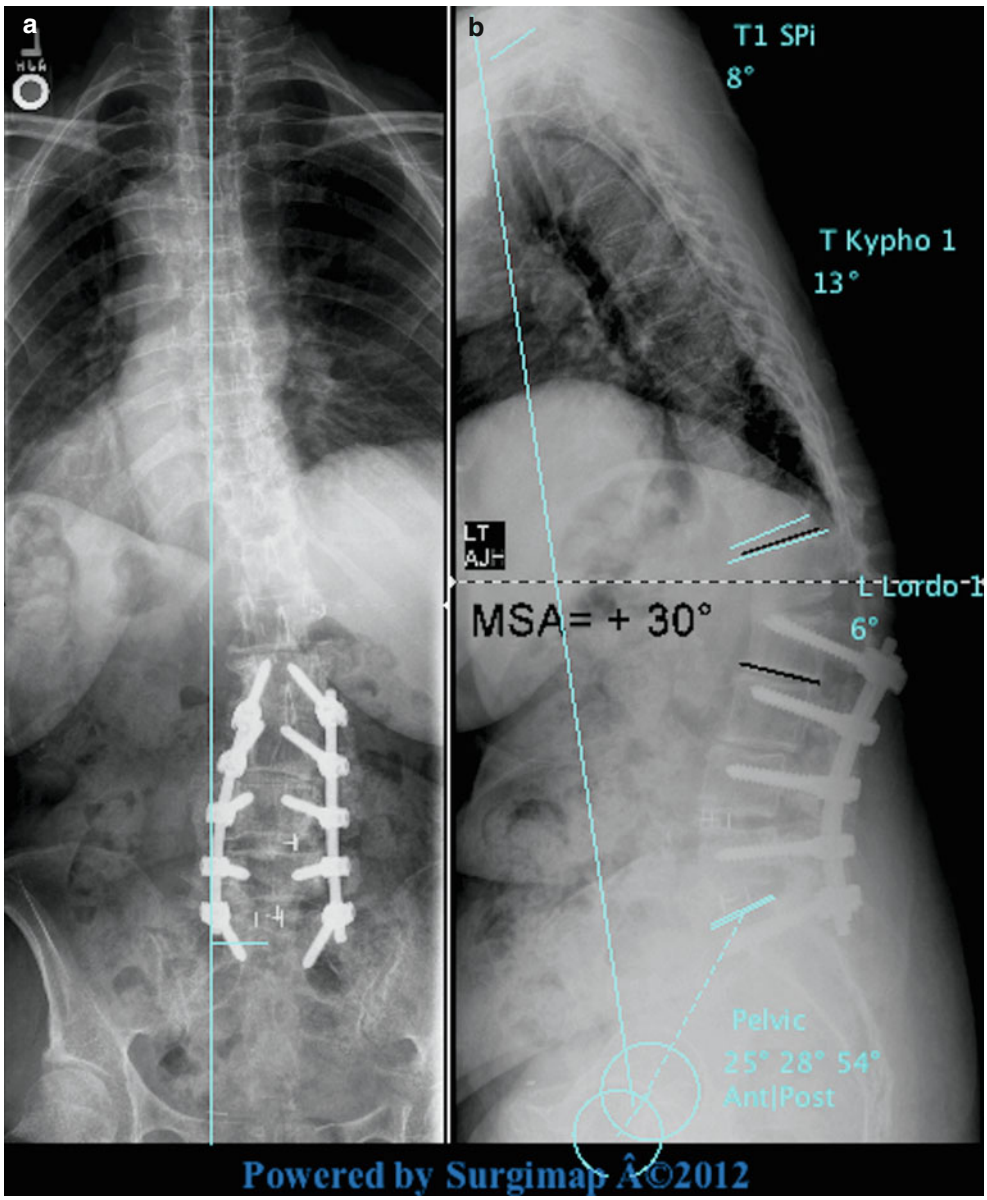


Fig. 30.3 (**a**, **b**) AP and lateral preoperative radiographs of a 71-year-old female with degenerative scoliosis (T8–L2 = 39°), truncal shift (C7PL = 110), and thoracolumbar kyphosis and sagittal imbalance (+110 mm). Pelvic parameters were abnormal (PI = 44°, PT = 27°, and LL = +1°). (**c**) Intraoperative fluoroscopic image of L1–L2 with MSA (+24°) and IDA (+1°) before ACR. (**d**) Typical lateral view of disc space with interbody device in place. (**e**) Final fluoroscopic image with screw fixation at the cephalad level and improvement in MSA (+4°) and IDA (+14°). (**f**, **g**) Latest AP and Lat radiographs of the patient after anterior column reconstruction (ACR) and posterior spinal fusion (T8–L2 = 6°, C7PL = 0, PI = 48°, PT = 9°, and LL = −54°) (Courtesy of Robert K. Eastlack, Department of Orthopaedic Surgery, Scripps Clinic, San Diego, with permission)

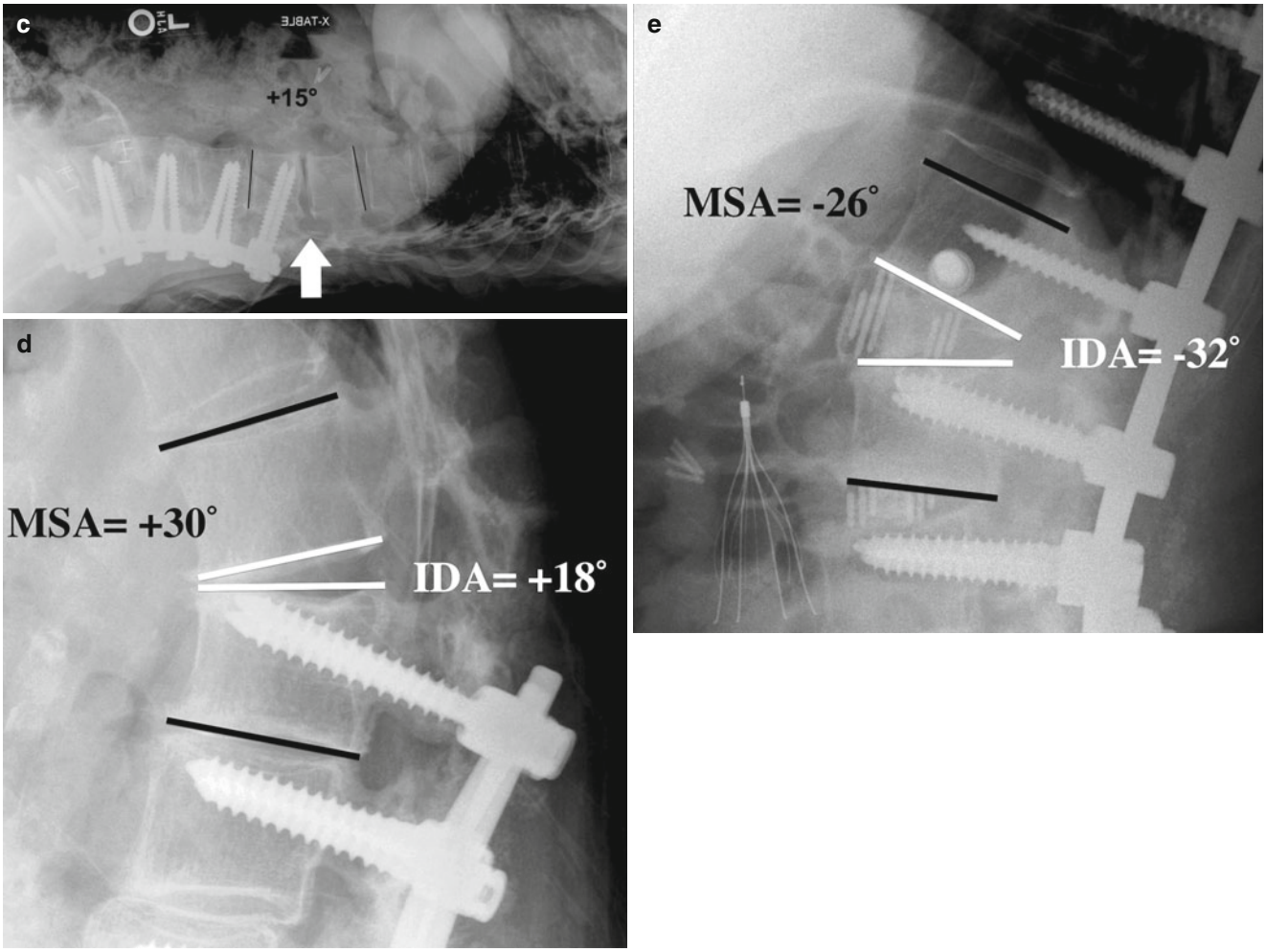
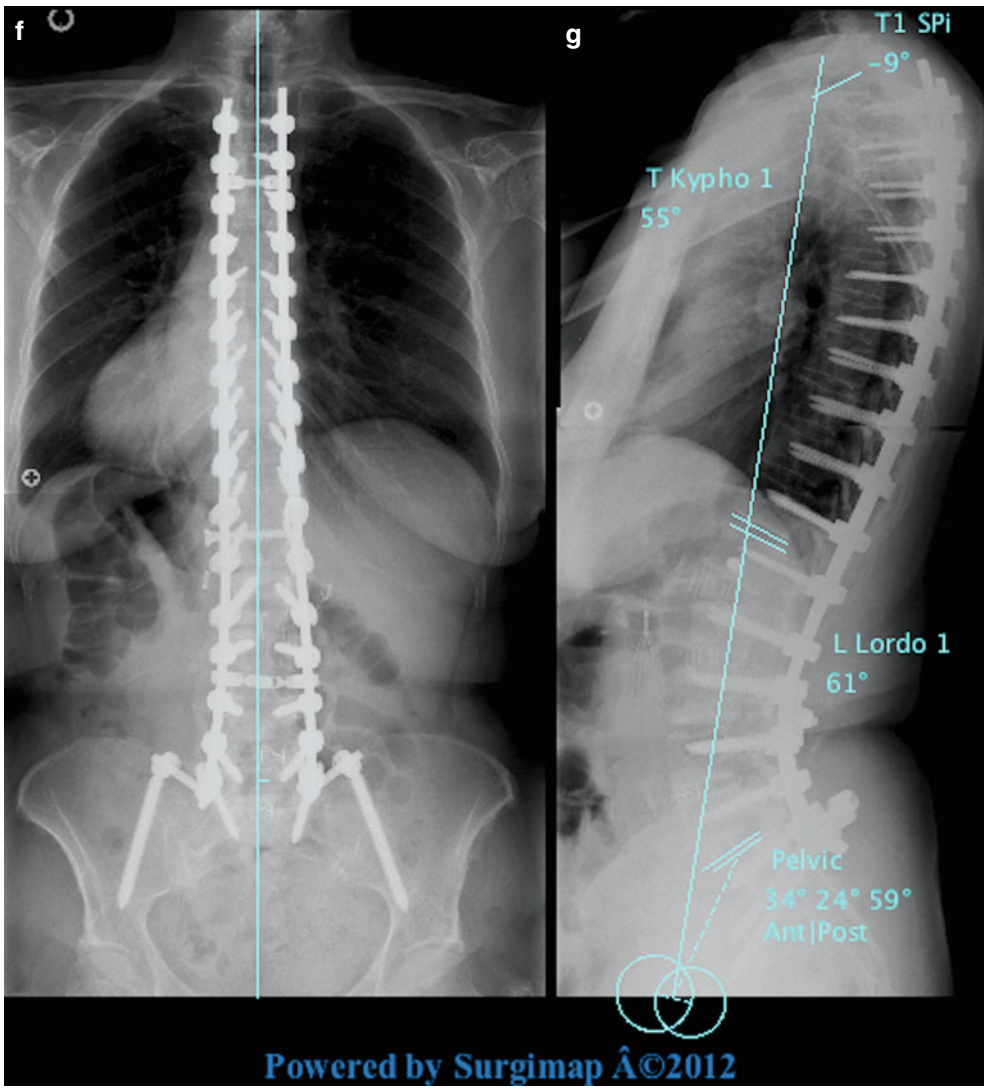


Fig. 30.3 (continued)

Fig. 30.3 (continued)



The final two complications occurred in patients who had L4–L5 ACR and multilevel LIF for degenerative scoliosis with sagittal imbalance. One developed quadriceps weakness and LFCN numbness, which resolved by 6 months, and one with persistent weakness in multiple nerve roots (L3, L4, L5), which has persisted beyond 6 months postoperatively.

Six patients had complications associated with the posterior approach. Two patients had early (less than 3 months) proximal junctional kyphosis including one fracture. Both required revision with extension of the fusion to the proximal thoracic spine, and one was treated with kyphoplasty at the site of fracture. One incidental durotomy occurred at the site of a revision laminectomy and was repaired primarily without sequelae. There was one deep posterior enterococcus faecalis infection that required two irrigation and debridement procedures and 6 weeks of culture-specific intravenous antibiotics. One patient had persistent anterior thigh and medial shin pain after a PSO. Finally, one patient developed acute radiculopathy following the posterior stage. She was worked up with a CT scan and found to have a medially directed L4 and L5 pedicle screw necessitating revision instrumentation during the same hospital stay, with resolution of her symptoms immediately after revision surgery.

Smith et al. [30] reviewed the short-term morbidity and mortality associated with surgical correction of thoracolumbar fixed sagittal plane deformity in 578 patients from SRS morbidity and mortality committee data and found 170 complications (29.4 %) in 132 patients. Osteotomies were performed in 402 cases (70 %), including 215 pedicle subtraction osteotomies (PSO), 135 Smith–Petersen osteotomies (SPO), and 18 vertebral column resections (VCR). The most common complications were iatrogenic dural tear (5.9 %), wound infection (3.8 %), new neurological deficit (3.8 %), implant failure (1.7 %), wound hematoma (1.6 %), epidural hematoma (1.4 %), and pulmonary embolism (1.0 %). The authors found an incremental increase in complication rate from no

osteotomy (17.0 %) to SPO (28.1 %), to PSO (39.1 %), and to VCR (61.1 %). Interestingly, complications were not significantly associated with patient's age, surgeon's experience, and history of previous surgery. The mortality rate was 0.5 %, with deaths resulting from multisystem organ failure, myocardial infarction, and pulmonary embolism.

Conclusion

Adult sagittal realignment surgery has a historically high postoperative complication rate. This is likely due to the need for 3 column osteotomies to achieve spinopelvic harmony. Minimally invasive techniques will be an important venue to decrease this high complication rate; however, the principles of sagittal plane restoration cannot be overlooked in an attempt to make the surgery less complicated. This is made clear by the addition of posterior-based osteotomies to achieve the sagittal alignment desired. ACR is a promising new technique to treat focal sagittal kyphosis and perhaps as an adjunct to treat global sagittal imbalance. We report a complication rate of 24 % for the ACR alone, which increases to 50 % for with PSF. It is important to note, however, that of the four complications associated with ACR, three were transient or resolved postoperatively. Perhaps the morbidity of these complications is less severe than for more traditional approaches. Furthermore, three of the four complications occurred during an ACR at the L4–L5 level, making this technique a relative contraindication at L4–L5 with very serious thought given to other corrective approaches.

In conclusion, ACR is a promising new technique to manage focal kyphotic deformity in the thoracolumbar spine. Its utility is currently limited to a disc space that has evidence of motion and is contraindicated in fixed kyphoscoliosis. Its impact on global alignment is dependent on the level operated, and its overall effect on the SVA remains unknown in terms of planning. The lower the ACR is performed, the longer the lever arm and subsequent correction (similar to PSO data); however, we have yet to quantify this given the different size grafts. ACR is still in its early stages of development, and further biomechanical and long-term clinical data is needed in order for it to develop into a technique that has the potential to reduce the morbidity associated with sagittal realignment surgery.

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Thoracolumbar Spine Trauma

31

Kelley E. Banagan and Steven C. Ludwig

Introduction

Approximately 150,000 people sustain vertebral column injury per year in North America, with the vast majority of injuries involving the thoracic and lumbar spine [1, 2]. The most common mechanism of injury is motor vehicle collision. These injuries often cause serious clinical sequelae and result in significant financial consequences for the patient and for society as a whole [3–7].

Historically, spine trauma was managed conservatively with traction, casting, and bed rest [8]. However, with the increasing availability of surgical methods and with studies showing that surgical intervention leads to improved neurological outcomes and improved pain scores when compared with nonoperative management, operative treatment of thoracolumbar fractures has become more common [9, 10]. The treatment goals of spine trauma are the same regardless of the type of treatment chosen: prevent the development of a neurological deficit, enhance neurological recovery, achieve stabilization to allow for rehabilitation, and prevent deformity and pain.

During the past decade, minimally invasive spine surgery (MISS) techniques have developed for the treatment of degenerative spinal conditions, tumor, deformity, infection, and trauma. MISS has been purported to avoid the morbidity and increased complications associated with traditional open procedures [11]. If a patient has an unstable thoracolumbar injury, the surgeon might deem the patient a candidate for MISS.

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Rationale and Indications

Traditional open approaches for the treatment of spine trauma have resulted in increased infection rates and increased blood loss [3, 12]. Furthermore, the open posterior approach can generate muscle damage secondary to muscle denervation and ischemia. Infection rates in the trauma population have been hypothesized to result from extensive soft tissue exposure in the setting of already traumatized muscles [13]. A postoperative infection rate of up to 10 % has been shown in the trauma population, and the median estimated blood loss has been reported to be greater than 1,000 ml for open cases [3, 12, 14]. Outcome reports for MISS have indicated a 0.22–1.5 % surgical site infection rate compared with the 4.2 % infection rate associated with open procedures [15, 16]. Unlike degenerative disc disease, which has disease-specific outcomes, there are no such measures for MISS. On the contrary, MISS surgery does not have generalizable outcomes.

Surgical decision making for the treatment of thoracolumbar spine trauma is dependent on multiple factors, including fracture morphology, the neurological status of the patient, and the competency of the posterior ligamentous complex. Decision making regarding the necessity for operative intervention can be aided with the Thoracolumbar Injury Classification and Severity Score [17]. Should operative intervention be warranted, the surgeon can then decide whether minimally invasive techniques can be used. Relative indications for MISS in the trauma setting include unstable thoracolumbar burst fractures, stable burst fractures for which nonoperative treatment has failed or is contraindicated, flexion and extension distraction injuries, and unstable pelvic fractures requiring lumbopelvic fixation [18–20].

Figures 31.1 and 31.2 show the anteroposterior (AP) and lateral view radiographs of a 22-year-old woman who was involved in a high-speed motor vehicle collision. At the time of her presentation at a level I trauma center, she was found to have a small bowel injury, a splenic injury, and the spine fracture depicted in Figs. 31.1 and 31.2, which reveal a bony

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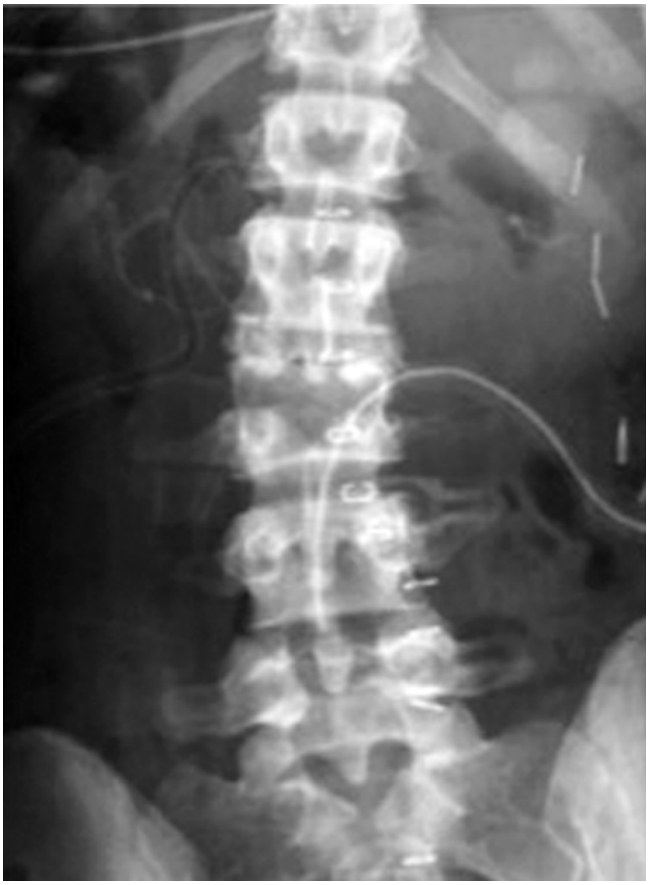

Fig. 31.1 AP view radiograph of the lumbar spine of a 22-year-old patient who was involved in a high-speed motor vehicle collision and incurred a bony Chance fracture at L3

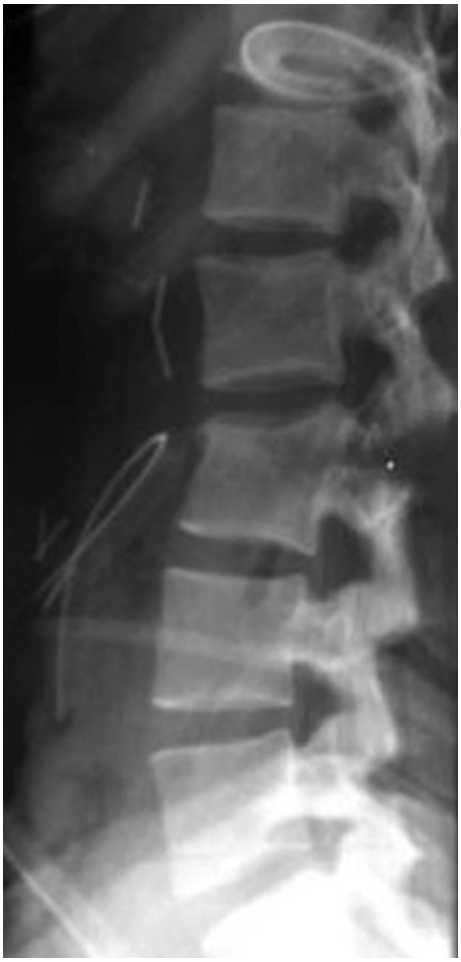

Fig. 31.2 Lateral view radiograph of the patient shown in Fig. 31.1

Chance fracture. Figures 31.3 and 31.4 show a sagittal view computed tomographic (CT) scan and a magnetic resonance image, respectively, obtained at the time of injury. Because of the unstable nature of the patient's spine fracture, operative treatment was warranted. In consideration of her other injuries, minimally invasive techniques were chosen to stabilize her spine fracture. Figures 31.5 and 31.6 show the postoperative AP and lateral view radiographs, obtained after the patient had undergone minimally invasive fracture stabilization.

Despite evidence to suggest that MISS is beneficial in the trauma setting, the disadvantages of MISS must be considered, and MISS is not indicated for every patient. MISS techniques are dependent on pristine intraoperative fluoroscopic visualization of the spine and relevant anatomy. Knowledge of the surgical anatomy is of paramount importance considering that traditional tactile and visual landmarks are not present. Consequently, not only is there a potential for screw misplacement but operative times and radiation exposure might be increased in the hands of an inexperienced surgeon. Additionally, corrective and reduction maneuvers cannot be performed as readily with MISS as with open procedures, and achieving biological fusion can be difficult [21].

Certain clinical situations require fusion across the segments being instrumented in a minimally invasive fashion. A solid biological fusion is often an important operative goal for treating the traumatically injured spine. For instance, for a patient with an injury requiring anterior decompression, such as a neurologically incomplete thoracolumbar burst fracture, a solely posterior minimally invasive approach is not appropriate. In such clinical settings, corpectomy often is necessary, and anterior interbody fusion is performed at the time of corpectomy. If possible, the morbidity associated with an anterior exposure can be minimized if the surgical working zone is targeted and a lateral interbody approach is used. However, in most instances, to regain spinal stability, posterior minimally invasive percutaneously placed pedicle screws are additionally used. This technique allows for neurological decompression, anterior column reconstruction, and biological fusion to occur through the anterior or lateral approach, while the mechanical stability is restored through the posterior MISS approach.

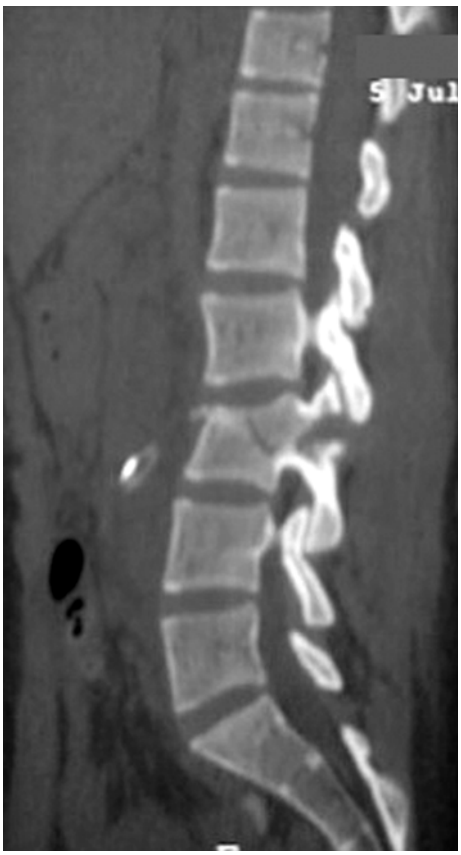

Fig. 31.3 Sagittal view CT scan of the L3 bony Chance fracture and associated ligamentous injury depicted in the plain radiographs in Figs. 31.1 and 31.2

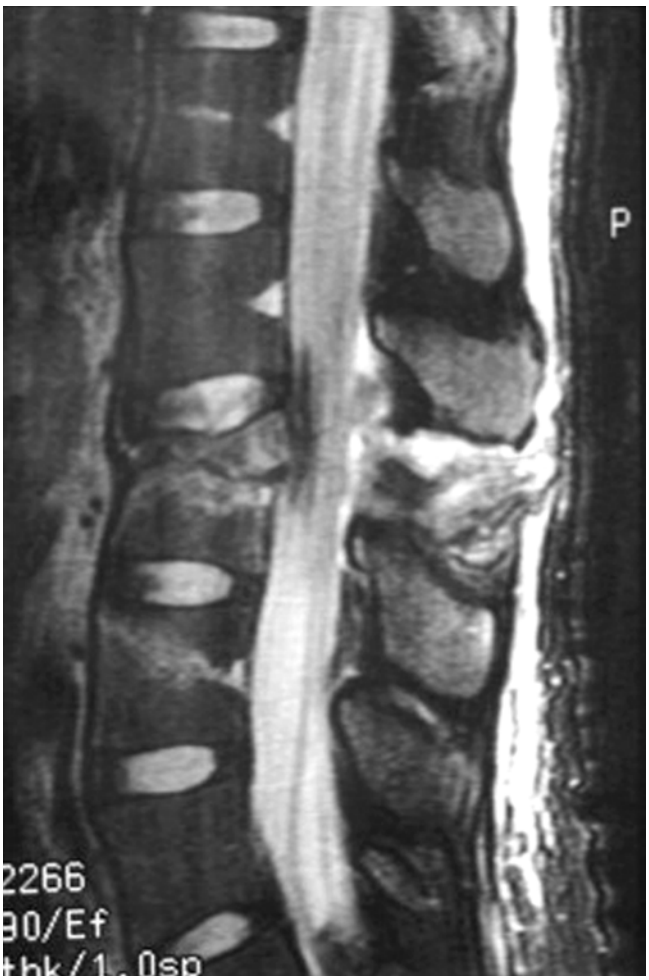

Fig. 31.4 Sagittal view magnetic resonance image of the L3 bony Chance fracture shown in Fig. 31.3

In patients with unstable burst fractures or traumatic fracture dislocations necessitating posterior stabilization and fusion, a "hybrid" MISS approach can be used. This involves a mini-open approach at the dislocated segment. The spine is reduced with percutaneously placed pedicle screws, and a midline fusion is performed simultaneously with the use of a speculum-type retractor that is placed through the midline approach and used to elevate the muscles off the spine. A midline decortication is then performed and bone graft placed in the fusion bed. For those patients who are physiologically unstable after percutaneous fixation, a delayed return to the operating room for standardized open midline posterior fusion can be planned.

Operative Techniques

The patient is positioned prone on a radiolucent table, as one would be for a traditional open procedure. Bony prominences are well padded, and careful attention is paid to be sure that the abdomen is free of compression. The ability to obtain fluoroscopic images is critical to performing MISS. Consequently, once the patient is positioned, each vertebra to be treated should be imaged to assure that obtaining a true AP view radiograph is possible. A true AP image is obtained when the x-ray beam is parallel to the superior end plate of the vertebra to be treated. The anterior and posterior margins of the vertebra should be superimposed, creating a single superior end plate shadow. The spinous processes should be of equal distances from the pedicles, and the pedicle shadow should be slightly inferior to the superior end plate. In the case of MISS for treatment of the upper thoracic spine, careful attention must be paid to the upper thoracic kyphosis. Proper radiographic imaging of this area can be difficult secondary to patient positioning or body habitus. Placing the patient in a Mayfield head holder in an effort to flex the cervical spine and translate the spine anteriorly can be of assistance [13].

Four methods of percutaneous pedicle screw instrumentation have been described: biplanar fluoroscopy, image-guided navigation, the Magerl or "owl's eye" technique, and true AP targeting. Our preferred method is true AP targeting. This technique allows two surgeons to work simultaneously, one on each side of the spine, avoids the potential breach of

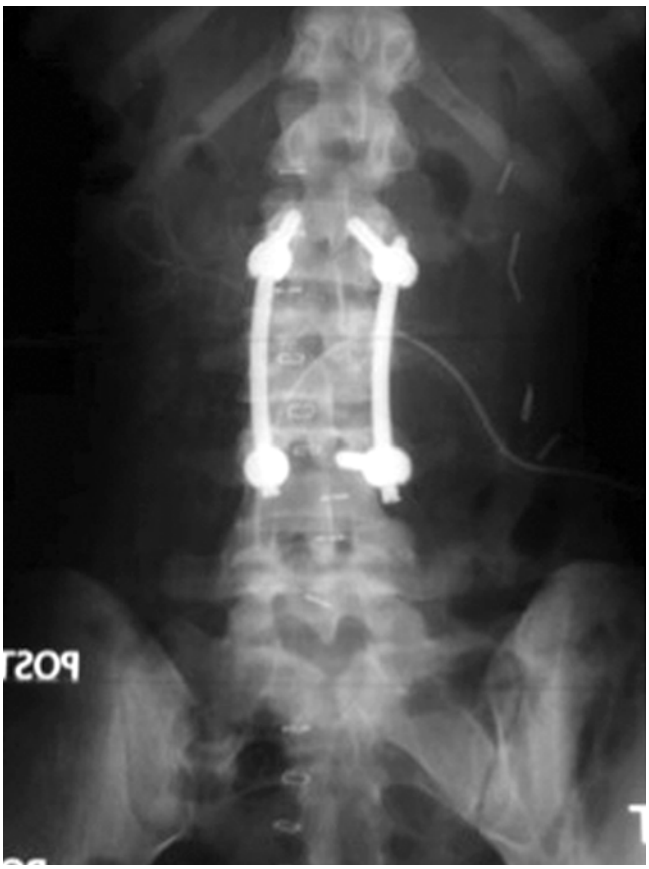

Fig. 31.5 Postoperative AP view radiograph of the patient shown in Figs. 31.1, 31.2, 31.3, and 31.4, obtained after she underwent minimally invasive posterior stabilization of the fracture

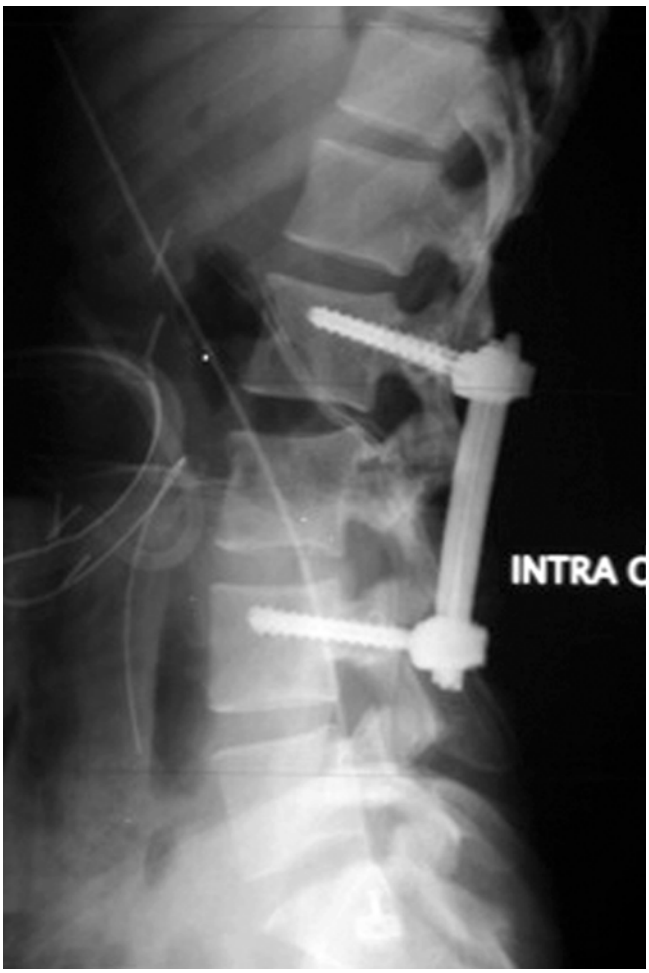

Fig. 31.6 Postoperative lateral view radiograph of the patient shown in Figs. 31.1, 31.2, 31.3, 31.4, and 31.5

the sterile field inherent with using biplanar fluoroscopy, and is relatively time efficient. AP targeting as an MISS surgical approach is contraindicated if appropriate radiographic visualization cannot be obtained, such as in patients with severely deformed anatomy, osteopenia, or morbid obesity [13, 22]. No published data are available regarding the percentage of times this occurs clinically. However, it has been our experience that this occurs in a minority of cases.

After a true AP view image is obtained, the pedicle screw trajectory is determined by placing a Kirschner wire (K-wire) on the patient's skin and marking the coronal position of the pedicles. The K-wire is first oriented vertically, over the lateral border of each pedicle, and then a horizontal mark is made through the center of the pedicle. Skin incisions are then made 1 cm lateral to the intersection of the two lines at each respective pedicle [13].

The skin and fascia are incised with the use of sharp dissection, and muscular tissues are dissected bluntly. Jamshidi needles are inserted into the incisions and are docked at the intersection of the lateral border of the inferior facet, the transverse process midline, and the upslope of the pars interarticularis. On a true AP view image, this docking position corresponds to the mid-lateral wall of the pedicle: the 3 and 9 o'clock positions, respectively, on a clock face. After proper positioning of each Jamshidi needle is confirmed with fluoroscopy, the needle is tapped a few millimeters into the cortex with the use of a mallet. The needle tip should be aligned so that it is parallel to the superior end plate. The shaft of the needle is then marked 2 cm above the skin to track the depth of the needle as it is advanced into the pedicle. The needle is then advanced into the pedicle to the marked depth, with the shaft parallel to the end plate on the true AP view and with 10–12° of lateral to medial angulation. Once the needle is advanced to the appropriate depth and at the base of the pedicle, a blunt tip guidewire is placed through the needle into cancellous bone and advanced 10–15 mm past the tip of the needle. Guidewire placement is confirmed with lateral fluoroscopy. The guidewire should be visualized just past the pedicle vertebral body junction on the lateral fluoroscopic view. The guidewire remains in place as the needle is removed, the trajectory of the screw is tapped over the wire, and a cannulated pedicle screw is placed. The size and length of the screws should be measured preoperatively. The entry sites of the screws should be aligned in a coronal plane, and the depth

of the screw heads should not be substantially different. The screws should be advanced to a depth at which they meet slight resistance against the lateral border of the facet joint. A lateral radiograph is then obtained to assure that the screws at each level are the appropriate length [13, 23].

After the pedicle screws have been successfully placed, attention is turned to passing the rods on each side of the construct. Rod length is measured, and the rods are cut to the appropriate size and contoured with the appropriate coronal and sagittal bends. Once appropriately contoured, each rod should be passed in a cranial to caudal manner deep to the fascia, with the bend of the rod used to facilitate passage through the screw heads. A two-handed technique is used to pass the rod. The surgeon's dominant hand is placed on the rod holder, while the nondominant hand manipulates the screw extensions. The rod holder is pushed as the screw extensions are rotated and derotated. If the screw extensions are capable of being rotated 360°, the rod has been inappropriately placed outside the extensions. Lateral view fluoroscopy is used to assure that the rod is the appropriate length and within the screw heads [13]. Depending on the area of the spine being instrumented, the rods are contoured into kyphosis or lordosis. If the rods are being passed across the thoracolumbar junction, they are left in neutral.

MISS for Damage Control

Early percutaneous fixation of thoracolumbar trauma offers the advantage of early stabilization in a clinical setting in which the patient might not tolerate a traditional open procedure. In a patient with multiple traumatic injuries, the basic treatment goals are hemodynamic resuscitation, management of life-threatening injuries, débridement and stabilization of open long bone and pelvic ring fractures, and early stabilization of spine fractures.

The principles of traditional damage control orthopedics were born of studies conducted on the treatment of femoral shaft fractures with external fixation, as opposed to intramedullary nailing, in the context of concomitant life-threatening injuries. The principles can be extrapolated to the treatment of thoracolumbar spine fractures with MISS. MISS offers the advantage of decreased blood loss and decreased surgical time in a critically ill patient [24]. Furthermore, MISS for the stabilization of thoracolumbar spine trauma has been shown to decrease the risk of respiratory complications and respiratory failure [5]. Hemodynamic instability, elevated or rising serum lactate levels, coagulopathy, and hypothermia are contraindications to performing any type of procedure, open or minimally invasive [25]. Figures 31.7, 31.8, and 31.9 show sagittal view CT scans of a 72-year-old man who was involved in a motor vehicle collision in which he was a front seat passenger. At presentation, he was found to have a T8 extension fracture,

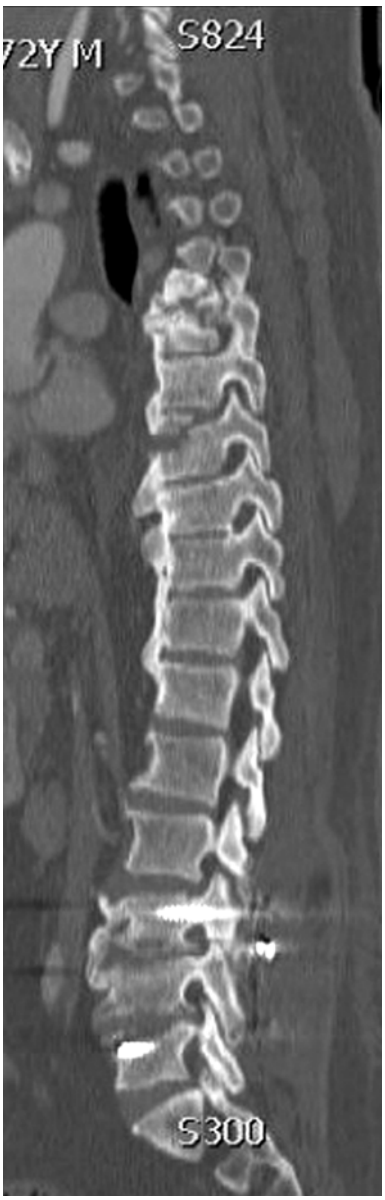

Fig. 31.7 Sagittal view CT scan of a 72-year-old patient who was involved in a motor vehicle collision and incurred a T8 extension injury and multiple other systemic injuries

multiple facial fractures, a subarachnoid hemorrhage, an American Association for the Surgery of Trauma (AAST) Grade III liver laceration, an AAST Grade I splenic laceration, a right-sided pneumothorax, and rib fractures. Figure 31.10 shows a coronal view CT scan, and Fig. 31.11 shows an axial view CT scan at the level of the injury. The unstable nature of the spine fracture necessitated operative stabilization, and considering the patient's multiple other life-threatening injuries, he clearly was a candidate for damage control surgery. Figures 31.12 and 31.13 show postoperative AP and lateral view radiographs, obtained after the patient had undergone stabilization via minimally invasive methods.

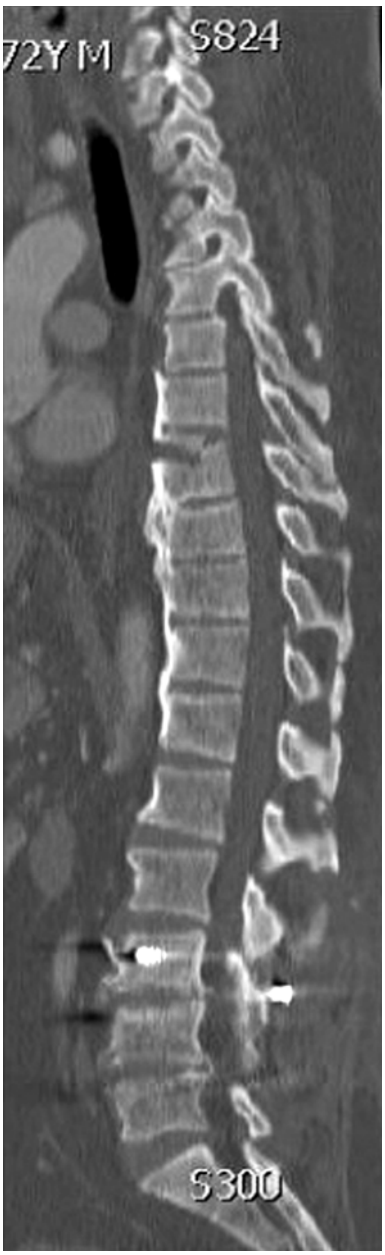

Fig. 31.8 Sagittal view CT scan of the patient shown in Fig. 31.7, obtained at a different level

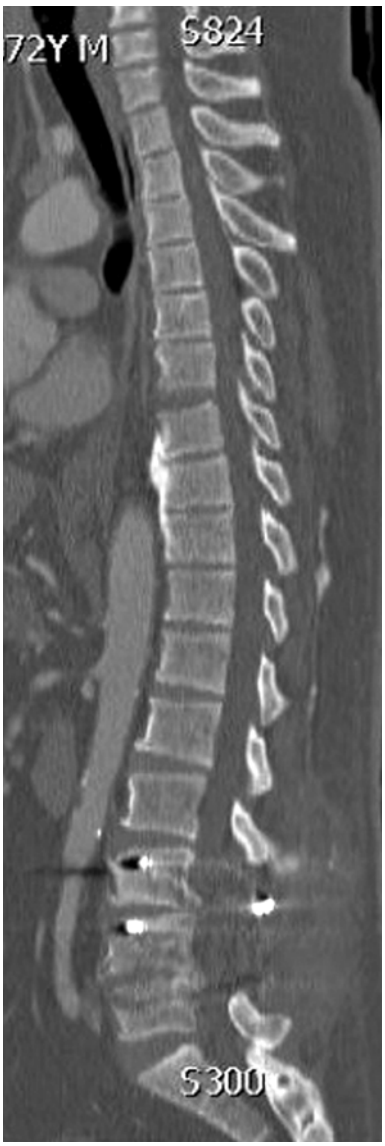

Fig. 31.9 Sagittal view CT scan of the patient shown in Figs. 31.7 and 31.8, obtained at a different level

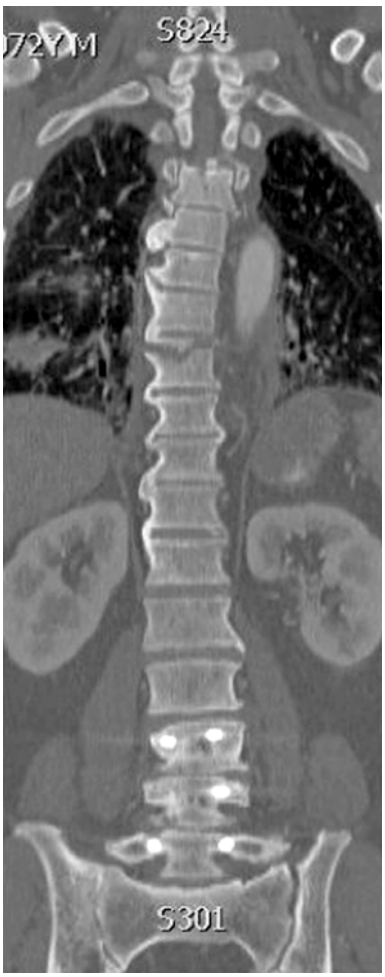

Fig. 31.10 Coronal view CT scan of the patient shown in Figs. 31.7, 31.8, and 31.9, obtained at the level of the T8 injury

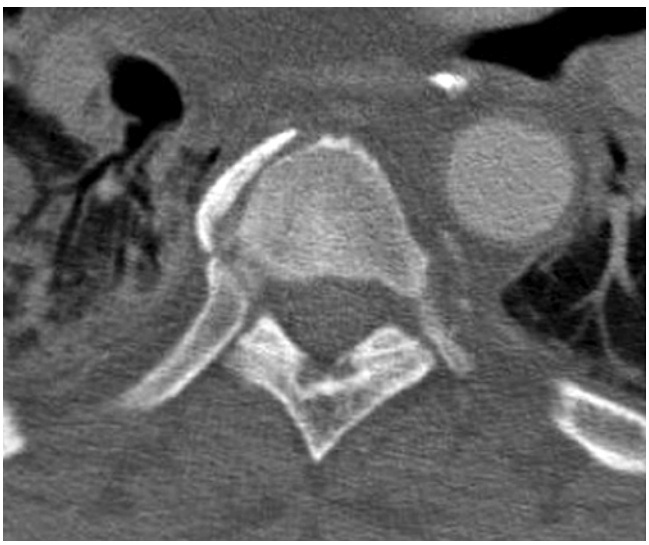

Fig. 31.11 Axial view CT scan of the patient shown in Figs. 31.7, 31.8, 31.9, and 31.10, obtained at the level of the T8 injury

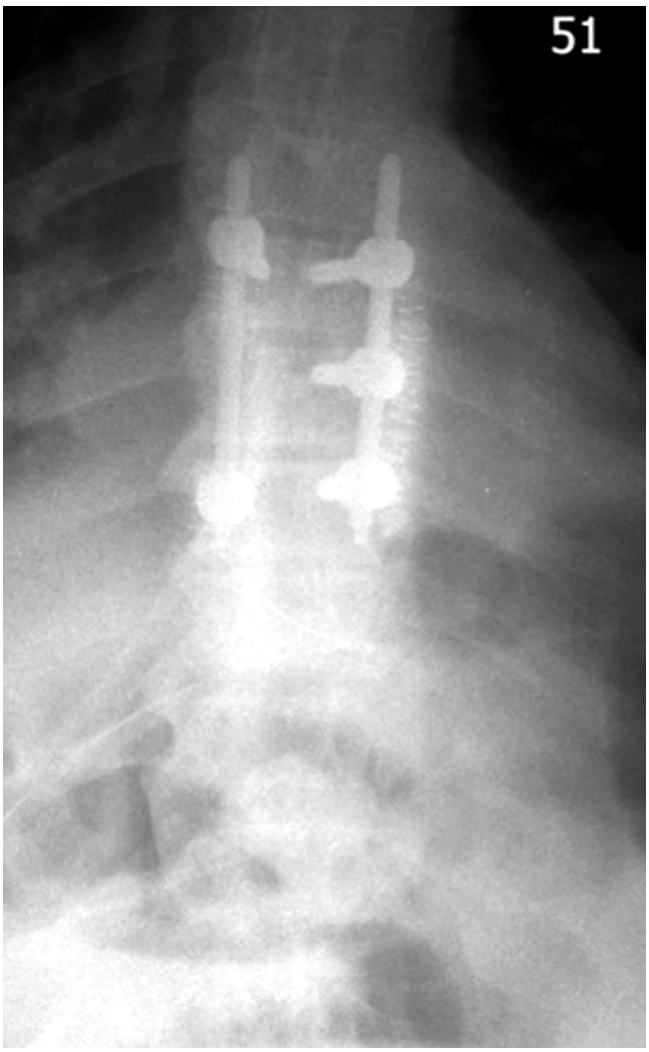

Fig. 31.12 Postoperative AP view radiograph of the patient shown in Figs. 31.7, 31.8, 31.9, 31.10, and 31.11, obtained after he underwent minimally invasive damage control spine surgery

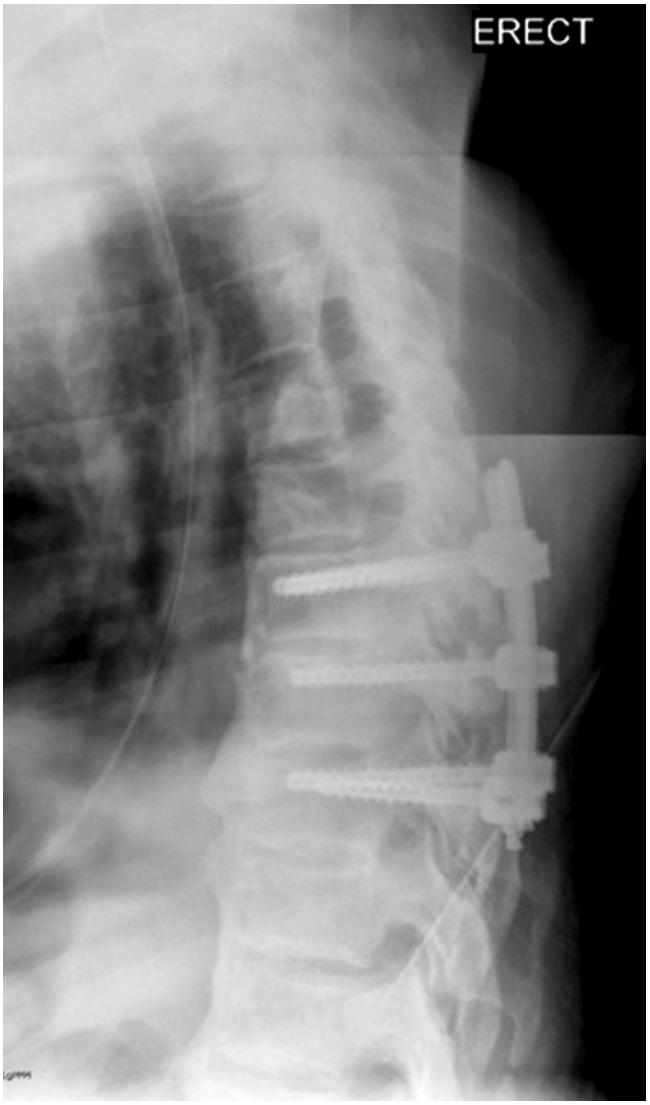

Fig. 31.13 Postoperative lateral view radiograph of the patient shown in Figs. 31.7, 31.8, 31.9, 31.10, 31.11, and 31.12, obtained after he underwent minimally invasive damage control spine surgery

Conclusion

In patients with blunt trauma presenting at emergency departments, the incidence of spinal injury has been reported to be as high as 6.3 %, and approximately 150,000 people sustain vertebral column injury per year in North America [2, 13]. The majority of injuries involve the thoracic and lumbar spine. The advancement of minimally invasive surgical treatment options has provided surgeons with another technique for stabilizing thoracolumbar spine fractures. These potentially significant advances work best in non-obese patients with adequate bone stock. MISS approaches are easier to perform at the thoracolumbar junction because kyphosis in the upper thoracic spine is more technically challenging. The ease of performing the surgery is skill dependent.

The decreased morbidity associated with minimally invasive spine surgery makes it an appealing choice for the treatment of spinal trauma. More specifically, minimally invasive stabilization of thoracolumbar fractures plays an important role in the treatment of critically ill patients as part of the damage control algorithm.

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Minimally Invasive Surgery for Spinal Tumors

32

William D. Smith, Kyle T. Malone, and Dean Chou

Introduction

While cancer in the spine as a primary tumor site is relatively rare, metastatic disease to the spine is remarkably common, with most metastasizing from the breast or lungs [1]. With the spine being the most common osseous site of tumor metastases, as many as 30–90 % of patients who die due to cancer have spinal metastatic sites present [1–3]. Despite the high incidence of metastatic disease to the spine, symptomatic patients are less common. Spinal cord compression in spinal neoplasms has been reported in as little as 5 % to as many as 40 % of cases, with 10–20 % of those exhibiting symptoms requiring surgery [2]. This results in approximately 25,000 cases of surgery for spinal neoplasms a year in the United States [2]. With 1.4 million new cases of cancer diagnosed in the United States each year, and half of those eventually succumbing to the disease or related complications, and these numbers projected to increase, effective and expedient treatments are needed to manage the growing problem [3, 4].

The treatment of spinal neoplasms is complicated by many factors. To begin with, psychological issues are common in these patients because of the devastating diagnosis, quality of life, and needs and expectations [5]. Factors impacting surgical decision-making include the tumor type and biology (malignant, benign, aggressive, etc.), presence of multiple or peripheral metastases, extent of systemic disease, general health and physical condition of the patient, location in the spine, portion of the vertebra(e) involved, (anterior and/or posterior element or dural involvement), symptomology (pain most common), the presence and severity of neural compression, pending adverse neural or structural changes, the extent and type of prior or concurrent adjuvant therapies (radiation therapy, radiosurgery, chemotherapy, etc.), patient preferences, and life expectancy [1, 3, 6, 7]. This leads to the requirement for both a multidisciplinary and individualized care plan developed between spine surgery, medical and radiation oncology, radiology, palliative care, and rehabilitation services, with a hastened postoperative recovery taken into account during anticipated scheduling [3, 8].

When looking to the published literature, one finds many publications ranging from case examples of rare tumors to large meta-analyses. A simple MEDLINE/PubMed search for the terms *spine*, *tumor*, and *surgery* provides 8,196 unique results, 1,202 of which are review articles. This leads, unsurprisingly, to a lack of universal terminology concerning tumor classifications and surgical approaches, further complicating evidence-based medicine (EBM) decision-making [6, 9, 10]. This is not unique to the treatment of spinal tumors, as these same elements make decision-making in other spinal subspecialties difficult [11–15]. As Fisher et al. [9] outlines in their 2005 overview of the surgical management of primary spinal tumors, the terms most frequently used improperly are those describing the margins of tumor resection and the manner in which the tumor is removed. In general, spinal surgical margins for tumor removal are described as wide (removing the entire tumor with a case of healthy surrounding tissue), marginal (dissecting at the capsule of the tumor), or intralesional (learning the tumor behind). Standard tumor resection naming includes the terms piecemeal (curettage, or in parts) or en bloc (also called gross total resection or radical resection), where the tumor is removed as a whole [8, 9, 16]. Accurate terminology that describes surgical resection is critical because the type of resection may increase the risk of recurrence and decrease the potential for survival [9].

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Regardless of the inconsistencies in terminology and reporting, the case for en bloc resectioning of spinal tumors is relatively recent. Prior to the 1970s and 1980s, radiotherapy was the primary treatment option for spinal tumors [10, 17, 18]. Early operative techniques for spinal tumors were purely palliative, focusing on posterior decompressive laminectomies to reduce tumor-induced central stenosis [10, 17–19].

Young et al. [19] in 1980 performed a randomized trial comparing laminectomy followed by radiation therapy to radiation therapy alone. In these patients, the authors found no difference in outcome between the groups across pain relief, improved ambulation, or improved sphincter function, with increased morbidity in the laminectomy group [19]. Thus, through the 1980s and early 1990s, spinal surgery was largely avoided, in preference for radiotherapy alone [20], even though anterior decompressive techniques were subsequently shown to address spinal cord compression in the field in which the compression is present (the majority of tumors compress the spinal cord anteriorly) [21–23] while significantly improving function, quality of life, and survivability [24, 25]. A randomized trial by Patchell et al. [20] in 2005 found in 51 patients treated with radiotherapy alone and 50 patients treated with direct decompressive spine surgery followed by radiotherapy significantly increased ability to ambulate postoperatively (84 % vs. 57 %) and maintenance of that ability long term (62 % vs. 19 %), with fewer use of corticosteroids and opioid analgesics in the surgical compared to radiotherapy alone groups, respectively. In a meta-analysis of surgery versus conventional radiotherapy for spinal tumors by Klimo et al. [26] in 2005 found in 999 surgical and 543 radiotherapy patients that surgical patients had a 33 % higher rate of post-treatment ambulation and were twice as likely to eventually regain ambulatory function. Overall, ambulation was achieved in 85 % of surgical and 64 % of radiotherapy patients. The authors concluded, based on their findings, that surgery should, in the setting of cord compression in non-radiosensitive tumors, be the primary treatment option for spinal tumors with radiotherapy used adjuvantly [26].

Surgical Considerations

Because pain is the most common symptom of spinal tumors (axial pain in 85–96 % of symptomatic cases [27]), it is the principal indicator for surgery as there is a large palliative component to surgery [28]. With advancements in surgical techniques and EBM, however, there has been a shift from surgical intervention being primarily palliative—which it still is in most cases—to potentially curative [6]. Other indications for surgical intervention include improvement of neurologic function, increase in quality of life, local control of tumor burden, and correction or prevention of deformities [1, 4, 9, 25, 27, 29–31].

The general health of the patient is a major consideration when assessing an individual patient's ability to tolerate surgery. Spinal oncology patients often exhibit several baseline comorbidities, including a compromised immune system and a history of spinal radiation. Suppressed immune function increases the risk for infection, especially in posterior approaches, but also leads to a relative inability for the large incision areas in conventional surgical approaches to heal. As such, in patients with prior radiation therapy, subsequent surgery is correlated with higher risks of complications, local recurrence, and wound breakdown [32]. Using less-invasive approaches, overall morbidity is substantially decreased, most notably with a lower incidence of wound healing issues [33–38].

The most common location for spinal tumors is the thoracic spine (70 %), followed by the lumbar (20 %) and cervical (10 %) spine [3]. Anatomy in each area broadly dictates potential approach trajectories. In the upper cervical spine from C0 to C2, posterior approaches are most commonly utilized [39], though anterior transoral approaches (e.g., transoral atlantoaxial reduction and plating [TARP]) have been used and offer the potential for wider resectioning of the atlantoaxial region and fixation through a single-incision approach [40–42]. From C3 to C6, in the subaxial cervical spine, anterior approaches are more favorable due to the relative infrequency of posterior tumors and the exposure gained by an anterior approach. Where poor bone quality or multilevel disease is present, a combined anterior and posterior approach is recommended in this region [39]. At the cervicothoracic junction (C7–T1), anterior or posterior approaches can each be effectively used, depending on the individual characteristics of the disease and patient [4, 39].

In the thoracic spine, from T1 to T2, options are limited to an anterior approach through a modified manubrium osteotomy and clavulotomy or posterior approach. From T2 to T5, Anterior approaches are more problematic due to the position of the heart and great vessels; however, a high thoracotomy or axillary approach can be used. In addition, when examining EBM findings, there are strong recommendations for surgery [4], from T5 to L5, though only weak recommendations for specific approaches, as benefits have been shown each for anterior, posterior, and posterolateral approaches in specific situations [3, 6, 9, 27]. Several reports, however, have advocated the use of anterior approaches due to the benefits of exposure and the increased flexibility with placing individualized fixation (anterolateral and/or posterior) [16, 34, 43–52].

Many attempts have been made to address surgical staging in spinal tumor surgery, because the standard oncological staging systems used for the treatment of extremity tumors do not readily apply to spine tumors [6, 9, 44]. Two classification schemes useful for spine tumors have been developed,

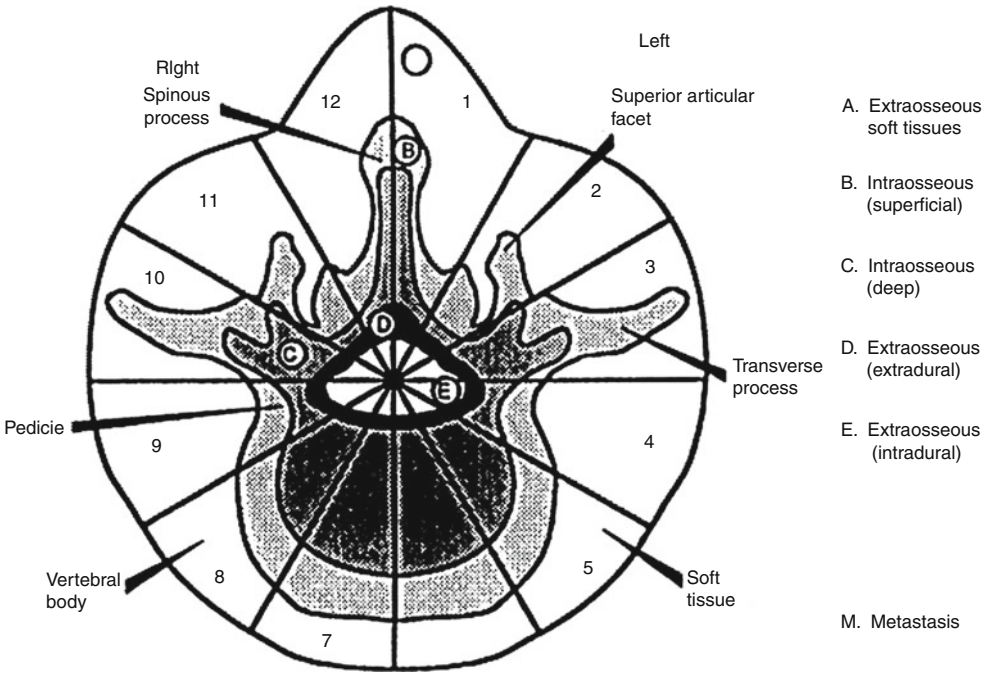

Fig. 32.1 Axial vertebral illustration showing the Weinstein-Boriani-Biagini (WBB) classification for the surgical staging of spinal tumors (Image used with permission of Wolter Kluwer Health. From Boriani et al. [55])

the Enneking staging system [53, 54] and the Weinstein, Boriani, and Bagini (WBB) classification system [55]. Using the WBB lesion classification, an axial section of the spine is divided into 12 equal and radiating parts, numbered from 1 to 12 clockwise, with 12 at the spinous process. Additionally, a five-layer (A–E) classification is used to show infiltration of the tumor from the paravertebral zone (A) to within the dura (E) (Fig. 32.1). Applications of the WBB staging system include general guidelines for surgical procedures based on lesion zone, including vertebrectomies for zone 4–8 or 5–9 tumors, sagittal resections for zone 2–5 or 7–11 neoplasms, and posterior approaches for localized posterior tumors (rare) in zones 10–3 [9, 55]. With these relative guidelines to approaches, the location, morphology, and biology of tumors are the next surgical consideration. By far, the most common location of spinal tumors is in the anterior column, with 66–85 % of tumors affecting the vertebral body with 33 % or less in the posterior arch [1]. This is important in surgical decision-making for two reasons: first, anterior exposures are considered the "gold standard" exposure with a superior working window to address anterior tumors compared with posterior approaches [8, 16, 44, 45, 47–49, 56], and second, posterior approaches for anterior-based tumors require bony resectioning of the posterior elements, which necessitate instrumentation to stabilize [1, 45]. In posterior-based tumors, posterior approaches are naturally indicated. It should be noted, though, that recent results of modern minimally invasive posterior approaches for anterior corpectomy have shown great utility in treating both anterior and anterior-/posterior-based tumors [36, 57].

Surgical Approaches

Conventional Approaches

With the near-universal abandonment of decompressive laminectomies for palliative treatment of spinal tumors, most conventional posterior or posterolateral exposures aim to access the anterior column for decompression with or without reconstruction and posterior fixation through a single-incision approach.

Holman et al. in 2005 reported on patients treated with either a posterior decompression and posterolateral fusion with pedicle screw-rod constructs, transpedicular vertebrectomy, or combined anterior-posterior approaches (either simultaneous or staged) for lumbar metastatic disease reconstruction [28]. In this study, 139 consecutive patients were treated with 166 surgeries over a 7-year period. Mean patient age was 55 years and all had a life expectancy of greater than 3 months. The most common primary malignancy sites were Lung (24%) and bone (31%). 64 % of patients had received some form of preoperative oncological treatment. Anterior-only approaches were performed in 54 (39 %) cases, with posterior-only surgical approaches performed in 63 (46 %) cases. Combined anterior and posterior approaches were used in 22 (16 %) patients. A total of 98 vertebrectomies were performed with a median estimated blood loss (EBL) of 1,500 mL (range 25–21,000 mL) and an average packed red blood cells (RBC) replacement of 2 units (range 0–41 units). Anterior vertebrectomies also resulted

in lower blood loss when compared to transpedicular EBL (1,375 mL vs. 2,000 mL). Adjuvant oncological therapy was initiated in 58 % of patients and 27 reoperations were performed in 17 patients, including 11 for local recurrence. Fifty-four early onset complications occurred in 38 (27 %) patients. Differences in morbidity between approaches included an absence of infections for anterior procedures and 7 (11 %) in posterior procedures, with overall complication rates highest for combined anterior and posterior approaches (75 %), lowest for posterior-only approaches (19 %). Anterior approaches had a complication rate of 31 %.

Neurologic maintenance or improvement was seen in nearly all (95 %) patients. However, neurologic improvement was more common in anterior or combined anterior-posterior approaches than in posterior approaches alone (41 % vs. 50 % vs. 27 %, respectively).

Survival at 6 months, 1 year, and 5 years was 67, 54, and 23 %, respectively.

Similarly, Fourney et al. [58] treated a series of 26 patients for complex thoracolumbar spinal metastases with simultaneous anterior and posterior approaches. Metastatic tumors were present in 58 % of patients with primary spinal tumors in 42 %. Twenty (77 %) patients received preoperative adjuvant oncological therapy. Mean operative time was 636 min (range 423–882 min) with a median EBL of 2,100 mL (range 750–10,000 mL). Median hospitalization (LOS) was 10.5 days (range 4–57) and 54 % of patients received postoperative adjuvant therapy. Nine (35 %) major early complications occurred in seven (27 %) patients, including one case of CSF leak and subsequent meningitis, deep wound infection, neurological deterioration, pneumonia, gastrointestinal hemorrhage, anuric renal failure, and postoperative confusion. In addition, five (19 %) minor early complications occurred, for a total complication incidence of 54 %. The majority of patients (96 %) presented with pain, with all but one of those patients experiencing either complete or partial improvement of pain. Neurologic maintenance or improvement was observed in all but one patient treated. No deaths were reported in the first 30 days postoperative, with a 1-year survival rate of 68 %.

In a series of 25 patients treated with an open transpedicular approach for treatment of spinal metastases with spondylectomy, decompression, and circumferential fusion, Bilsky et al. [59] found an average EBL of 1,700 mL, ORT of 7 h, and LOS of 11 days. Complications occurred in 48 % of patients, including two infections and three 30-day mortalities. Pain was improved in all patients and neurologic status was improved or maintained in 80 % of patients.

In general, the literature show significantly increased rates of postoperative infection following posterior, particularly open exposure, approaches for bony resectioning and/or placement of instrumentation, while anterior approaches largely avoid infections. This is particularly relevant due to the importance for early postoperative wound healing to allow early adjuvant therapy. For instance, a 19.4 % wound complication and 16 % infection rate was reported by Bauer [60] following 67 patients who underwent posterior decompression and instrumentation for thoracolumbar neoplasms. Similarly, a 50 % rate of wound dehiscence and infection following posterior procedures for tumors was observed by Harrington [61], with a comparative group of anterior procedures experiencing only a 1.3 % rate of infection.

Fisher et al. [9] reported results in 26 patients treated spinal malignancies with en bloc resectioning. Of the 26 patients, 19 exhibited malignant and 7 benign tumors including 7 chordomas, 4 chondrosarcomas, 3 osteosarcomas, and 3 osteoblasts, among others. Surgical approaches included two approaches performed in one or two stages. Generally, the procedures included iliac crest harvesting prior to posterior resectioning of what lesion was accessible through a posterior approach and fixation, followed by a second, combined anterior-posterior approach in the lateral decubitus position for circumferential tumor isolation and removal. Wide surgical margins were achieved in 15 patients, 4 with marginal, and 7 with intralesional resectioning at an average number of 2.6 vertebrae treated per patient (range 1–8 levels). Mean operative time (including stagings) was 18.6 h (range 1.3–56.3 h) with an average EBL of 3,880 mL. Early complications included massive blood loss (>5,000 mL) in 11 patients and deep and superficial wound infections (2 each), with a total complication rate of 92 %.

Less-Invasive Approaches

Spine surgery, in general, has seen expansion and utilization of modern minimally disruptive approaches over the past decade, ranging from endoscopic procedures to the development of muscle-sparing approaches with specialized retractor systems that maintain conventional surgical techniques to treat the pathology. These more-recent advances are gaining prevalence in their replacement of conventional exposures for a variety of reasons including patient demands and expectations, payer and societal pressures for attenuated surgical costs (e.g., lower morbidity) [62, 63], and an increased need for medical efficiency (less use of surgeon and hospital resources) in order to treat an expanding aging population [64].

As such, modern less-invasive, non-endoscopic approaches have more recently been applied to tumor resectioning in the thoracolumbar spine. Two procedures which will be the focus of the minimally disruptive approaches for spinal metastases are the mini-open transpedicular and mini-open lateral approaches for tumor resectioning and corpectomy [36, 51, 57, 65–67].

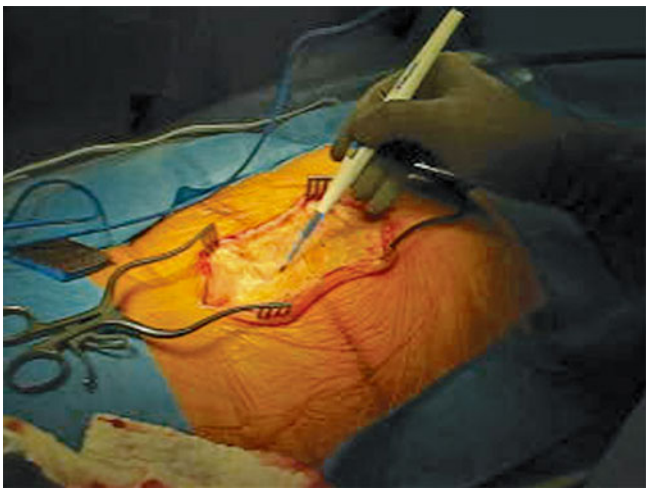

Fig. 32.2 Intraoperative photograph showing skin incision with preservation of the fascial layer for mini-open transpedicular approach for thoracolumbar corpectomy and posterior fixation

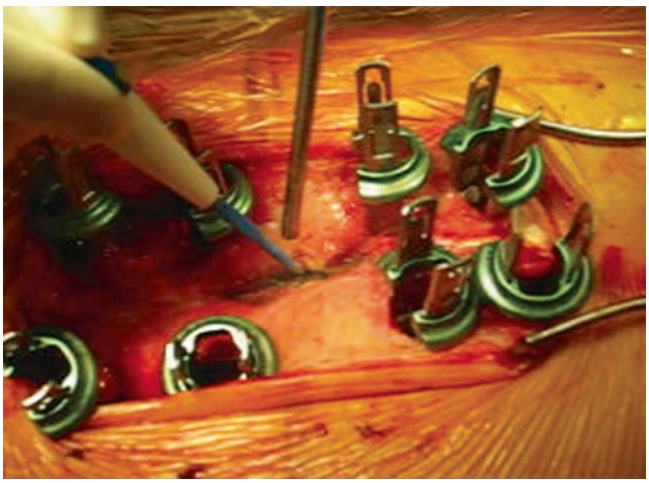

Fig. 32.3 Intraoperative photograph showing placement of percutaneous pedicle screws through the fascial layer

Mini-open Transpedicular Corpectomy

While less-invasive unilateral transpedicular approaches for corpectomy have been described, Chou and Lu [65] in 2011 described a mini-open bilateral transpedicular, 360° decompression, and expandable anterior cage placement. Such a procedure is particularly well suited to treat neoplasms, as the exposure allows for single-incision anterior resectioning and posterior instrumentation. One drawback of the approach is that even though it is a minimally invasive approach, some posterior muscle dissection and fascial opening are required for the procedure.

The mini-open transpedicular approach has previously been described [65] and utilizes a midline approach for 360° decompression followed by corpectomy and fusion. The procedure is performed with the patient placed prone on a Jackson Table. A midline skin incision is made over the operative level, with care taken to preserve the underlying fascial layer (Fig. 32.2). Through the skin incision, percutaneous pedicle screws are placed at two levels each above and below the index level using stab incisions through the fascial layer (Fig. 32.3). Next, a fascial incision is made at the level of the corpectomy, with the exposure extended to partially reveal the lamina above and below (Fig. 32.3). Either a split-blade or standard cerebellar retractor can be placed to maintain the fascial exposure (Fig. 32.4). Following a complete laminectomy at the corpectomy level, the transverse processes and ligamentum flavum are resected along with the exposed portions of the laminas at the adjacent levels, with the rib heads preserved (Figs. 32.5, 32.6, and 32.7). In the thoracic spine, nerve roots are sacrificed followed by removal of the pedicles using rongeurs. The disc spaces above and below the corpectomy level are identified. The corpectomy is then performed through the transpedicular space, with half performed through each side, using a combination high-speed burr, pituitary rongeurs,

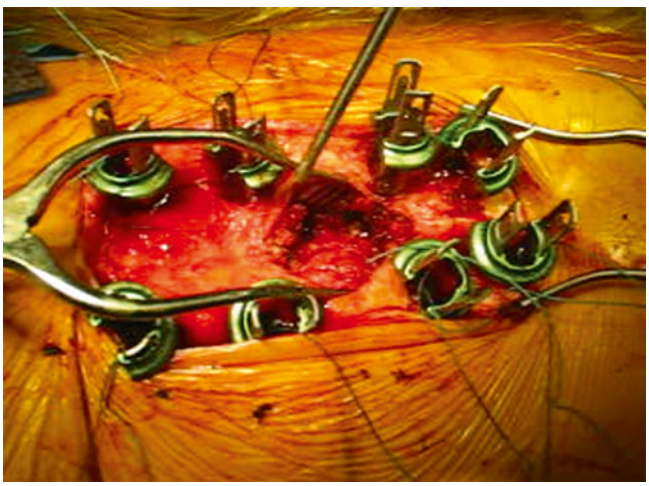

Fig. 32.4 Intraoperative photograph showing fascial incision and exposure of the corpectomy site from the borders of the lamina at the adjacent levels, laterally to the transverse processes

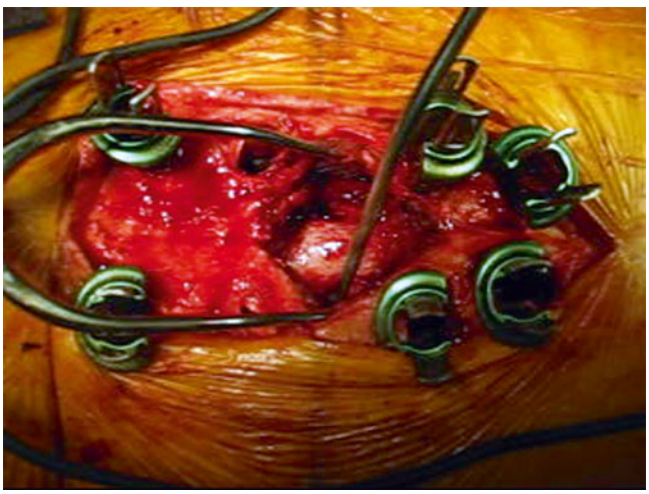

Fig. 32.5 Intraoperative photograph showing posterior decompression prior to transpedicular corpectomy

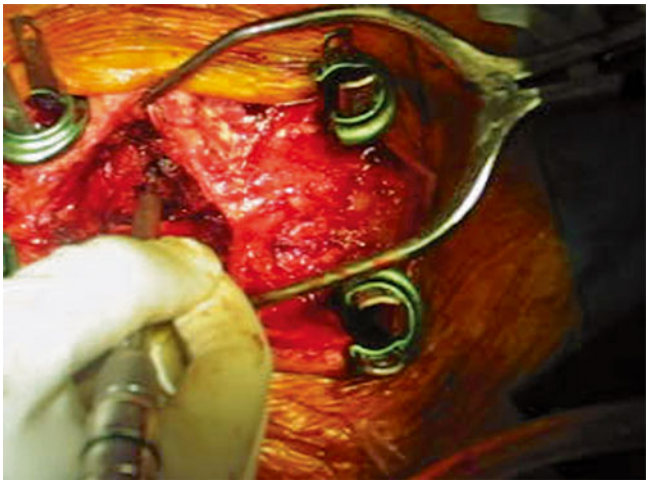

Fig. 32.6 Intraoperative photograph showing posterior decompression prior to transpedicular corpectomy

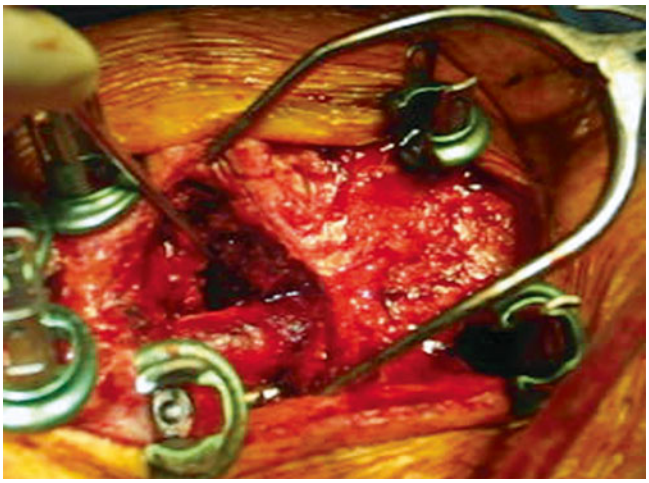

Fig. 32.7 Intraoperative photograph showing exposure to the anterior column through the mini-open transpedicular approach

and 0.25 inch osteotomes. Following the first half of the corpectomy through the first transpedicular approach, a single temporary rod can be placed on the ipsilateral side for maintenance of the segment through the second half of the corpectomy. Following completion of the corpectomy through the contralateral exposure, the discs are removed and the adjacent endplates are prepared. The posterior longitudinal ligament (PLL) is mobilized from the dura using a Woodson dissector and resected to prevent interference during intervertebral distraction.

The rib head is released using electrocautery approximately 3 cm lateral to the costovertebral junction followed by a trap-door rib-head osteotomy using a matchstick-type burr. If needed, a rib-head disarticulation technique can be used to further release the rib head [65]. Next, a small expandable vertebral body replacement device is delivered

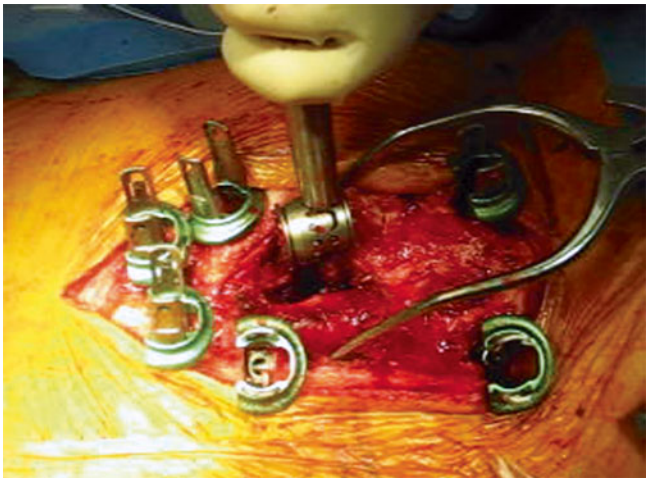

Fig. 32.8 Intraoperative photograph showing placement of a vertebral body replacement device in a mini-open transpedicular corpectomy

into the anterior column by pushing laterally and downward over the rib head past the spinal canal (Fig. 32.8). Then, the cage is moved medially to occupy the space ventral to the dura. A split-blade retractor can interfere with this final maneuver and thus should be considered to be removed and replaced with a cerebellar retractor. The cage is expanded to the appropriate size, based on local pathology and restoration needs, with confirmation made on lateral and anterior-posterior (AP) fluoroscopy (Fig. 32.9). Graft material is delivered around the cage and the second rod is placed and secured, followed by two cross-links (Fig. 32.10). The procedure is completed by placing drains in the epidural space, closure of the corpectomy fascia, closure of the fascial screw holes using figure-of-eight sutures, and the subdermal layer and skin are closed in the standard fashion (Fig. 32.11).

Several papers in the literature describe the use of and outcomes following a mini-open transpedicular corpectomy for a variety of thoracolumbar indications, including tumors. In a technical note and comparison of eight cases with mini-open transpedicular corpectomy compared with eight matched open corpectomy patients (majority of both groups were metastatic patients), Chou and Lu [65] reported an 8-h ORT with 1,250 mL average EBL. The comparative open group experienced an average ORT of 6.75 h, though with average EBL of 2,450 mL, nearly twice that of the mini-open group. A single complication (infection) was observed in the mini-open group, while two epidural hematomas were observed in the open group. Neurologic status was maintained or improved in all mini-open cases, while one patient in the open group experienced neurologic deterioration postoperatively.

In a series of 18 patients treated with mini-open transpedicular corpectomy for spinal neoplasm with a 9-patient open comparative group, Lu et al. [36] found a mean blood

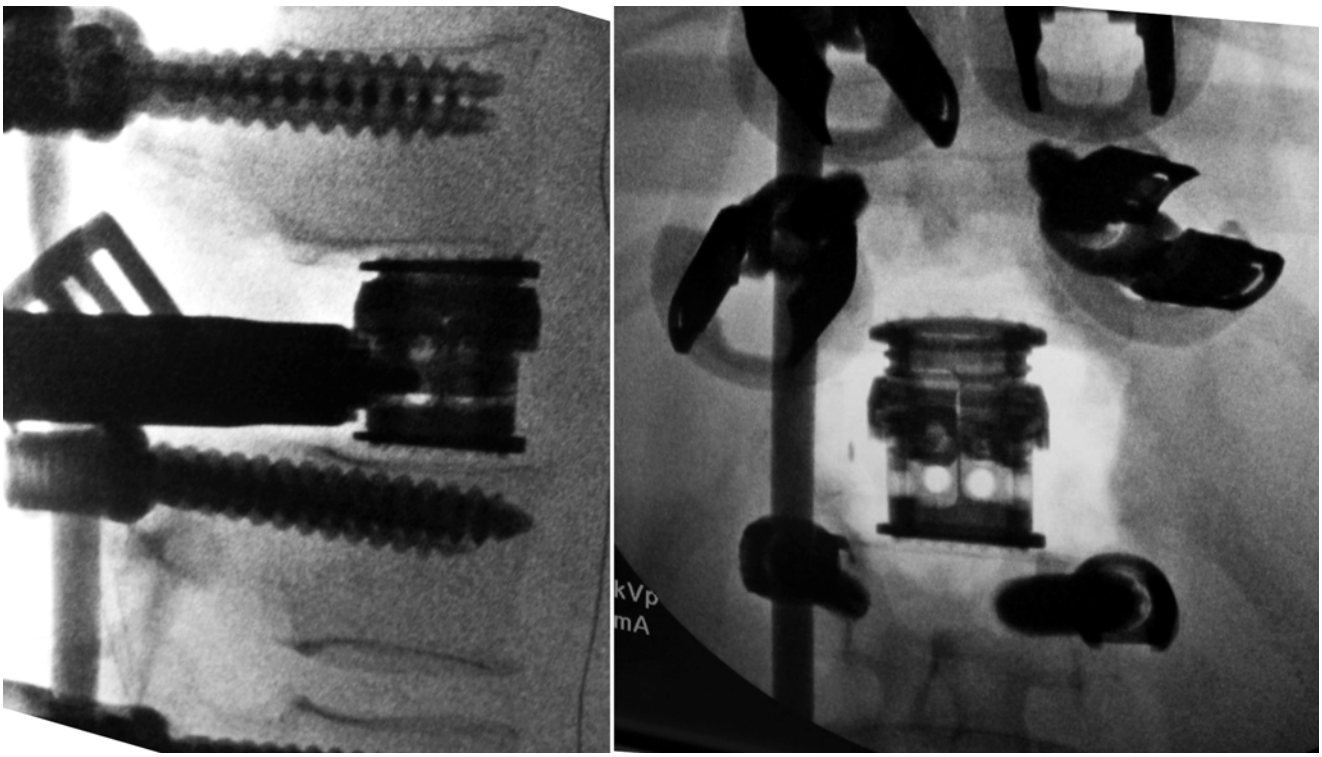

Fig. 32.9 Lateral (*left*) and anterior-posterior (AP) intraoperative fluororadiography showing VBR cage placement in a mini-open transpedicular corpectomy

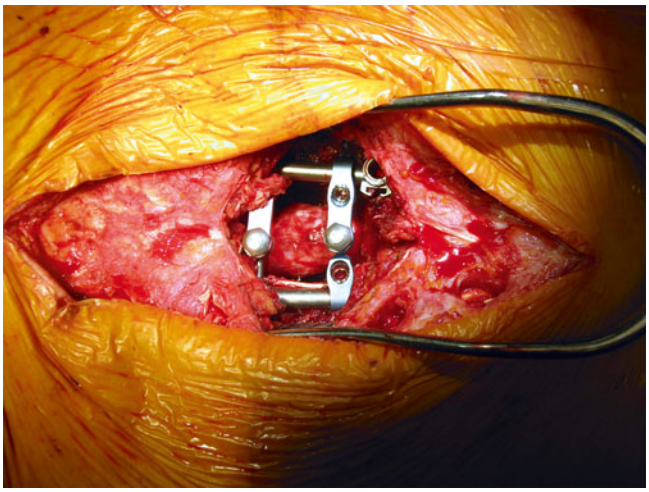

Fig. 32.10 Intraoperative posterior photography showing a single skin and multiple fascial incisions when performing a bilateral transpedicular corpectomy with bilateral transpedicular fixation

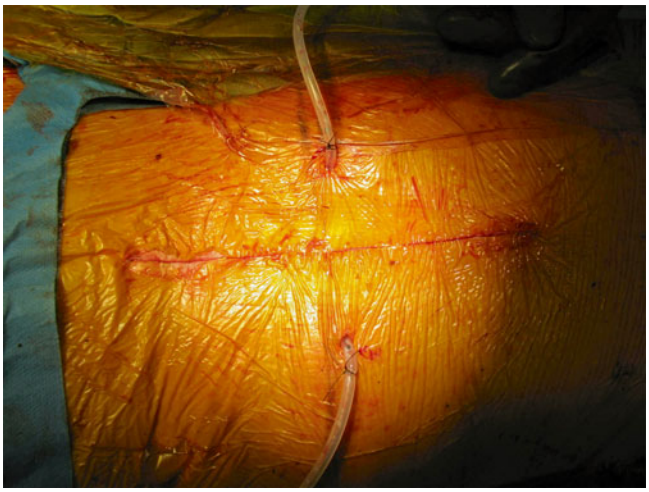

Fig. 32.11 Intraoperative photograph showing final incision closure and lumbar drain placement in a mini-open transpedicular corpectomy

loss of 153 mL, surgical time of 239 min, and length of stay of 5 days. Compared to a matched group treated with open posterior approach, blood loss was 372 mL, surgical time was 273 min, and length of stay was 8 days. One complication occurred in each group (5.5 % vs. 11 %, respectively). Neurological maintenance of improvement was observed in all patients in both groups.

Similar favorable results have been shown in the procedure's use in treating extradural foraminal tumors of the lumbar spine [67].

Mini-open Lateral Transpsoas Approach

The mini-open, 90° lateral, retroperitoneal transpsoas approach for interbody fusion (extreme lateral interbody

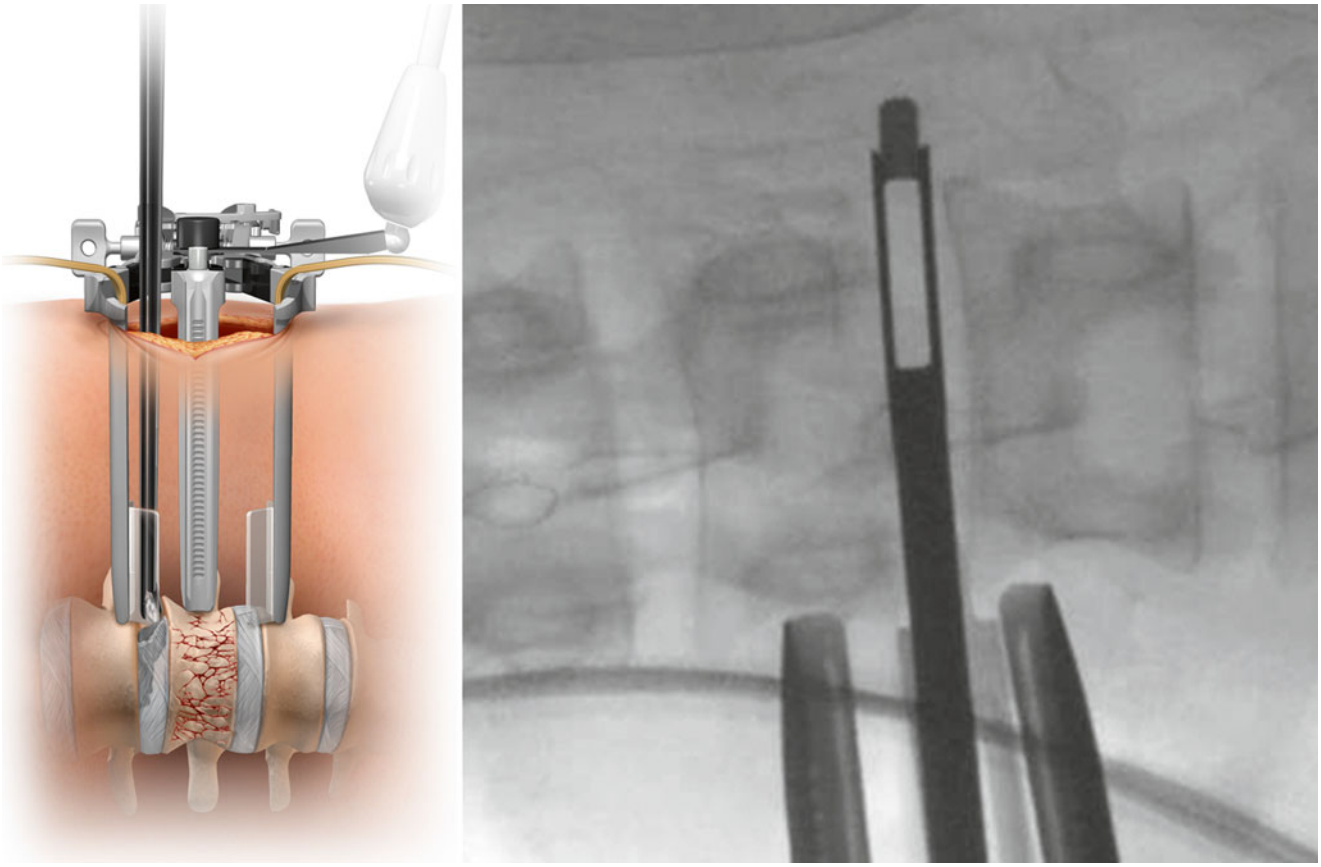

Fig. 32.12 AP illustration and intraoperative fluororadiography showing a discectomy adjacent to the corpectomy level (Copyright NuVasive, Inc., used with permission)

fusion (XLIF®, NuVasive Inc., San Diego, CA)) was developed in the late 1990s and first introduced in the literature in 2006 [68]. Being a less-invasive approach for access to the anterior column from the anterior plane, the lateral transpsoas approach has since been utilized for increasingly advanced applications into the thoracolumbar spine from approximately T4 to L5. Advantages of the approach include providing the "gold standard" anterior exposure for traumatic and tumor indications with less of the associated morbidity of thoracotomy [69].

The approach, in summary, involves blunt dissection to the lateral disc space, transpsoas in the lumbar spine: retro- or transpleural in the thoracic spine, through a minimally invasive (approximately 2–4 cm for interbody, 4–7 cm for corpectomy) incision. Advanced neuromonitoring is integrated into approach and procedural instrumentation to provide real-time discrete threshold and directional electromyographic (EMG) feedback about the lumbar plexus when performing lumbar procedures [70]. The utility of the mini-open lateral procedure in thoracic disease and thoracolumbar corpectomy has been previously described [69, 71–76], though less so in tumor applications [51, 66, 73].

Lumbar

Corpectomy in the lumbar spine using a mini-open lateral transpsoas approach follows the same general approach for lumbar interbody fusion. The retroperitoneal space is exposed through a 90° off-midline incision and the lateral border of the psoas muscle is accessed using blunt finger dissection. Sequential dilators integrated with advanced neuromonitoring (NV M5®, NuVasive, Inc.) that provides real-time geographic information about the lumbar plexus are used to access the lateral aspect of the anterior spine. In performing a lumbar corpectomy, separate exposures through the psoas muscle are used to first access the disc spaces above and below the corpectomy level. Complete discectomies and endplate preparation are performed to release the segment and prepare for fusion prior to performing the corpectomy (Fig. 32.12). At each access through the psoas muscle, fluoroscopy and diligent adherence to neuromonitoring should be followed. The third passage through the psoas muscle will be mid-vertebral at the vertebral body of the corpectomy. Upon exposure, the segmental artery should be identified and ligated. Lateral fluoroscopy (verified to be in a true lateral orientation, orthogonal to the floor) will provide

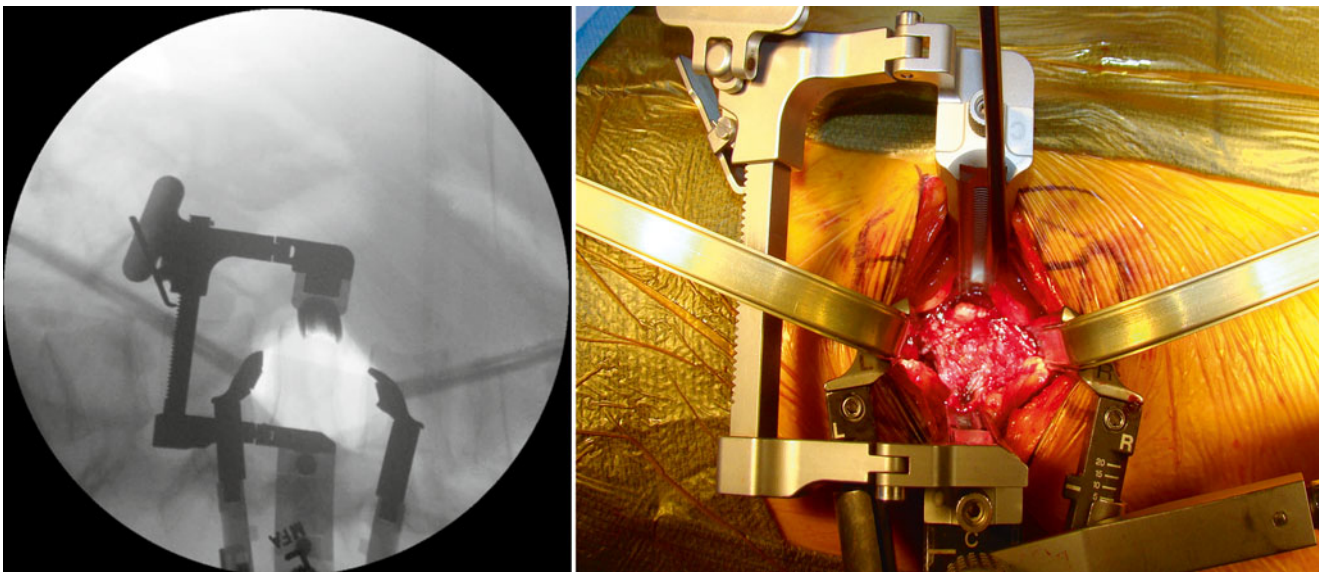

Fig. 32.13 Lateral intraoperative fluororadiography (*left*) and photograph (*right*) showing retractor placement in a mini-open lateral corpectomy, with the anterior and posterior borders of the surgical field defined by the anterior and posterior blades of the retractor. With these blades in place and a 90° working corridor confirmed on true lateral (orthogonal to the floor) fluoroscopy, the vessels anteriorly and dura posteriorly are avoided

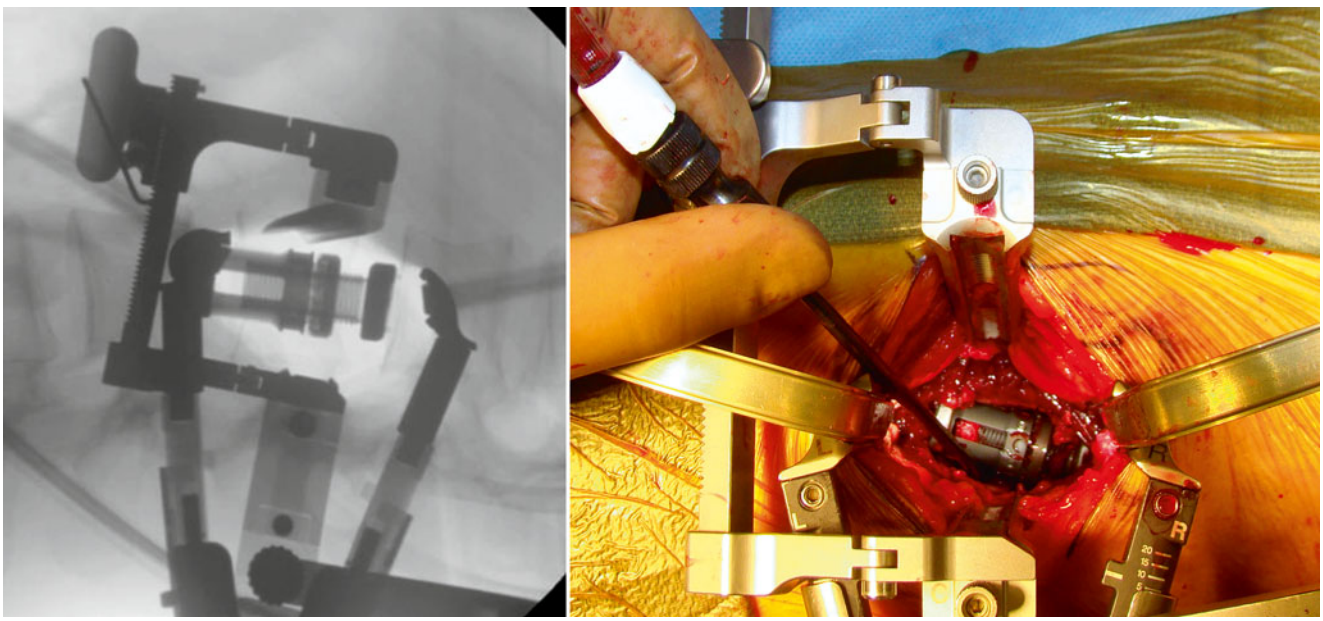

Fig. 32.14 Lateral intraoperative fluoroscopy (*left*) and photograph (*right*) showing wide-footprint cage placement in a mini-open lateral corpectomy

guidance for placement of the retractor and define the working window, limiting risk to sensitive anatomical structures. The center (posterior) blade establishes the working corridor anterior to the dura, while the anterior border of the retractor provides protection against injury to the great vessels (Fig. 32.13).

When performing the corpectomy in the lumbar spine, an Epstein curette can be used to remove bony elements from the posterior decompression site, as the position of the lumbar plexus may make direct visualization of the thecal sac challenging, especially in the lower lumbar spine. Following the corpectomy, a vertebral body replacement (VBR) device is placed and expanded to restore the segment. Anterolateral fixation can be used for single-incision corpectomy and fixation, or posterior fixation can be used (Figs. 32.14, 32.15, and 32.16).

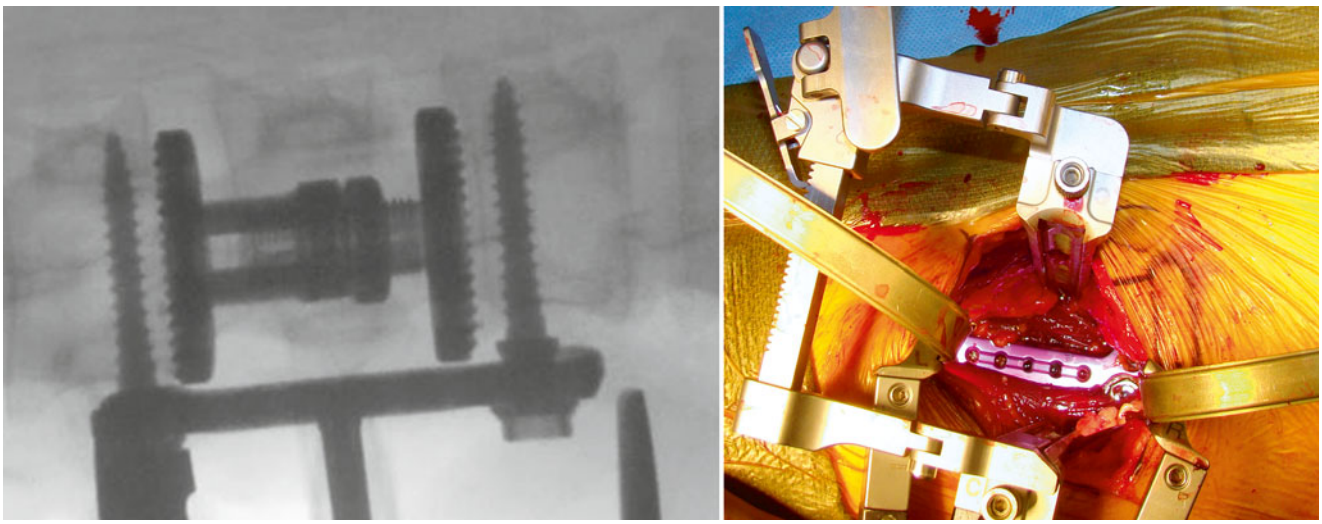

Fig. 32.15 AP intraoperative fluoroscopy (*left*) and photograph (*right*) showing wide-footprint cage placement and anterolateral plating in a mini-open lateral corpectomy

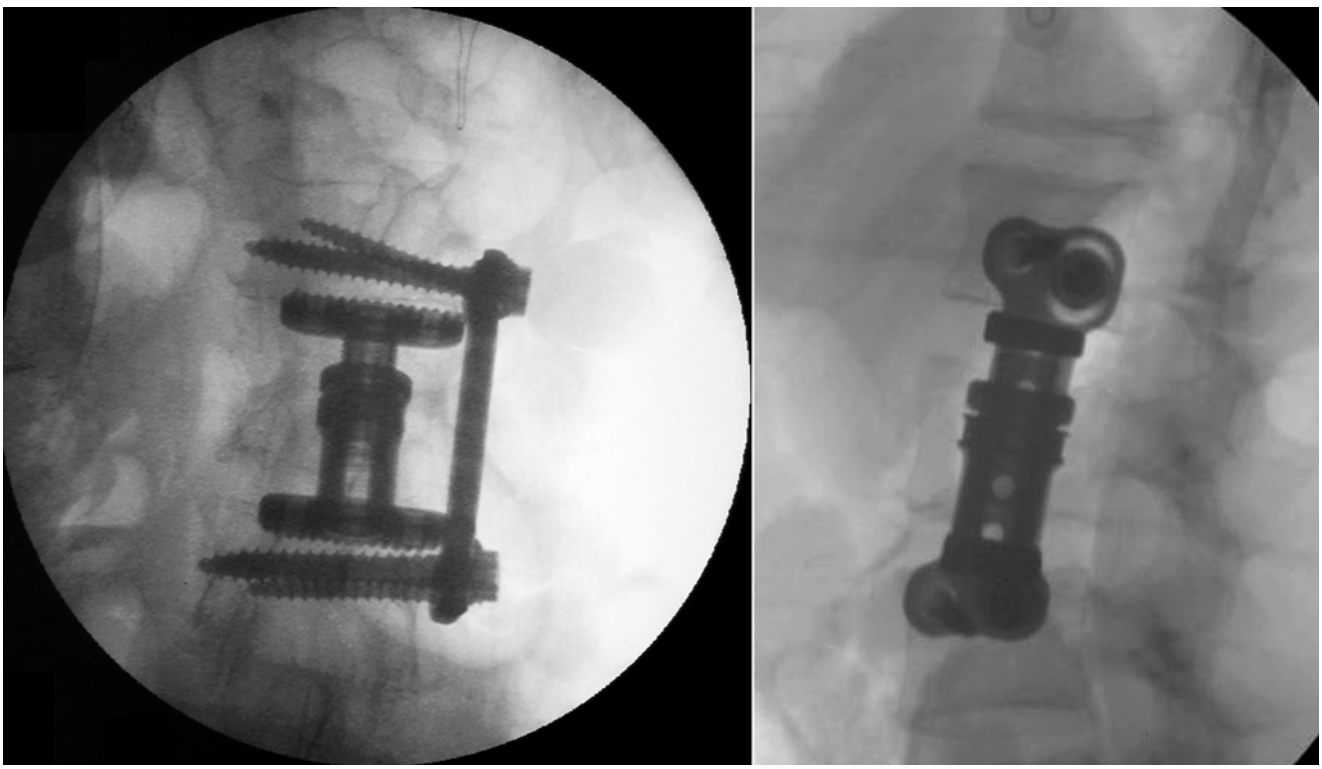

Fig. 32.16 AP (*left*) and lateral (*right*) intraoperative fluororadiography showing wide-footprint VBR device placement and anterolateral plating in a mini-open lateral corpectomy for 2-column stabilization from a single incision

Thoracolumbar Junction

A mini-open lateral approach at the thoracolumbar junction requires consideration of the diaphragm and the pleural cavity. Of note, in immunocompromised patients, the diaphragm may pose a particular challenge, as the tissue may be less pliable and more prone to violation. Maintenance of the diaphragm and the pleura decreases the risk of debris migrating to the lung, cancer spread, and general complications. In this application, retraction of the diaphragm protects lung parenchyma as well. It is essential in a mini-open lateral approach at the thoracolumbar junction to take care to follow natural tissue planes. This will limit dissection and lower morbidity. The anatomy of the thoracolumbar junction with respect to the mini-open lateral approach has been previously described

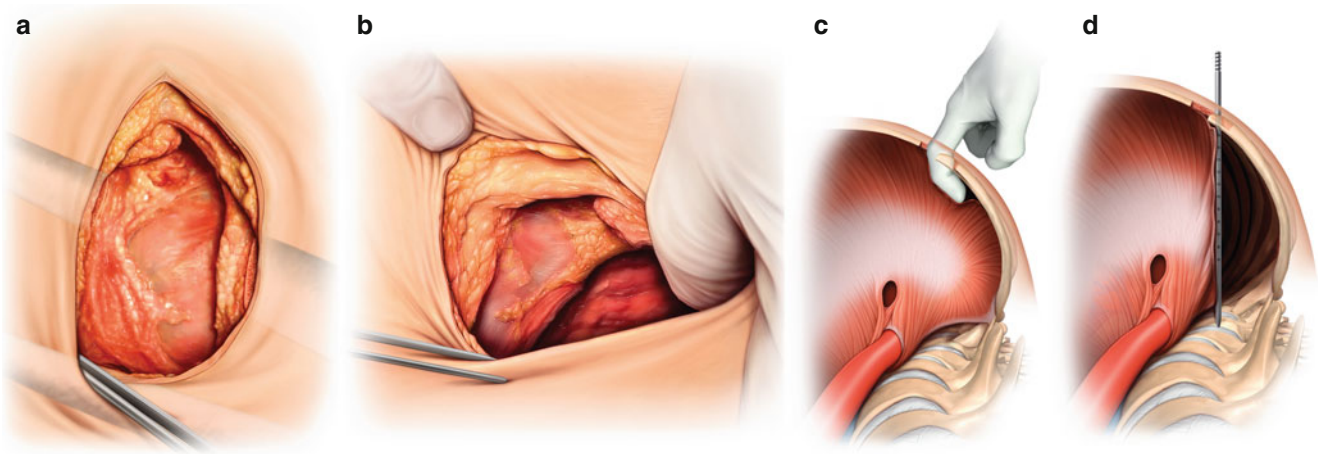

Fig. 32.17 Illustrations of rib resection (**a**) with pleural cavity exploration (**b**), diaphragm mobilization (**c**), and initial dilator placement into the retropleural space (**d**) in a mini-open lateral corpectomy at the thoracolumbar junction (Copyright NuVasive, Inc., used with permission)

in detail [73]. For thoracolumbar corpectomy, resection of a portion of the T11 rib at the incision site is typically required, though whichever rib will maximize exposure should be taken. The rib (e.g., T11 rib) at the exposure site should be resected starting with digital dissection of the T12 rib to mobilize the neurovascular bundle off of T12. Then the diaphragm should be mobilized medially and superiorly to develop the retropleural space to communicate with the retroperitoneal space. The exposure to the lateral spine should then be possible in the retropleural space (Fig. 32.17), and the retractor should be placed posterior enough so that access to the ipsilateral lamina, facet, and pedicle can be made. Upon docking on the lateral aspect of the spine, the posterior blade of the retractor (MaXcess®, NuVasive, Inc.) should be 10–20 mm shorter to account for docking on the rib head and to allow for better posterior exposure. The modular nature of the retractor allows for individualization of the exposure to minimize tissue disruption. Once at the level, the corpectomy procedure is performed with the same general procedure as in the lumbar spine.

There are several additional considerations at the thoracolumbar junction for a mini-open lateral approach. As the diaphragm travels superiorly, it blends with the pleura, so care is needed to maintain the structure's integrity. If the pleura is violated during the approach or procedure, the procedure may continue, though a chest tube should be placed postoperatively. Also if the diaphragm is violated during the procedure, repair is generally not required if the violation is less than 2 cm. Finally, often, the pleura extends to and folds over the vertebral body, so both layers need to be reflected in order to access the spine.

Thoracic

With experience, it is common to be able to develop a retropleural exposure up to the T6 or T7 levels, though in patients with systemic illness, the pleura may be fragile and require a transthoracic approach to the lateral spine. Advantages of a retropleural approach in the thoracic spine include the ability to reduce pulmonary complications or injury as well as limit seeding of tumor into the lung. The lung, also, will be better contained in a retropleural approach, whereas in a transthoracic approach will be directly retracted and will inflate somewhat between retractor blades into the surgical field. A laparotomy sponge can be placed on the border between the lung and the retractor blade for further protection of the lung during the procedure. The mini-open lateral approach in the thoracic spine simplifies anesthetic requirements by not requiring dual-lumen intubation, thus decreasing the risk of atelectasis and pneumonia postoperatively.

In lateral thoracic approaches, preoperative CT evaluation of the level to be treated is critical to establish the position of the rib head with respect to the canal, the disc, and the pedicle. Once docked on the lateral aspect of the thoracic spine, the rib head can be excised using rongeurs, a high-speed drill, or chisel based on surgeon preference. Once the rib articulation is removed, a pediculectomy (complete or partial) from the lateral approach can be performed to expose the spinal canal and dura, thus improving visibility and the ability to protect these structures under direct visualization. Of note, under intraoperative AP fluoroscopy, the high-speed drill can be used to thin down the pedicle from lateral to medial, realizing that aggressive removal can be performed with the drill so long as one works from the lateral to the medial border. The medial cortical layer of the pedicle can be removed at the end of this maneuver using a Kerrison punch or an equivalent instrument.

In thoracic, and all corpectomies, maximizing the footprint of the VBR is important to best reduce the deformity and maintain correction. Anterolateral plating provides two-column support through a single exposure and still allows for posterior fixation should additional stability be required.

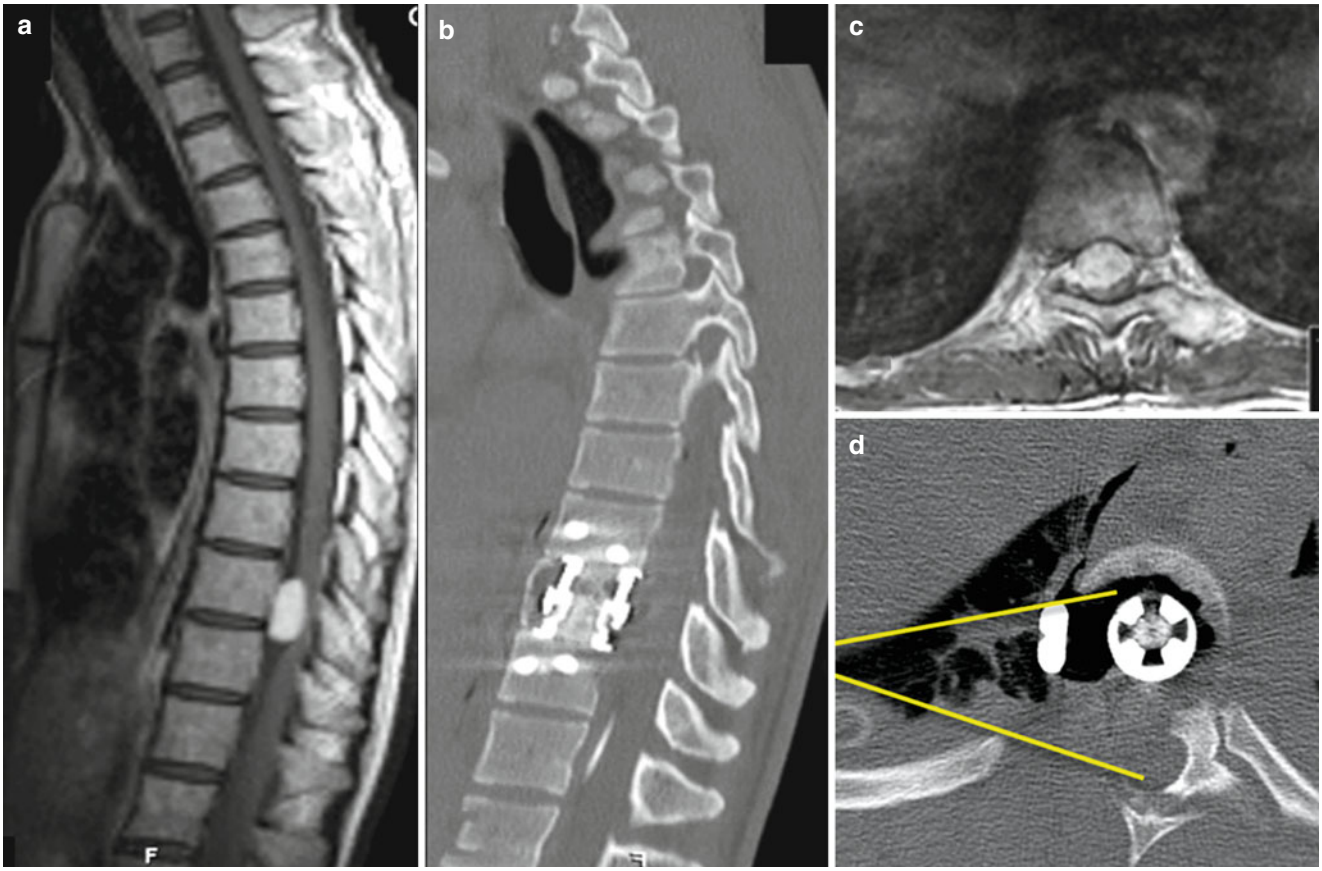

Fig. 32.18 Preoperative sagittal and axial magnetic resonance imaging (**a**, **c**) and postoperative sagittal and axial computed tomography (**b**, **d**) showing a T9 corpectomy for resection of meningioma and placement of an expandable titanium cage with supplemental anterolateral plating. Approximate exposure area of the mini-open lateral approach is indicated by the *yellow lines* (**d**)

Reported Results

In 2010, Uribe et al. [51] reported the results of 21 consecutive patients treated with the XLIF approach for thoracic neoplasm at two institutions over a 3-year period. Average patient age was 57 years and the majority of patients were male. The most common tumor type was meningioma, followed by neurofibroma, and plasmacytoma. Thirteen (62 %) underwent anterior corpectomy, 5 (23 %) underwent interbody fusion, and the remainder were left uninstrumented (e.g., neurofibroma removal). Mean follow-up was 21 months. In their series, the authors reported mean EBL of 291 mL (range 25–1,650 mL) and LOS of 3 days. Instrumentation included anterolateral plating (72 %) and pedicle screw fixation (28 %). One (5 %) postoperative complication occurred, pneumonia. Two patients had subtotal resection of their tumor and two patients died (one at 6 months, one at 12 months) due to their primary metastases during the follow-up period. Pain (visual analog scale [VAS]) and disability (Oswestry Disability Index [ODI]) improved by 62 and 53 %, respectively.

In a series of three cases treated with the XLIF approach for neurofibroma removal, Dakwar et al. [66] and found a mean EBL of 150 mL, ORT of 85 min, and LOS of 2 days, without complication and with substantial improvement of pain and function. Similarly, there was a report of a single retropleural neurofibroma located in the T11–T12 neural foramen treated with a retropleural approach for T11–12 XLIF [73]. Treatment characteristics included EBL of 150 mL and an ORT of 2 h without complication.

Case Examples

Case 1: A 30-year-old female presented with progressively increasing back pain and bladder dysfunction. Preoperative imaging revealed a T9 intradural meningioma (Fig. 32.18a, c). The patient was treated with a transpsoas approach for a T9 corpectomy with anterolateral plating with 240 mL of blood loss and was discharge home 72 h postoperatively (Figs. 32.18b, c and 32.19).

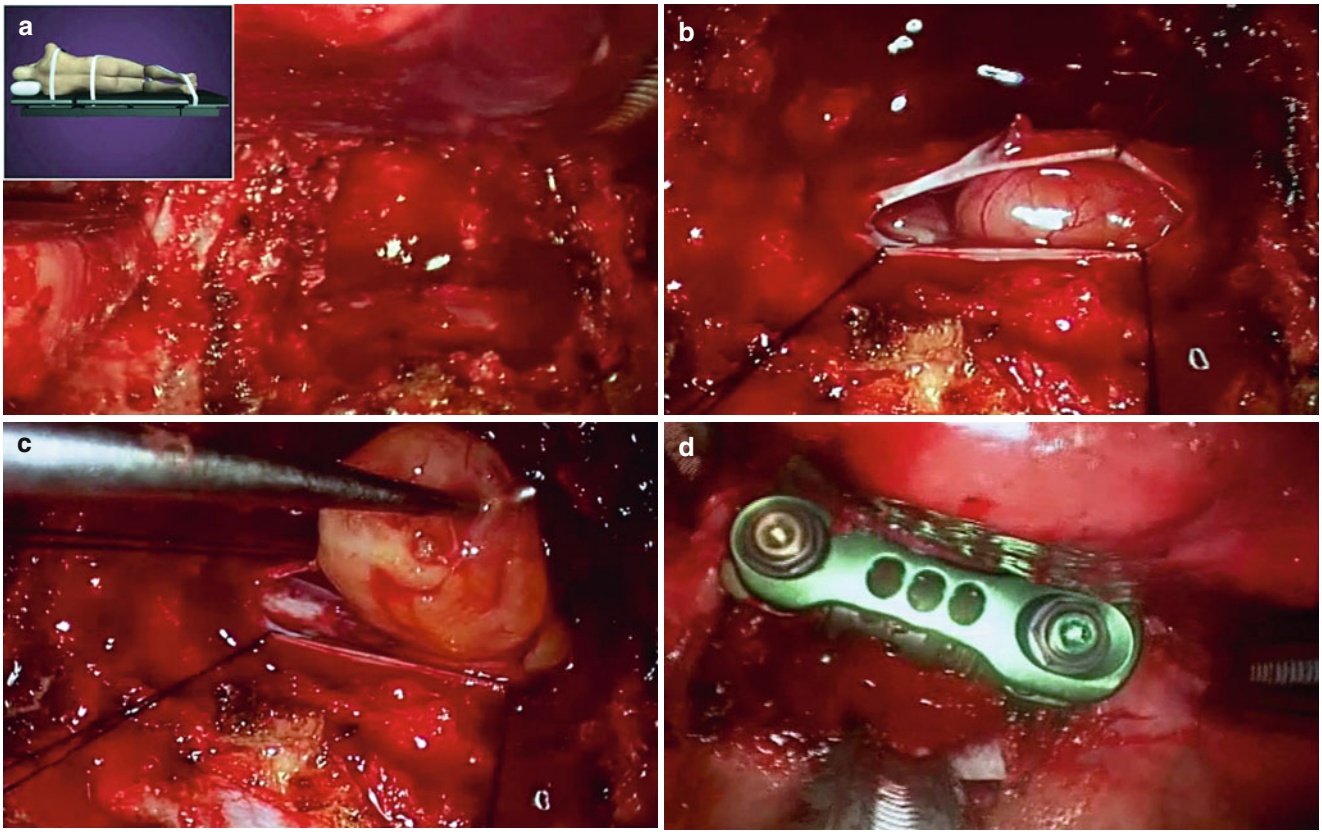

Fig. 32.19 Intraoperative photographs of T9 corpectomy illustrating exposure of the dura (**a**), intradural tumor visualization (**b**), tumor resection (**c**), and placement of an expandable titanium cage and lateral plate (**d**)

Case 2: A 43-year-old obese male with stage 1 squamous cell carcinoma of the tongue was treated in 2009 with radiation therapy and glossectomy. Recurrence occurred in 2010 in the left side of the neck which resulted in a left radical neck dissection. The patient presented in 2012 to the emergency room with severe back pain and bilateral lower extremity paresis. Computed tomography (CT) revealed a pathologic compression fracture of the T12 vertebral body with an approximately 2 cm T11 left vertebral body and pedicle lesion consistent with metastasis. MRI of the brain revealed an enhancing mass in the lateral aspect of the right cerebellar hemisphere, consistent with further metastases. The patient underwent a retropleural exposure for T12 corpectomy using a wide-footprint expandable cage and lateral-position laminectomy and facetectomy followed by anterior lateral plating (Fig. 32.20). No intraoperative complications occurred and the patient was discharged to hospice 10 days postoperative.

Case 3: Transpedicular technical example is included in Figs. 32.21, and 32.22.

Considerations/Conclusions

In the treatment of spinal neoplasms, the goals of surgery are dictated by the histology first and foremost, patient prognosis, overall patient health, tumor location, and patient preference. Therefore, the future of surgical treatment of spinal tumors may actually be an amalgamation of historical surgical techniques and a less-invasive approach. The surgical goals remain the same, yet hopefully the approach becomes less morbid.

The care of metastatic tumors to the spine is continually changing. This "shifting paradigm" of metastatic disease care may be reflecting a modified role for surgical intervention, improvements in, and development of new adjuvant therapies [77, 78].

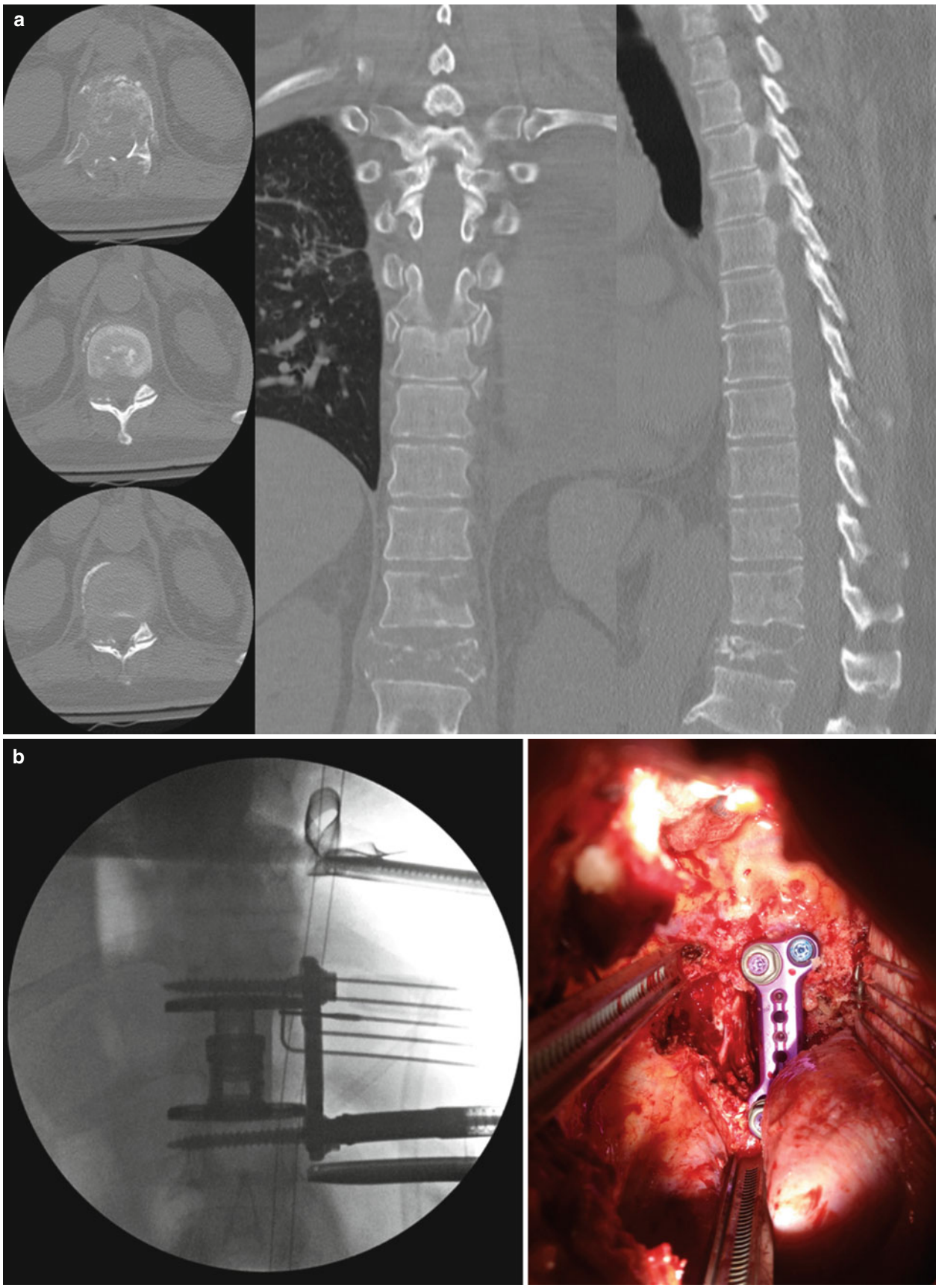

Fig. 32.20 Preoperative computed tomography (CT) showing T11 metastasis in the vertebral body and pedicle (**a**) treated with a retropleural approach for lateral corpectomy, laminectomy, and facetectomy (**b**) following by placement of a wide-footprint expandable cage with anterolateral plating (**b**, **c**). Postoperative axial CT shows area of decompression (approximately zones 4 through 11 on the WBB scale) available through the lateral XLIF approach for corpectomy (**d**) (Used with permission of Wolter Kluwer Health. From Boriani et al. [55])

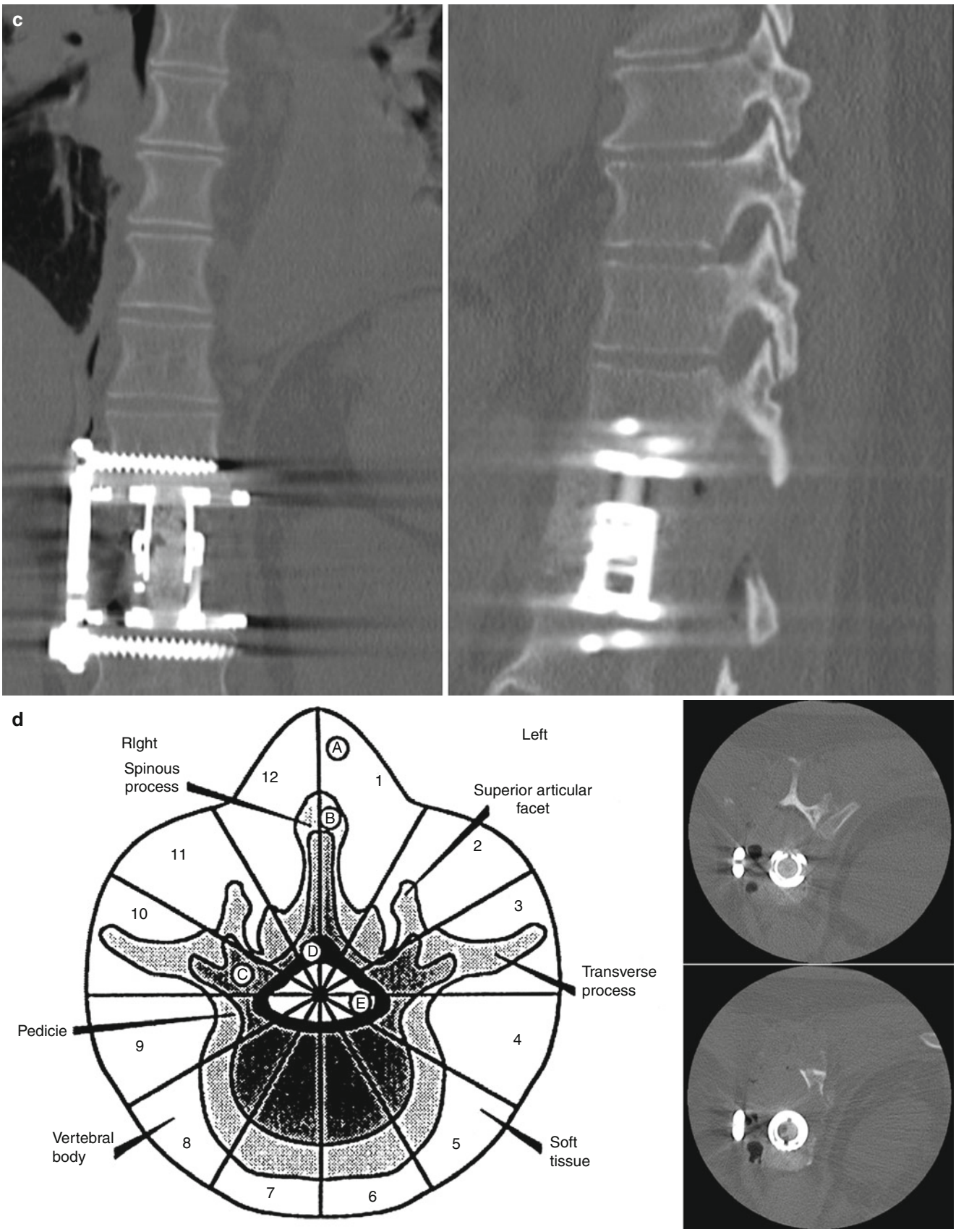

Fig. 32.20 (continued)

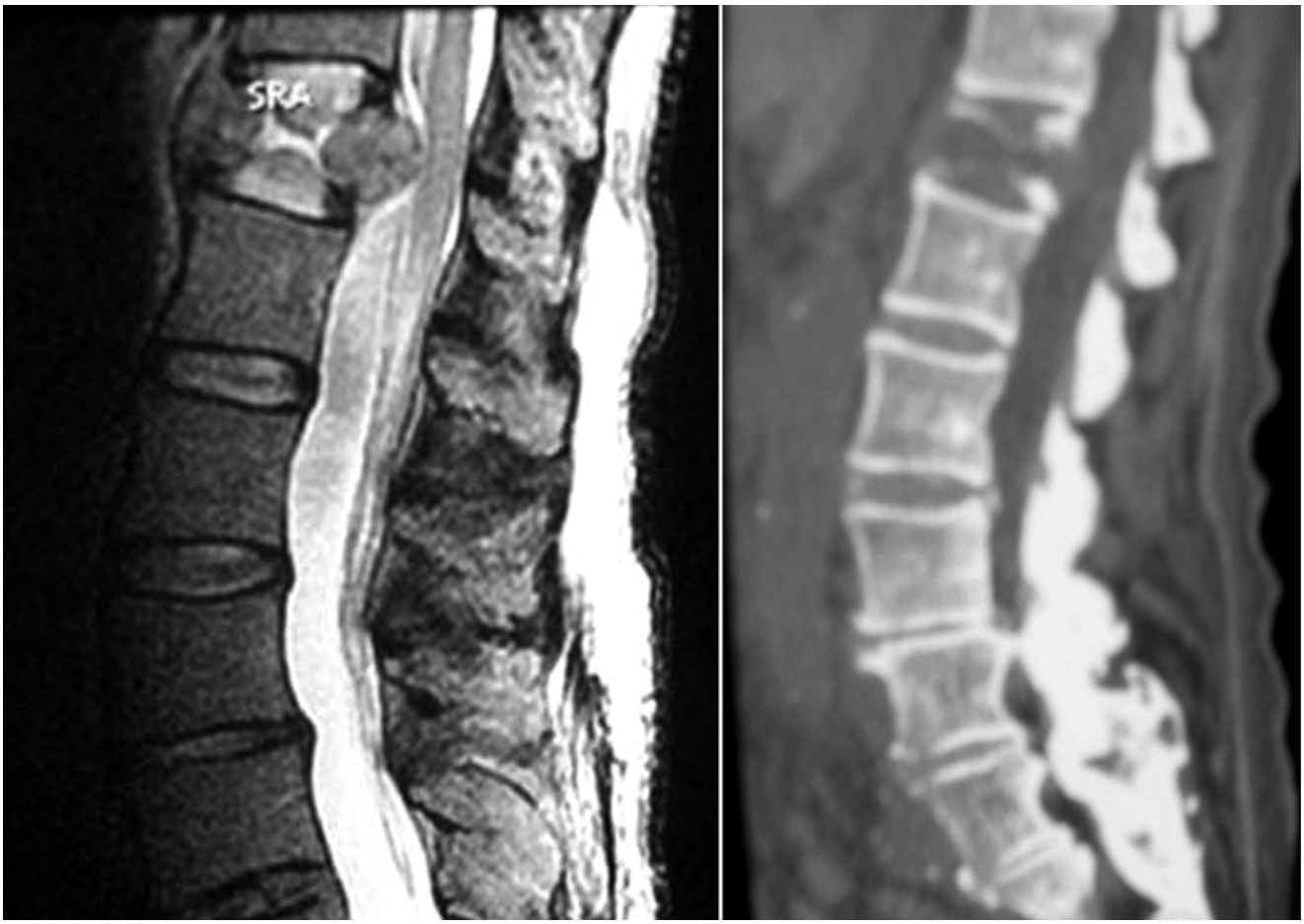

Fig. 32.21 Mid-sagittal magnetic resonance imaging (*left*) and computed tomography (*right*) of a metastatic T12 renal cell carcinoma

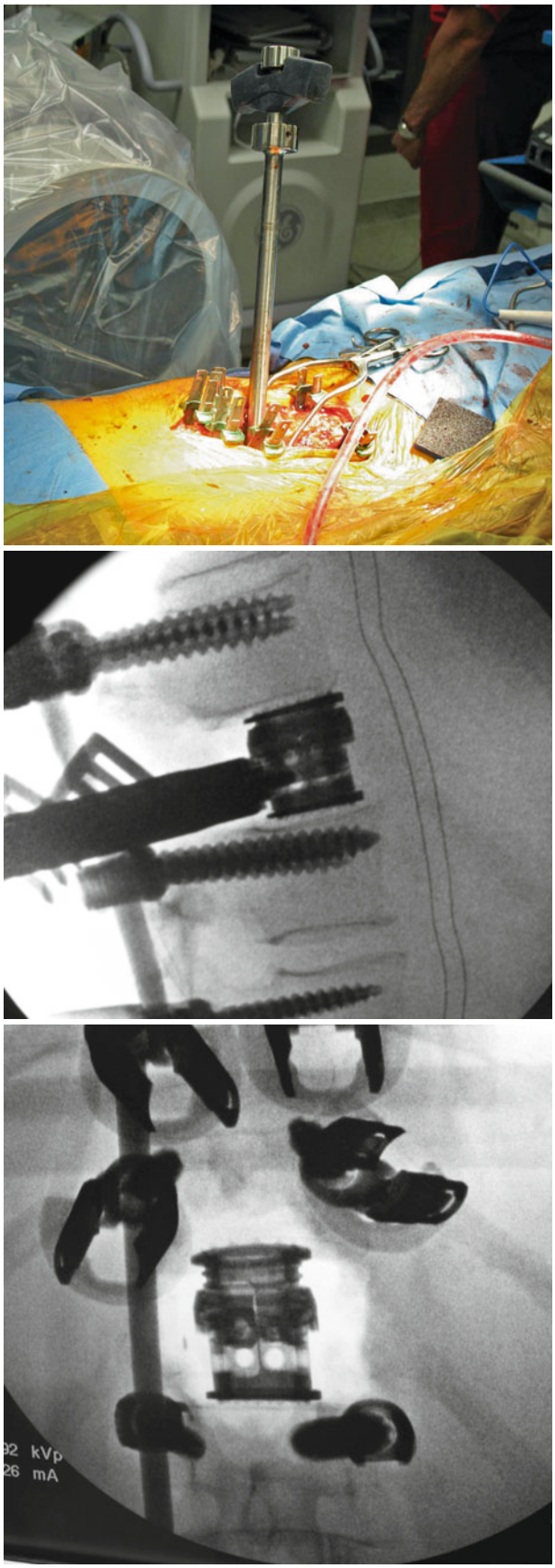

Fig. 32.22 Intraoperative photograph (*top*) and lateral (*middle*) and anterior-posterior (*bottom*) fluororadiography showing percutaneous screw placement including delivery and expansion of an expandable titanium cage in a bilateral transpedicular corpectomy

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Pathologic Fractures

33

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Introduction

Pathologic fractures are fractures that occur in weakened bone. Bone can be weakened by disease, cancer, infection, or the natural aging process. In the spine this usually occurs in the cancellous vertebral body, leading to vertebral compression fractures that can cause pain, neural compromise, and deformity. The most common cause of pathologic vertebral compression fractures is osteoporosis (85 %), followed by metastatic spine disease. Other less frequent conditions that can cause pathologic fractures of the spine include Paget's disease, osteitis, osteogenesis imperfecta, and bone cysts [1].

Epidemiology

Osteoporotic vertebral compression fractures (OVCF) are a serious health concern in the United States. These fractures affect approximately 25 % of postmenopausal women and almost 40 % of women 80 years of age and older [2–4]. In a Medicare population, patients with OVCF had twice the mortality over 8 years compared to age-matched controls [5]. It is estimated that approximately 750,000 OVCF occur annually in the United States with a healthcare cost of 13.5 billion dollars in 1995 [6]. The predicted increase of OVCF is estimated at 300 % from 1994 to 2044 [7].

Melton et al. showed the overall age- and sex-adjusted incidence rate of OVCF was 117 per 100,000 person-years in a group of residents from Rochester, Minnesota [8]. In this population of 341 patients, 47 (14 %) followed severe trauma, 282 (83 %) followed moderate or no trauma, and 12 (3 %) were pathologic. Incidence rates for fractures following moderate trauma were higher in women than in men and rose steeply with age in both genders. In contrast, fractures following severe trauma were more frequent in men, and their incidence increased less with age.

Human Cost

Vertebral compression fractures lead to a high rate of morbidity as well as impaired physical function and quality of life. Both lumbar and thoracic vertebral compression fractures can lead to a reduced lung vital capacity [9, 10]. Vertebral compression fractures cause chronic back pain, progressive kyphotic deformity, decreased activity tolerance, difficulty with sleep, depression, and loss of independence [11, 12]. Conservative treatments of vertebral compression fractures include bed rest, analgesics, and bracing. Bed rest and decreased physical activity lead to disuse osteoporosis, muscle deconditioning, deep venous thrombosis, pulmonary emboli, urinary tract infections, sacral decubiti, infections, and death [13]. Side effects from analgesics can include respiratory depression with narcotics and renal or gastrointestinal impairment caused by anti-inflammatory medications.

The treatment goals for pathologic compression fractures are to obtain a definitive diagnosis through biopsy, stabilization of the spinal column, preservation of neurologic function, and treatment of the root cause of the compression fracture. Minimally invasive surgery (MIS) is an appealing treatment option because of the ability to provide fast pain relief and stabilization while minimizing soft tissue damage associated with traditional open surgery and avoiding complications from prolonged immobilization. Thus, MIS may be performed in older or more debilitated patients who otherwise may not be candidates for open surgery.

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Indications for Treatment

Indications for surgical management of pathologic fractures include instability of the spinal column, pain, and neurologic deficits. The development of safe and effective techniques for stabilizing the spine affected by pathologic fracture, and for decompressing neural elements has expanded the indications for surgical care in the management of pathologic fractures [14, 15, 16]. MIS treatment of osteoporotic vertebral compression fractures preserves surrounding stabilizing spinal structures, decreasing the risk of instability and allowing for faster recovery. In debilitated patients who are medically contraindicated for open spine surgery, MIS offers a therapeutic alternative for pain relief, recovery of function, and sometimes a cure.

The indications for spine surgery in the setting of pathologic fractures or lesions have traditionally been spinal instability, progressive deformity or neurologic deficit, isolated metastasis, and primary tumor of the spine [17, 18]. The stability of the spinal column is an important consideration in choosing operative care for tumors involving the spinal column. The Spine Instability Neoplasia Score (SINS) is useful in quantifying radiographic and clinical characteristics that are associated with spinal instability [19]. MIS techniques, including percutaneous cement augmentation such as vertebroplasty and kyphoplasty, and minimally invasive internal fixation may restore stability to the spinal column while limiting the morbidity of an open surgical approach. MIS techniques may expand the indications to the treatment of intractable and debilitating pain unresponsive to palliative or conservative measures.

Spinal Stabilization

Stabilization Considerations

In the case of neoplastic spinal pathologic fractures, the goal of surgical stabilization is to provide a stable construct that will provide lasting pain relief. Bone grafting has a limited role in metastatic disease as the bone has a low capacity of healing, which may be further compromised by chemotherapy and radiation. However, high fusion rates have been reported with the use of rib or iliac crest autograft after en bloc vertebral resection [17, 20]. Spinal stabilization techniques can be divided into anterior and posterior approaches, which can be further subdivided according to spinal level: craniovertebral junction, subaxial cervical spine, thoracic spine, lumbar spine, lumbosacral junction, and sacral spine. Each of these areas should be evaluated individually as certain tumors have a local and regional predilection, and each region of the spine has its own characteristic biomechanical considerations. Different open surgical options [17, 21–27] may be indicated when accounting for factors such as the patient's overall health, level of activity, prognosis, tumor histology, and anatomic location [27, 28]. These same considerations should be applied when performing minimally invasive surgery.

At the craniocervical junction, the most common site of metastatic disease is the base of the dens. These can cause fractures associated with translational deformities, with a low incidence of neurologic deficit because of the wider diameter of the upper cervical canal. Patients often complain of mechanical neck pain from instability, and posterior spinal stabilization is usually the procedure of choice [29–31].

In the subaxial spine, anterior corpectomy is used to stabilize the spine and decompress the canal. This may require supplementation with posterior lateral mass screw stabilization, depending on the number of levels and the quality of bone. It is highly recommended to cross the cervicothoracic junction in order to prevent kyphotic deformity progression in multilevel fusions [31, 32].

Thoracic spine metastases most often affect the vertebral bodies. Because of the narrow diameter of the canal in this region, decompressive vertebrectomy and/or laminectomy is often indicated. This should be supported with posterior stabilization if the posterior stabilizing structures are compromised, or if multiple levels are involved, in order to avoid kyphotic deformity. Additionally, posterior stabilization should be performed if there is already severe kyphotic deformity. The thoracolumbar region is particularly vulnerable to kyphotic deformity because of the sagittal orientation of the facet joints. Additionally, there is a high concentration of stress at the thoracolumbar junction because of the transition from the more-stiff thoracic spine to the more-mobile lumbar spine [33, 34].

In the lumbar spine, a retroperitoneal anterior approach can be considered if there is extension of tumor into the retroperitoneal cavity. A posterior decompression and stabilization with or without vertebrectomy can also be performed and supplemented with posterior pedicle screws.

The lumbosacral junction experiences the highest concentration of spinal loads. To achieve maximum stability, careful consideration to surgical technique in placing S1 tricortical screw and long iliac screws is paramount, as high cantilever forces in the sacrum can cause hardware failure and/or sacral insufficiency fractures [35, 36].

Specific Techniques

Vertebroplasty and Kyphoplasty

Vertebroplasty was introduced in 1987 in France by Galibert to treat fractures of the spine secondary to hemangiomas. Acrylic cement is percutaneously injected into the fractured vertebral body via large bore cannulas for fracture stabilization [37]. Kyphoplasty emerged in 1994 with the proposed advantage of restoring vertebral height and reducing kyphotic deformity. Kyphoplasty uses an inflatable balloon tamp that is inserted in the vertebral body through one or both pedicles. The balloon

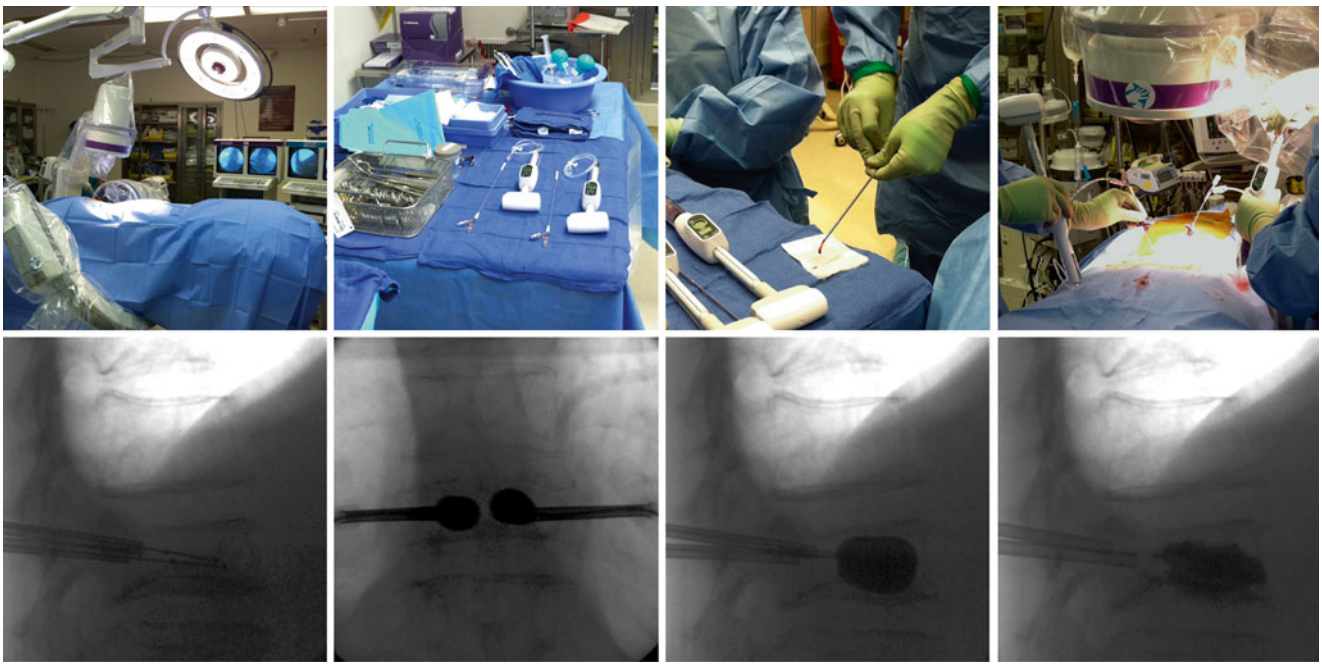

Fig. 33.1 *Top row*: intraoperative biplanar fluoroscopy setup, kyphoplasty balloon cannulas, core biopsy prior to cement augmentation, and cement augmentation. *Bottom row*: balloon expansion and cementation

is expanded, creating a cavity within the vertebral body, and cement is injected under biplanar fluoroscopic guidance [38, 39] (Fig. 33.1). Advantages of kyphoplasty over vertebroplasty include lower injection pressures with lower risk of cement extravasation and fracture reduction with restoration of vertebral body height, which can result in improved spine biomechanics [40–43]. Traditionally, radiopaque polymethylmethacrylate (PMMA) cements have been used, although new interest is emerging regarding the use of biocompatible calcium phosphate cements [44–46]. The applications of vertebroplasty and kyphoplasty have expanded to the treatment of other types of pathologic fractures, metastatic lesions, osteoporotic vertebral compression fractures recalcitrant to conservative treatment, and traumatic burst fractures [40, 47–51].

Minimally invasive percutaneous vertebral cement augmentation has revolutionized the treatment of pathologic vertebral compression fractures by providing immediate stability and pain relief, allowing for fast recovery and return to preinjury level of activity. Mechanisms of pain relief may involve fracture stabilization, heat-induced cytotoxic necrosis of nerve endings, and tumor necrosis from the high curing temperatures and the acrylic content of PMMA cement [52–54].

Minimally Invasive Posterior Approach

Early attempts at minimally invasive surgery in the setting of pathologic fractures consisted of performing circumferential decompression, reconstruction, and stabilization through a posterior-only approach as opposed to an anterior-posterior combined approach. Many variants of anterior thoracolumbar corpectomies from a posterior-only approach have been described [55–59]. With the advent of expandable reconstruction cages and percutaneous screw placement, thoracolumbar corpectomies can now be performed from a posterior approach with minimal soft tissue damage through a mini-open approach [60, 61].

Mini-open Transpedicular Corpectomy

The term minimally invasive surgery for posterior-based corpectomies is controversial, as MIS is often associated with the use of endoscopes. Although transpedicular corpectomies have been described in the past [62], Chou et al. recently described the surgical technique utilizing a mini-open approach with an expandable reconstruction cage [63].

Technique

A midline posterior skin incision is made down to the fascial layer. Percutaneous pedicle screws are placed through the fascia, and the fascia is then incised the length required to excise the vertebral body, thus minimizing soft tissue dissection. The authors reported that they went away from using multiple stab incision through the skin because it had a higher rate of infection and also was cosmetically unappealing. Once the vertebral body is dissected, the corpectomy starts on one side by first isolating and removing the pedicle and then the lateral aspect of the vertebral body by piecemeal resection. Before proceeding to the contralateral side, a

temporary rod is used to stabilize the corpectomy. The posterior longitudinal ligament is removed from the ventral dura, and meticulous endplate preparation is carried out if discectomy is necessary. A trap-door rib-head osteotomy is performed in the thoracic spine allowing rib-head mobilization and placement of an expandable cage [64]. Thoracic corpectomies may necessitate ligation of a unilateral nerve roots. The corpectomy void and cage are filled with the graft material of choice and the cage is placed and expanded under direct visualization and fluoroscopic guidance (Fig. 33.2).

Minimally Invasive Anterior Approaches

Anterior minimally invasive approaches to pathologic spine fractures can be divided into endoscopic-assisted approaches and tubular-assisted approaches from a direct lateral entry. These techniques are not designed to allow for wide surgical margin excision, and thus may not be curative, and are therefore seldom indicated for the treatment of primary spine tumors. These minimally invasive techniques can however present an attractive alternative for debilitated patients with spinal metastatic disease, osteomyelitis, and fragility and traumatic vertebral compression fracture where the main objective is not to provide cancer cure but to provide decompression and stabilization with the minimal amount of collateral damage.

Simultaneous Thoracoscopic and Posterior Decompression and Stabilization

If posterior decompression along with anterior corpectomy is deemed necessary to obtain appropriate decompression of the neural element, the patient can be positioned prone. Surgery can then proceed with a traditional decompression laminectomy and instrumented stabilization followed by thoracoscopic anterior corpectomy and reconstruction following the same principles stated above. The only difference is the working angle of the thoracoscope and thoracoscopic instruments coming from a posterior to anterior direction in the thoracic cavity [65].

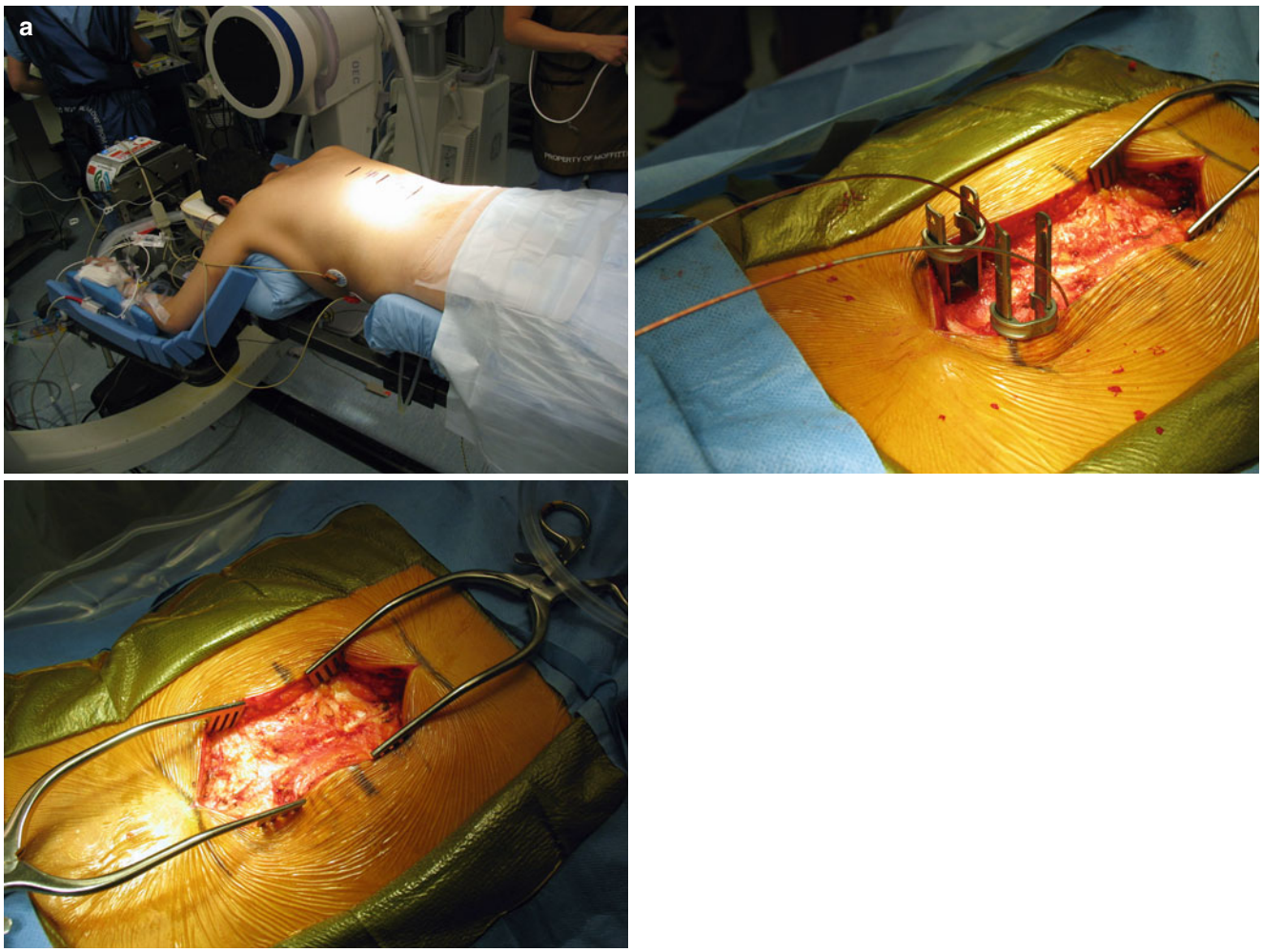

Fig. 33.2 Mini-open transpedicular corpectomy. (**a**) Patient positioned prone with fluoroscopic localization of levels and incision down to fascia. (**b**) Fluoroscopically assisted percutaneous screw placement through the fascia, mini-open fascial incision with circumferential spinal canal decompression after corpectomy, and fluoroscopically assisted placement of reconstruction expandable cage

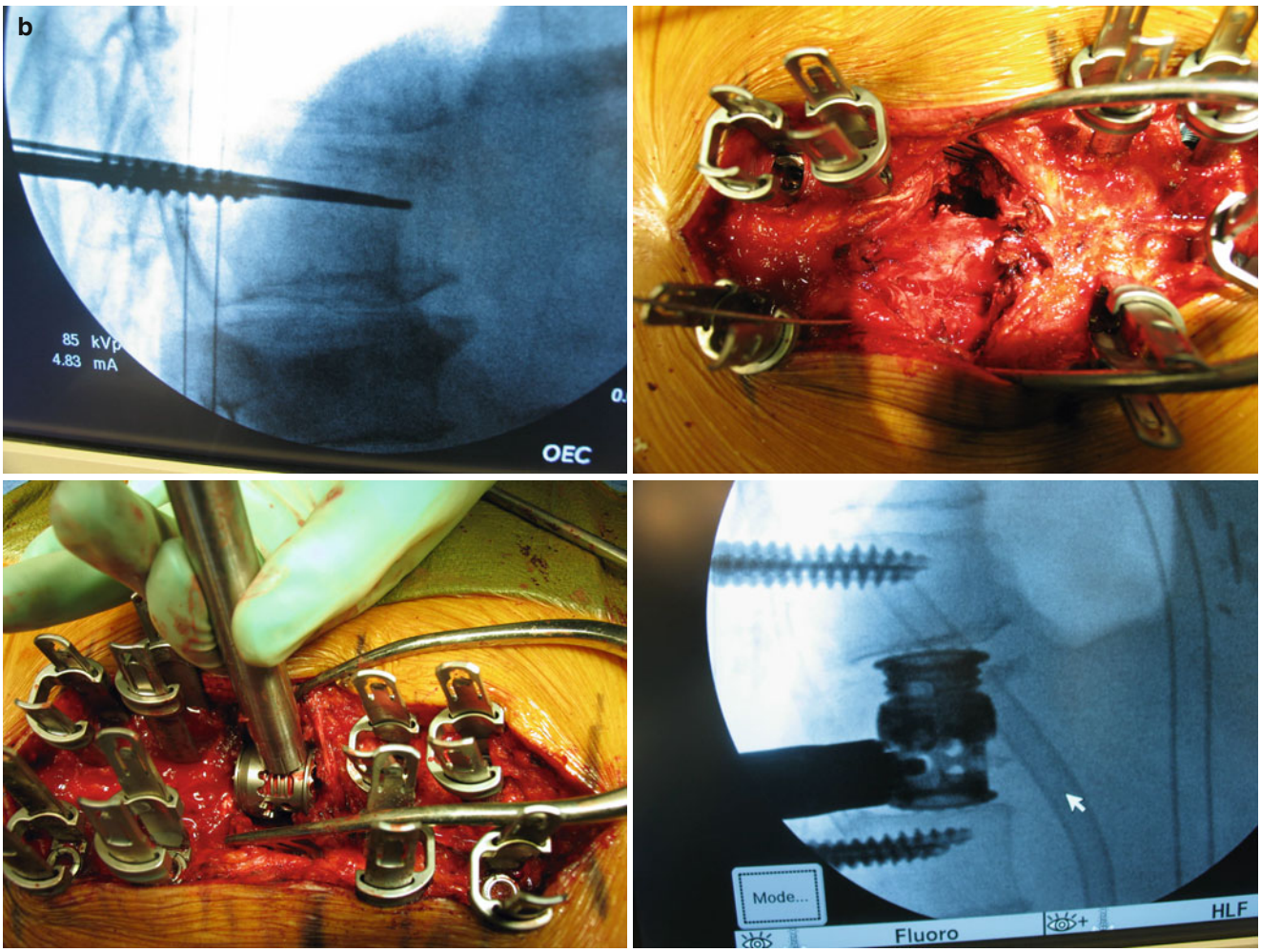

Fig. 33.2 (continued)

Endoscopically Assisted Posterolateral Thoracic Approach

Endoscopic techniques can also be utilized to decrease the morbidity of fully open techniques [66–68]. A few authors have used the endoscope to aid in the visualization of the anterior and contralateral structures when performing a posterolateral open thoracic decompressive vertebrectomy from a posterior approach.

Technique

The patient is placed prone on a Wilson frame in order to preserve thoracic kyphosis and aid in the decompression. A standard open laminectomy is performed at the affected level through a midline incision, exposing the spinous process, lamina, transverse process, and proximal rib. A corpectomy is undertaken through a unilateral transpedicular approach and the visible tumor is excised piecemeal with the aid of curettes, rongeurs, and high-speed drills. A 70° endoscope can then be introduced to aid in visualization and decompression of the dura and to finalize the corpectomy on the contralateral side. The corpectomy defect can then be reconstructed with an expandable reconstruction cage. This technique can avoid the morbidity of transthoracic surgery in carefully selected patients.

Endoscopic Lumbar Approach

Although endoscopic or laparoscopic procedures are common in general surgery to address intra-abdominal pathology, these procedures have not experienced the same widespread use in the treatment of lumbar spinal pathology. This is likely due to the complex anatomy and vital structures that are present and are more at risk of injury from mobilization from endoscopic portals as well as the fact that the open anterior lumbar approach is not as morbid as the open anterior thoracotomy. Indeed, while there are some anecdotal reports of lumbar endoscopic discectomies and fusions, this technique has not experienced the same widespread use [69–73].

Technique

The patient is placed in the supine position with bolsters underneath the hips to accentuate lumbar lordosis and at 30° of Trendelenburg to facilitate cephalad retraction of the abdominal contents. The first portal is established through

the umbilicus and CO_2 is insufflated to a pressure of 15 mmHg. A trochar is placed and a 30° endoscope if introduced. Under direct visualization, accessory portals are created lateral to the epigastric vessels. These portals serve to pass vessel retractors as well as dissecting monopolar Endo Shears. The ureters must be identified and protected. Dissection proceeds by mobilizing the sigmoid colon right to left to access the aortic bifurcation in the retroperitoneal space. A suprapubic portal allows direct access to the sacrolumbar junction. If necessary, the middle sacral artery (at the L5–S1 level) or the left iliolumbar vein (at the L4–L5 level) may be mobilized and ligated. The inferior hypogastric sympathetic plexus at the level of the inferior vena cava needs to be identified and protected to avoid retrograde ejaculation in males and vaginal dryness in females. After the great vessels are safely mobilized and retracted, endoscopic decompression can be performed. Before closure of the portals, the CO_2 insufflation is reduced to assess hemostasis. The posterior parietal peritoneum is repaired and the portals closed.

Direct Lateral Approach

A direct lateral approach to the lumbar spine initially developed as a minimally invasive lumbar interbody fusion technique by Ozgur et al. has also been utilized to perform minimally invasive corpectomies in the setting of pathologic fractures [74]. Depending on the level being treated, a direct lateral corpectomy can be performed through a transthoracic/transpleural access (T11 and above), a retropleural/extracavitary access (T12–L1: thoracolumbar junction), or a retroperitoneal/transpsoas access (below L1).

Technique

The patient is placed in the direct lateral decubitus position with the break of the table at the level of the greater trochanter for thoracolumbar or lumbar approaches or at the mid-thoracic level for thoracic approaches. All bony prominences are well padded and the patient is secure to the table with tape. The surgical table can then be flexed to increase the rib-pelvis or intercostal distance and facilitate exposure. The OR table is then rotated and titled as necessary to provide a perfect AP and lateral fluoroscopic image of the appropriate vertebral level while maintaining the C arm at perfect right angles to the floor. The vertebral level is identified with K-wire under lateral fluoroscopy (Fig. 33.3).

Transthoracic/Transpleural Access

A 5-cm oblique incision is made in between the ribs at the level of the vertebral body and at the midaxillary line. If a portion of rib needs to be resected for exposure, it is carefully dissected subperiosteally from its intercostal muscles with the aid of a rib dissector tool in order to preserve the neurovascular bundle at the inferior rib border. A 5-cm rib segment can be resected with a rib removal tool and the bleeding bone edges are covered with bone wax or Gelfoam. The parietal pleura overlying the excised rib is then incised, permitting entrance into the pleural cavity. The diaphragm and lung are identified and retracted anteriorly as needed to allow passage of the sequential tubular dilators over a K-wire. During a left-sided approach, the aorta and hemiazygos vein are retracted anteriorly. Care should be exercise to avoid damage to the segmental vessels. Once the position is confirmed via fluoroscopy, the tubular retractor is placed over the dilators and secured to the operating room table rail with an articulating arm. A pointed shim or screw is used to dock the retractor to the vertebral body. Bifurcated light cables are affixed to the inner aspect of the retractor blades to permit clear visualization. The retractor blades can then be expanded to allow proper access to the entire vertebral body. Final docking and retraction are assessed with AP and lateral fluoroscopy [75–78].

Retropleural/Extracavitary Access

The initial steps are similar to that of the transthoracic access. Once the rib is cut, careful dissection of the parietal pleura from the endothoracic fascia is carried out. The pleura is then mobilized anteriorly. This permits visualization of the diaphragm whose attachment is then dissected from the inner surface of the rib wall and allows access to the thoracolumbar junction. The tubular retractor is then placed following the same steps as above [76–78].

Retroperitoneal/Transpsoas Access

This approach can be executed with one or two skin incisions depending on the surgeon's comfort and/or preference. The single-incision technique places the incision right over the vertebral body. The accessory skin incision is placed posterolaterally to the first incision and aids in sweeping the contents of the peritoneal cavity anteriorly. Blunt dissecting scissors are used to spread the abdominal muscles and prevent damage to the superficial neural structure (iliohypogastric nerve) that can contribute to postoperative pain. Loss of resistance from the muscle tissue indicates arrival into the retroperitoneal space. The index finger is used to sweep the peritoneal contents anteriorly and create a working space for the tubular retractors. The psoas and transverse process can then be palpated. Dilators are the safely guided down to the surface of the psoas muscle. The lumbar plexus travels through the psoas muscle and is at risk during this approach; careful neuromonitoring, specifically electromyography (EMG), as well as anatomical knowledge, is essential [76, 79–83].

Once the tubular retractor is safely positioned, decompression can proceed with osteotomes, curettes, Kerrison Rongeurs, and high-speed drills designed for tubular access.

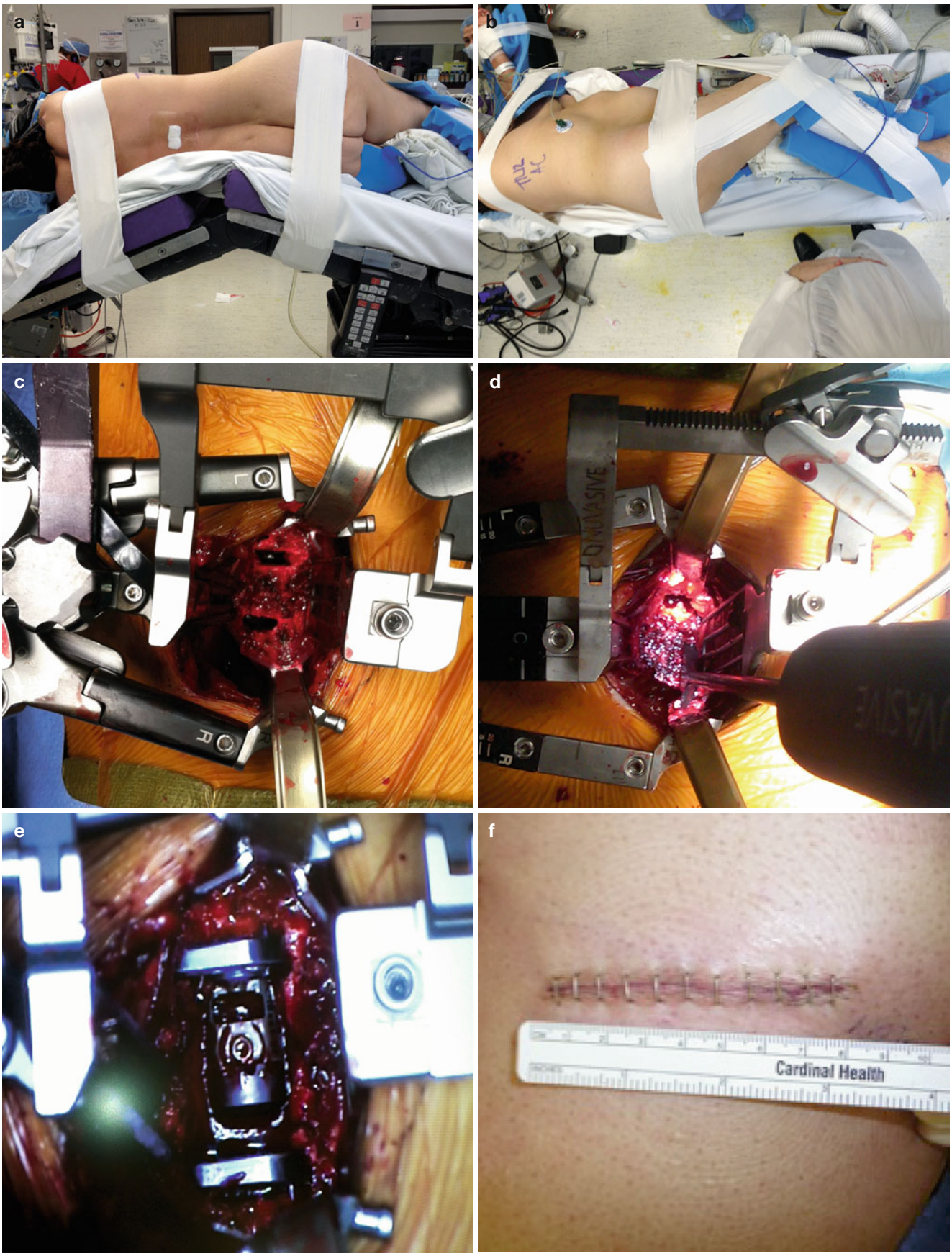

Fig. 33.3 Minimally invasive direct lateral approach, showing (**a**, **b**) patient in left lateral decubitus position, (**c**, **d**) discectomies and piecemeal resection of fracture with osteotome, (**e**) expandable reconstruction cage in place of corpectomy defect, (**f**) final incision, and (**g**) fluoroscopic AP and (**h**) lateral images verifying appropriate placement of cage and pedicle screws

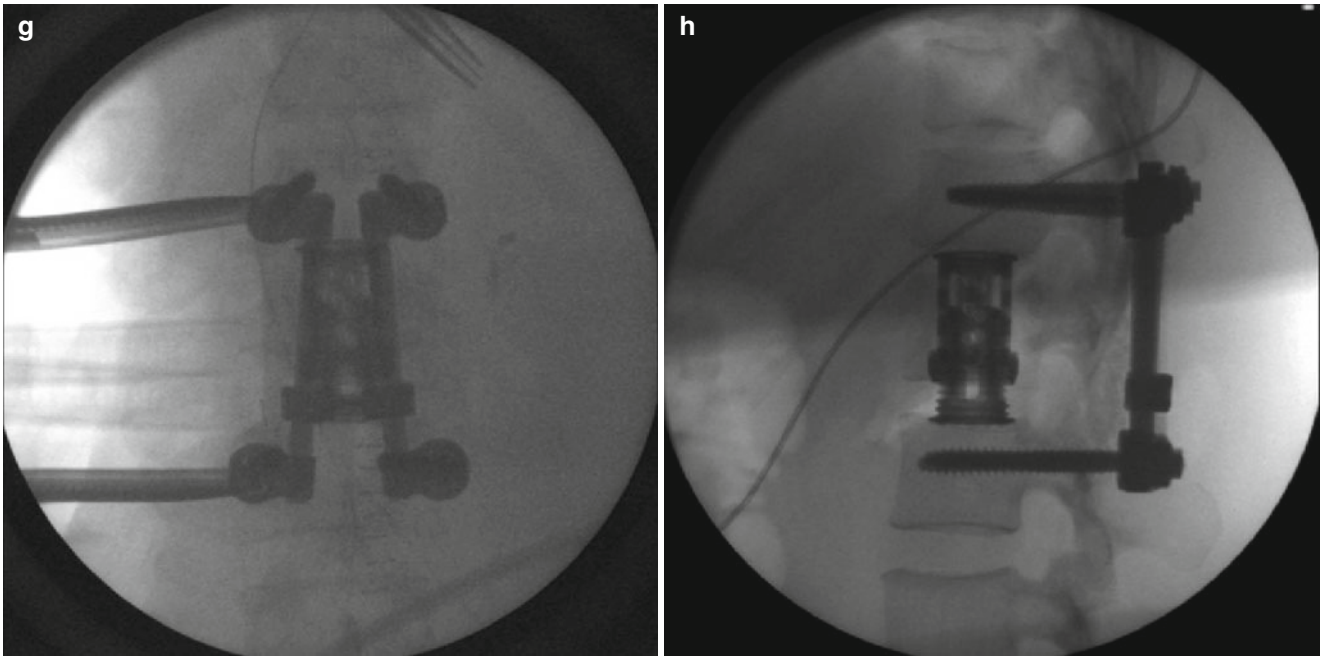

Fig. 33.3 (continued)

Ipsilateral corpectomy can be performed from this approach if it contributes to neural compression. The corpectomy defect is stabilized with an expandable cage. The construct can be further stabilized with a lateral plate placed through the tubular retractors or with unilateral percutaneous pedicle screws placed in the same lateral decubitus position, or with bilateral percutaneous pedicle screws that require placing the patient in the prone position.

Case Reports

Kyphoplasty

A 78-year-old woman with metastatic breast cancer and recent radiation treatment to the thoracic spine presented with 4/10 mid-thoracic back pain worsened with sitting and standing and relieved by bed rest. Plain film X-rays showed a compression deformity at T7 and T8, and MRI revealed epidural extension of tumor causing moderate spinal canal stenosis (Fig. 33.4).

Treatment options included conservative management, kyphoplasty, or open reconstruction of her spine. Because of her medical comorbidities, the patient and surgeon agreed that open spinal reconstruction was not a safe option. Initially the patient was managed with conservative therapy.

However, the patient returned to clinic 2 weeks later with significantly increased pain and disability that limited her ability to stand or walk. Kyphoplasty at T7 and T8 was performed. No cement extravasation was observed.

The patient was awoken from anesthesia without any complications, with significant pain relief, and was discharged home the same day. At her 4-week postoperative clinic visit, the patient denied any pain and had regained her pre-fracture level of function.

Mini-open Posterior Approach

A 56-year-old woman with a history of colon cancer resected 2 years earlier presented with debilitating back pain and lower extremity weakness. She was found to have a pathologic fracture at T12 caused by a metastatic lesion with epidural extension causing cord compression.

The patient underwent a mini-open posterior transpedicular corpectomy of T12 for removal of tumor and decompression of the spinal cord. An expandable cage was placed at the T12 level and the patient also underwent posterolateral fusion from T11 to L1.

She was awoken from surgery with no complications and was able to self-ambulate with a walker on post-op day four. She was discharged on post-op day six with a patient-controlled pain pump. Unfortunately the patient developed disseminated metastatic disease with recurrent neurologic deficit and went on to receive palliative radiation therapy (Fig. 33.5).

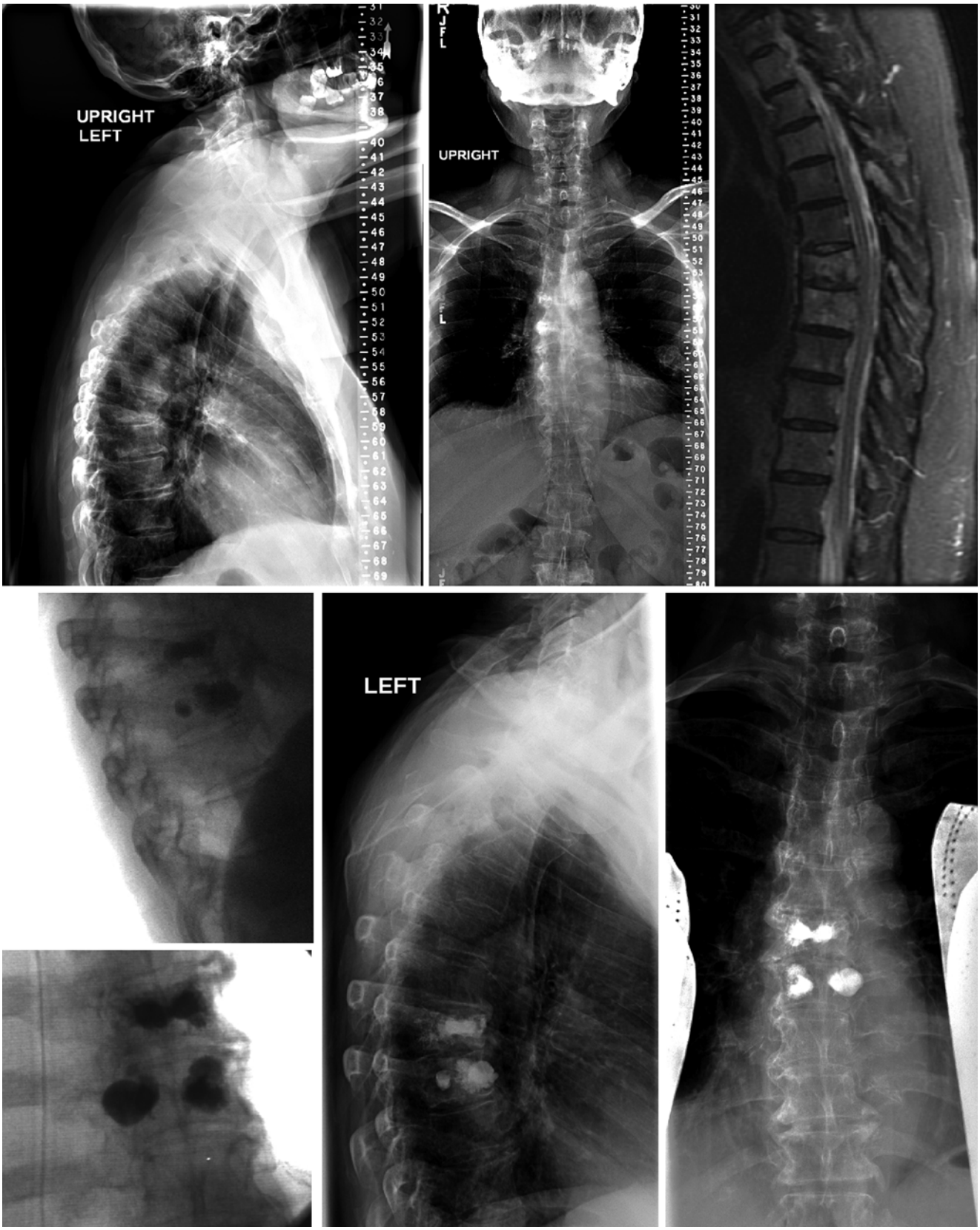

Fig. 33.4 Preoperative (*top*) and intraoperative and postoperative (*bottom*) images of a patient treated with kyphoplasty for painful vertebral compression fractures due to metastatic breast cancer

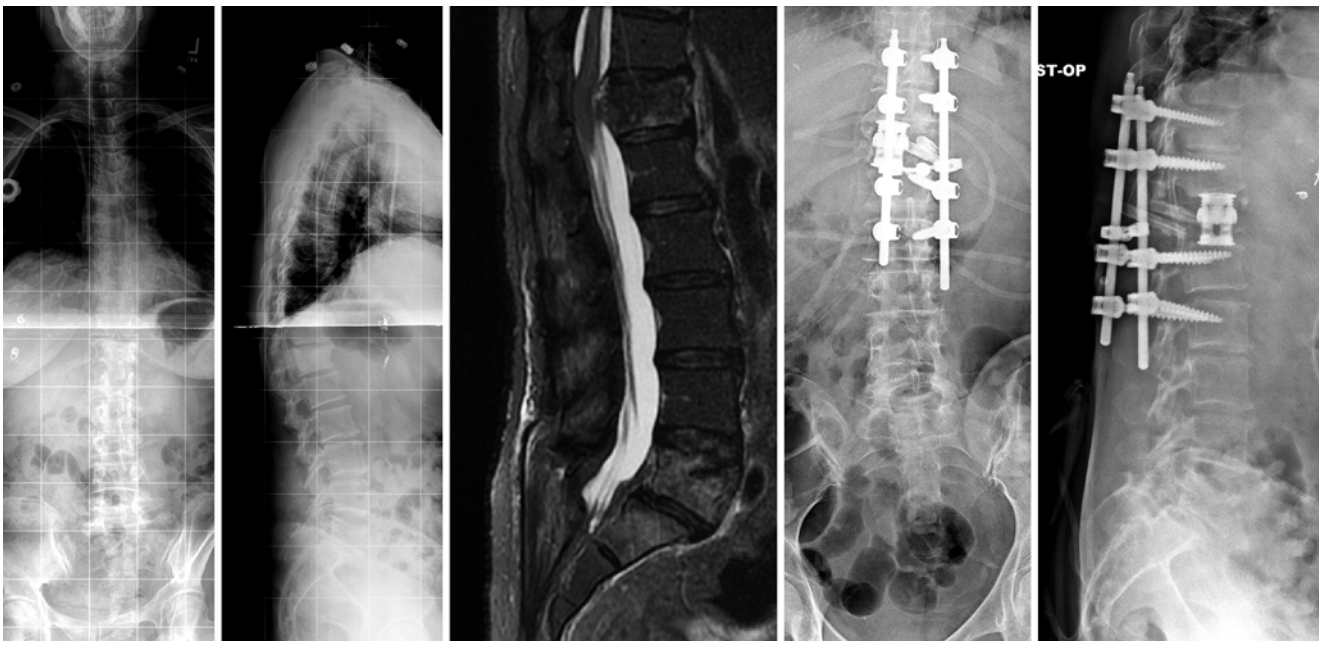

Fig. 33.5 Preoperative plain films and MRI of a patient with metastatic colon cancer and a pathologic fracture at T12 (*left*). She was treated with a mini-open posterior transpedicular corpectomy (*right*)

Direct Lateral Approach

A 59-year-old woman with a history of hepatitis C with liver cirrhosis presented with severe lower back pain and left leg weakness. She was found to have a vertebral fracture at L1 and was initially bedbound. Vertebral biopsy revealed undifferentiated adenocarcinoma and the primary site was found to be adenocarcinoma at the gastroesophageal junction. She was also found to have metastases to the liver and lung. Prognosis was greater than 6 months.

The patient underwent a two-stage procedure. First, a posterior incision was made and dissection carried down to the fascia. Percutaneous pedicle screws were placed from T10 to T12 and from L2 to L3. A mini-open excision of the L1 lamina was performed. Next, the patient was repositioned in the right lateral decubitus position. Retropleural dissection and direct lateral corpectomy of L1 was performed and an expandable cage was placed (Fig. 33.6).

The patient remained in the intensive care unit for 3 days because of intraoperative blood loss and hypovolemia. She was subsequently discharged on postoperative day ten with a TLSO brace and home physical therapy. She had complete resolution of her left leg weakness and her back pain.

Outcomes and Complications

Kyphoplasty and Vertebroplasty

There remains controversy about the efficacy of kyphoplasty and vertebroplasty for osteoporotic vertebral compression fractures. The American Academy of Orthopaedic Surgery guidelines recommend against the use of vertebroplasty for osteoporotic spinal compression fractures without neurologic deficits, and they give a weak recommendation for kyphoplasty [84]. However, debate continues as large prospective randomized studies report conflicting results [85–87].

Symptomatic complications related to vertebroplasty or kyphoplasty are relatively rare and are mostly related to PMMA cement leakage causing epidural or foraminal compression of neural elements. Patients with vertebral tumors may have cortical osteolysis, increasing the risk of cement extrusion. While a considerable number of studies have been published on biomechanics and surgical techniques, clinical studies on cement augmentation for pathologic fractures are more limited. Most studies are small and retrospective in nature and lack a standardized reporting measure of patient outcomes. In general, there is consensus that these techniques can offer significant improvements to patient's pain and mobility by stabilizing the affected vertebrae.

Regarding the benefits and safety of vertebroplasty and kyphoplasty for severe intractable back pain, some authors are expanding their indications even in the most debilitated patients. Hentschel et al. performed a retrospective study at a cancer center where they compared patients with vertebral compression fractures secondary to metastases or multiple myeloma [88]. Group one ($n=49$) consisted of patients with no contraindications for vertebroplasty, while the second group consisted on patients that would have been contraindicated for vertebroplasty according to literature reports (uncorrected coagulopathy, spinal canal compromise, radiculopathy, severe vertebral body collapse >75 %) [47, 89–92]. There were 11 % (12/114 levels) complications in

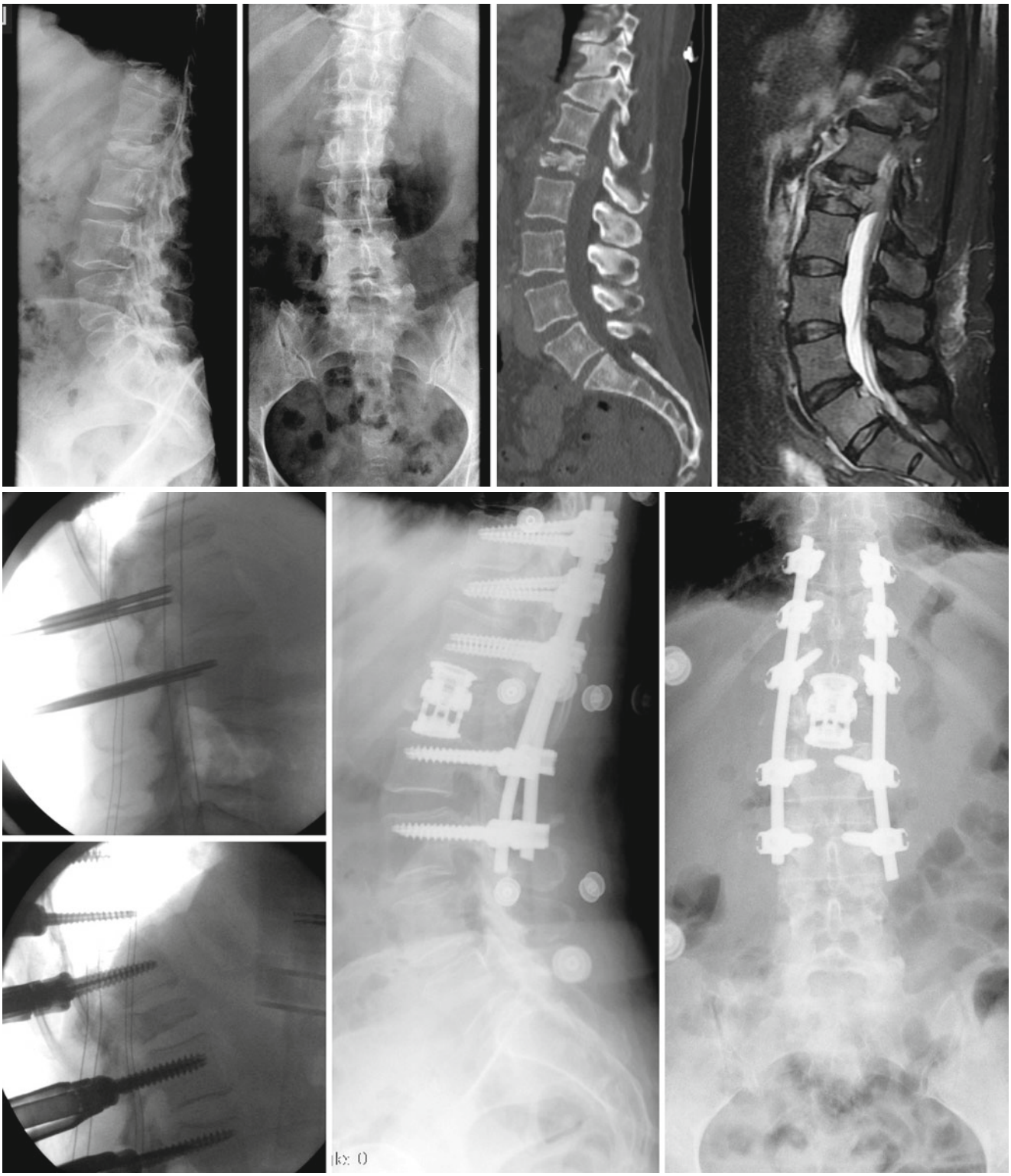

Fig. 33.6 Preoperative plain film, CT, and MRI showing a pathologic fracture at L1 due to metastatic gastroesophageal adenocarcinoma (*top*). Intraoperative fluoroscopy showing percutaneous placement of pedicle screws (*bottom left*) and postoperative plain films (*bottom right*) showing pedicle screw and expandable cage placement

group one and 39 % (7/18 levels) in group two ($p=0.03$). Even though they identified a higher incidence of cement extrusion in the contraindicated group, all but one leak into the neural foramen were asymptomatic and did not require further surgery. The authors pointed out that as technology and surgical technique improve, it is important to revisit the issue of contraindications in vertebroplasty as many patients not considered as candidates can receive significant benefit with minimal risk.

Weill et al. reported their results of vertebroplasty in 37 patients with spinal metastases [47]. Twenty patients (54 %) were able to discontinue analgesic medications and were observed to have improved quality of life. Overall, 24 patients (64.8 %) showed clear improvement, 7 (18.9 %) showed moderate improvement, and 2 (5.4 %) showed no improvement. Sixty percent of patients maintained pain control at 2 years follow-up.

Cortet et al. published results of 40 vertebroplasties in 37 patients with spinal metastases or multiple myeloma [40, 93]. Over half of patients had complete or significant improvement in pain, and 30 % showed moderate improvement. Only one patient failed to have relief of symptoms. One hundred percent of patients had improvement or maintenance of results at 1 month, but this number fell to 88.9 % at 2 months and 75 % at 3 months. Within this same cohort, it was also found that the percentage of lesion filling with PMMA cement did not correlate with pain relief [40]. Reported complications included 15 epidural leaks, eight intradiscal leaks, and two venous leaks of PMMA cement, all of which had no clinical importance. However, two of eight PMMA cement leaks to the neural foramen required surgical decompression, and one of 21 paravertebral leaks caused a transient femoral neuropathy.

Fourney et al. specifically evaluated complications of vertebroplasty and kyphoplasty in 56 cancer patients [94]. They observed extrusion of cement in 9.2 % of cases. Five of six cases involved leakage of cement into the adjacent disc through the fractured endplate, while in one case, cement leaked into the anterior perivertebral soft tissue; all cement leaks were asymptomatic. Additionally, they observed no cases where cement leaked into the posterior neural elements. Two patients with multiple myeloma required additional kyphoplasty for new fractures at other levels. Two patients required subsequent spine surgery; one for continued kyphosis, and a second for the development of new radicular pain, thought to be unrelated to the initial kyphoplasty.

Cement extrusion from vertebroplasty has been reported at much higher rates. A retrospective study in 2006 reported complications of vertebroplasty in 117 patients with spinal metastases [95]. There were 304 fractures treated with vertebroplasty. Postoperative CT scans were used to diagnose cement extravasation. Asymptomatic extravertebral cement leakages were observed in 423 of 304 treated vertebrae (median 2.0 per vertebrae, range 1–5); 78.5 % were in the venous network, 21.5 % were nonvascular, and only 6.8 % resulted in complications. Local complications included two hematomas and four venous extrusion of cement into the foramen causing radicular pain. Pulmonary embolus was detected at 30 days in two patients, although only one was symptomatic. Both patients had cement extrusion into the inferior vena cava (IVC) during the vertebroplasty. Multivariate analysis did not find an association between radicular pain and cement extrusion but did find that pulmonary embolus was associated with cement extrusion to the IVC.

A prospective study by Chew et al. found vertebroplasty to significantly in alleviate symptoms in 128 patients with myeloma or spinal metastases [96]. At 6 weeks, VAS pain scores fell 37 % (7.6 to 4.8) and Roland-Morris scores improved 27 % (18.6 to 13.5). Most patients reported subjective improvement in pain almost immediately after the procedure. Nine patients (18 %) reported no reduction or a slight increase in pain. Three complications were observed: one cement extrusion into the IVC, one local hematoma, and one neurologic deficit with loss of sensation at the T1 dermatome. The patient with cement in the IVC had asymptomatic pulmonary emboli of cement, one of which was removed percutaneously. They did observe asymptomatic paravertebral cement leaks but unfortunately did not report these numbers.

While kyphoplasty and vertebroplasty are widely used in metastatic pathologic lesions, this is not the case for primary spinal tumors. Indeed, percutaneous cement augmentation is not only associated with cement embolism but also with fat and bone marrow migration to the lungs [97], raising the question of possible neoplastic embolization during cementation. In a recent animal cancer model study, the authors demonstrated an increased risk of exporting neoplastic disease to the lungs after vertebroplasty and recommended the procedure only in patients with short life expectancy [98]. The use of vertebroplasty for local drug delivery for isolated spinal metastases and primary spinal tumors still remains to be studied.

Thoracoscopy

Reported outcomes after VATS or endoscopic surgery for pathologic spine fractures is very limited and consist of case reports or small case series. In fact, the steep learning curve and need for acquiring new cognitive and psychomotor skills for these techniques has prevented their widespread use [99–102]. Kan et al. reported a case series of five patients with metastatic cancer who underwent a MIS thoracoscopic vertebrectomy and stabilization [103]. Patients underwent right-sided vertebrectomy with interbody cage and anterolateral plate stabilization. All patients reported significant reduction

in pain at last follow-up. Two patients that had presented with motor weakness regained full strength. The mean EBL and operative time was 610 ml and 4.3 h, respectively. There were no intraoperative complications and all wounds healed successfully.

Dickman et al. reported on the use of VATS for thoracic vertebrectomy and reconstruction in 17 patients with thoracic myelopathy secondary to vertebral osteomyelitis, tumors, compression fractures, and calcified discs and compared these patients with a cohort of seven patients treated with open thoracotomy. They found no difference in operative time (347 versus 393 min, respectively), while EBL (1,117 versus 1,557 ml), narcotic use (4.1 versus 8.9 days), ICU stay (2.6 versus 6.4 days), and hospital stay (8.7 versus 15.8 days) were all less in the VATS group. The main complication in the VATS group were one intraoperative arrhythmia that resulted in death from massive myocardial infarction, two transient intercostals neuralgias, one moderate pleural effusion that resolved with thoracocentesis, and one pneumonia that resolved with antibiotics. In the thoracotomy group, the main complications were three intercostal neuralgias, two pneumonias, one pleural effusion, one tension pneumothorax, and one deep venous thrombosis.

MIS techniques have also been described for decompression and stabilization of vertebral osteomyelitis, as described in a case report by Amini et al. [104]. The patient was treated with a thoracoscopic discectomy and stabilized with a modular anterior construct. There were no complications; the patient did well and was pain-free with a solid fusion mass at 1-year follow-up.

Contraindications for VATS include inability of the patient to tolerate single lung ventilation, inability to collapse the lung secondary to prior surgery scarring or adhesions, emphysema, or trauma [105–107].

Mini-open Transpedicular Corpectomy

Clinical outcomes on mini-open transpedicular corpectomies are limited. This approach is well suited to treatment of vertebral tumors affecting the posterior elements with extension into the anterior column. Kim et al. reported on four clinical cases of vertebral compression fractures (three pathologic and one burst fractures) treated with a minimally invasive posterolateral corpectomy and reconstruction. Average EBL was 495 ml, operating time was 5.8 h, and length of hospital stay was 4.7 days. All patients had good pain relief and demonstrated significant neurologic improvement. There was no implant of graft failures reported [60].

Chou et al. compared the results of 16 patients (14 with cancer) who were treated with either traditional open posterior vertebral corpectomy ($n=8$) or with a mini-open posterolateral transpedicular corpectomy ($n=8$) [63]. There was no statistically significant differences in operative time or complication rate, but there was a trend toward significance in estimated blood loss of mini-open (1,213 ml) versus open cases (2,450 ml; $p=0.086$). All patients with preoperative motor deficits showed improvement in both groups, but no long-term follow-up was reported. Two (of eight) patients had epidural hematomas in the open group. There was one infection and one instrumentation failure in the mini-open group. The infection developed in the patient who underwent five separate skin incisions, while the rest had a single skin incision with multiple fascial openings.

Direct Lateral Corpectomy

Although the indications and applications of the direct lateral approach continue to expand (adult scoliosis, traumatic burst fractures, osteomyelitis, tumors), the literature on outcomes for the treatment of spinal pathologic fracture remains limited [75, 76, 108, 109]. Most of the literature focuses on direct lateral interbody fusion for the treatment of degenerative disc disease [77, 78] and reports significant improvements in clinical outcomes scores, radiographic measures, and cost-effectiveness [77, 110]. Operative times are short, with minimal blood loss, fewer complications (lower incidence of infection and visceral and neurologic injuries), and faster postoperative recovery with shorter hospital stays. The most common complication is transient medial thigh pain, while quadriceps palsy from injury to the lumbar plexus is extremely rare. Long-term outcomes are favorable, with maintained improvements in patient-reported pain, functional scores, and radiographic parameters including high rates of fusion [110, 111]. It is reasonable to think that some of the advantages of the direct lateral interbody fusion related to its minimally invasive approach can be extrapolated to the direct lateral corpectomy. Due to the location of the lumbar plexus within the psoas muscle, a direct lateral lumbar corpectomy may not be feasible given the limitation of creating a sufficiently large transpsoas window [112].

The MIS direct lateral approach has been shown to be cost-effective and have lower complication rates when compared to open anterior lumbar interbody fusion. In a retrospective study, Smith et al. reported lower complication rates (7 % versus 8.2 %, $p=0.041$) and lower cost ($91,995 and $102,146, $p<0.05$) of MIS direct lateral interbody fusion compared to ALIF, while functional outcomes were comparable at 2 years. A comparison of perioperative charges and outcome between open and mini-open approaches for anterior lumbar discectomy and fusion [113].

The direct MIS lateral corpectomy may be particularly advantageous in cases mainly involving the vertebral body with no involvement of the posterior elements. In a

prospective study, Uribe et al. examined the procedural and long-term complications of a mini-open direct lateral approach for removal of thoracic tumors in 21 patients. Average operating time, blood loss, and length of hospital stay were 117 min, 291 ml, and 2.9 days, respectively. There was only one perioperative complication consisting of pneumonia. Although two patients had recurrent disease (one myeloma, one meningioma), they were asymptomatic and did not require further surgery. The visual analog scale and Oswestry Disability Index improved from 7.7 to 2.9 and from 52.7 to 24.9 %, respectively [114].

A recent prospective multicenter study reported favorable outcomes for decompression and fusion via a direct lateral interbody fusion for adult scoliosis and remarked that higher early reoperation rates (all for deep wound infections) occurred in patients who had direct lateral interbody fusion with supplemental open posterior instrumentation, whereas there were no infections in the lateral interbody fusion standalone or with percutaneous instrumentation patients [115].

A recent retrospective study assessed outcomes of 22 patients treated with direct lateral interbody fusion of the thoracic spine for degenerative scoliosis (11), pathologic fractures from tumors (2), adjacent level disease from prior fusions (5), thoracic disc herniations (3), and discitis/osteomyelitis (1). There were three complications consisting of wound infection, subsidence, and adjacent level disease requiring additional surgery. At a mean follow-up of 16.4 months, the authors reported a 95.5 % substantial clinical benefit and 95.5 % fusion rate at 6 months, supporting the use of the lateral approach to treat diseases in the thoracic spine [109].

Conclusions

Minimally invasive surgery continues to evolve and its application for the treatment of pathologic fractures is increasing. As new medical treatments prolong life expectancy, the incidence of pathologic fractures will continue to increase. MIS spine surgery can provide treatment for these patients by stabilization, neural decompression, and deformity correction, while minimizing the comorbidities associated with open surgery. Determining what surgical approach is best should always take into account each individual patient, may necessitate an interdisciplinary dialogue to coordinate different treatment modalities, and should carefully weight patient prognosis and life expectancy versus surgical comorbidities. Minimally invasive surgery has made surgical treatment an option for a wider patient population, helping to improve quality of life in some of the most debilitated patient populations.

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Minimally Invasive Spine Surgery in the Elderly

34

R. Todd Allen and Andrew A. Indresano

Introduction

A significant percentage of the morbidity associated with spine surgery is related to exposing and accessing the spine. Since the first published articulation of "minimally invasive procedure" in 1987 by urologist John E. Wickman in the *British Medical Journal*, a continuous evolution of technology and surgical advances have occurred [1]. This, now familiar, concept has evolved into the term "minimally invasive surgery" (MIS) and has been applied to every surgical specialty in medicine, including the field of spine surgery. The concept of MIS has evolved as well, now including not only Wickham's initial definition as "minimal damage of biologic tissue at the point of entrance of surgical instruments" but also one that recognizes the importance of minimizing collateral damage, of the need to be less invasive to a defined norm or open "comparator," and to perform the same or better surgical procedure as would be done in open cases. In order to determine the utility and effectiveness of this concept, and these surgical techniques for spine disease, treatment algorithms must be developed, preferably treating specific pathologies and/or populations. One such population is the elderly, where spine disease can be severe and MIS strategies have the potential to markedly improve quality of life while minimizing potentially disabling complications and improving rehabilitation potential. One must also consider the durability of MIS spine procedures, since demonstration of improved long-term outcomes will likely be the best way to prove their cost-effectiveness and stand the test of time.

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We live in a rapidly aging population. It is estimated that by 2030, there will be more than twice as many individuals over the age of 65 years old as their counterparts in the year 2000, growing from 35 to 72 million, which represents nearly 20 % of the total US population [2]. Some of the most common afflictions of the aging population are spinal conditions such as degenerative spondylolisthesis (DS), lumbar and cervical spinal stenosis, cervical spondylotic myelopathy (CSM), and degenerative scoliosis/kyphoscoliosis. The SPORT trials showed that the decreased quality of life scores associated with DS and lumbar spinal stenosis respond more favorably with operative intervention as compared to nonoperative treatments [3, 4]. Additionally, improvement in disability scores with operative treatment, compared to nonoperative treatment for patients with adult spinal deformity (scoliosis) [4], has lead to an increasing number of patients electing for surgical intervention [5]. Cumulatively, with an increasing elderly population, a higher percentage of that population electing for spine surgery, and the fact that lumbar fusions have increased most rapidly in those over the age of 60, future costs of care may place a tremendous burden on society [6]. In our current health-care environment, resource utilization will require successful MIS spine approaches be married to improved quality of life (QoL) data, merging to produce data on the cost-effectiveness of these interventions. Despite a relative lack of higher level data at this time, the economic studies that do exist suggest that surgical management of common spine pathologies using MIS techniques improves patient outcomes; has lower complication rates, particularly versus larger open procedures; and has the potential to be both a short- and long-term cost-effective intervention [7].

Predictably, surgical morbidity and mortality are higher in the elderly [8]. Elderly patients commonly have comorbidities and a reduced physiologic reserve. Combined with poor bone stock and severe spine disease, these factors can escalate surgical difficulty, which can adversely affect surgical outcomes in the elderly patient [6, 9, 10]. More specifically, surgical invasiveness and age have been found to

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be significant risk factors for multiple organ system complications in the postoperative period, including pulmonary, cardiac, hematologic, neurologic, and gastrointestinal complications [11]. Clearly, extensive paraspinal muscle dissection can lead to muscle damage and necrosis and increased CPK levels and may correlate with back pain in the postoperative period [12, 13]. Additionally, many elderly patients have quite severe pathology that, when addressed via standard open techniques, requires more dissection and muscle retraction, leading to increased blood loss and operative time. These and other factors predispose the elderly population to higher rates of complications.

One potential remedy for the higher complication rates of spine surgery in the elderly is by using less invasive or "MIS" surgical techniques. Although data specific to elderly patients across diagnostic groups is lacking, MIS surgery is increasingly being compared to open surgery given its increase in popularity over the past two decades. Studies of MIS spine techniques have found that patients have a better potential for a quicker recovery, decreased hospital stay, and less soft tissue injury, compared to open procedures [14–16]. These benefits of decreasing the "invasiveness" of spine procedures is clear, but the ability of MIS spine procedures in the elderly to minimize complication rates may be uniquely suited not only to allow for improved and quicker recovery but by limiting the ability of a complication to snowball and affect physiologic reserve. In the general surgery literature, MIS techniques have been shown to be protective when looking at morbidity and complications in the colectomy patient population [17]. We have no reason to suspect this would be different in the aging spine population. Therefore, even if the current procedure already seems sufficient to the surgeon, MIS spine techniques may be of specific benefit to the elderly patient.

MIS Decompression

Cervical

Effective neural decompression of the symptomatic, stenotic spine segment is an important treatment modality. Evidence of efficacy is mounting for MIS decompressions of degenerative spine conditions. For stenosis that is amenable to a posterior approach, such as unilateral disk herniation/stenosis, use of a posterior cervical decompression via an MIS portal is increasing in popularity. Specifically, cervical radiculopathy can be treated with tubular-assisted posterior cervical laminoforaminotomy with comparable midterm patient satisfaction and similar operative times, with the additional benefits of reduced blood loss and decreased postoperative analgesic use and length of hospital stay compared to the standard open approach [18–20]. Although data specifically looking at the elderly population are lacking, these promising comparative results may aid in reducing operative and perioperative morbidity in the at-risk elderly population.

Lumbar

Minimally invasive spine approaches have also been shown to be effective for decompression of lumbar degenerative spinal stenosis via a posterior approach [21, 22]. Palmer and Davison revealed high patient satisfaction at 2 years' follow-up of 54 patients (average age of 67 years), consistently reporting reduced back pain, decreased pain medication requirements, and greater than 50 % reduction in mean visual analog scores (VAS) [23]. Similarly, Rosen et al. showed that 50 patients over the age of 75 years old had significant reduction in VAS scores, decreased leg pain, and improved ODI scores, physical function scores, and SF 36 body pain and physical function scores with MIS lumbar decompressions [24]. These data show relatively consistent early postoperative pain reductions with MIS decompressions, likely due to a combination of adequate decompression and reduced injury to the paraspinal musculature and surrounding stabilizing structures. Although more data are needed, one benefit of these MIS approaches postulated to account for the long-term improvement in outcomes is the preservation of spinal stability resulting from a more focused decompression at areas of noted pathology with preservation of osseo-ligamentous posterior stabilizing structures. Although not specifically studied and certainly not an absolute, minimizing "micro-instability" or abnormal motion that may be more prone to occur during open laminectomy with medial facetectomy is an attractive potential benefit of tubular or mini-open MIS spine approaches. Adding this to a surgeon's repertoire, especially when treating the elderly patient population, may be highly beneficial for the reasons discussed above.

One example of potential consequences of open laminectomy is destabilization of the elderly, at risk, spine (Fig. 34.1). Within 6 weeks following open L2–5 posterior decompressive laminectomies for severe lumbar stenosis, an L2 vertebral compression fracture occurred in an 88-year-old man. This is theoretically related to removal of the posterior elements and tension band and to the loss of muscle strength due to the open procedure, which may have been avoided via an MIS approach.

Another potentially advantageous feature of MIS, and potential way to maintain stability in the elderly, is by using a unilateral MIS portal (e.g., tubular) to perform a bilateral decompression (central, lateral recess, and foraminal) for severe symptomatic lumbar stenosis. This approach minimizes the morbidity associated with open or bilateral MIS decompressions. Bilateral decompression via a unilateral

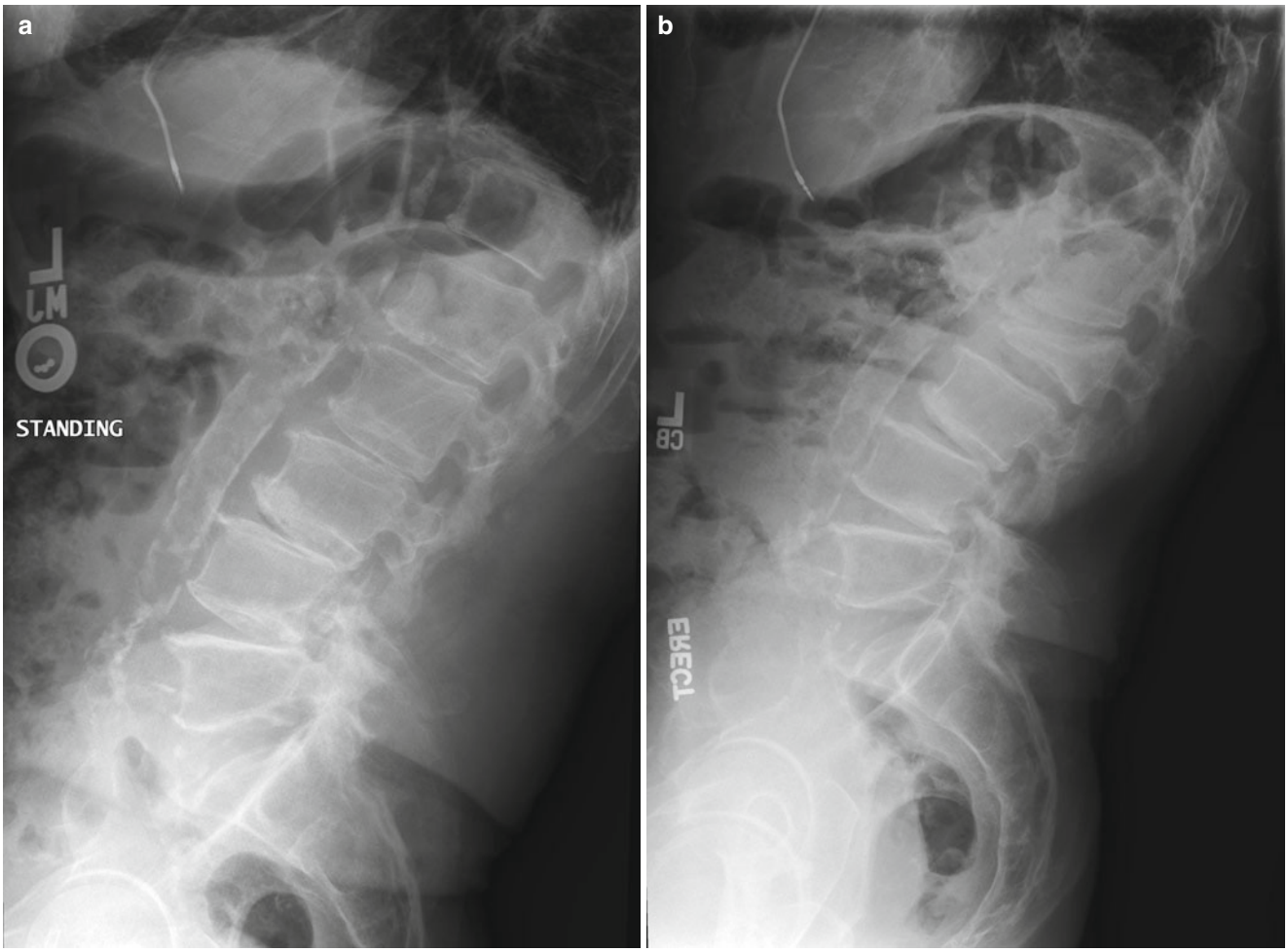


Fig. 34.1 (**a**) An immediate postoperative lateral image of an 88-year-old male spine following open laminectomy. (**b**) The patient's compression fracture at 6 weeks post-decompression. It is possible that muscle dissection and removal of the posterior elements/tether in this elderly patient during open decompression contributed to his subsequent severe compression fracture of the L2 vertebral body. Though his leg pain was gone, and walking tolerance improved, back pain due to fracture delayed his recovery. This highlights the potential benefit of MIS surgical decompression particularly in an elderly, osteoporotic population

tubular approach has been well described and used in a variety of pathologies producing lumbar stenosis, with equal 5-year outcome results compared to bilateral tubular decompression and potentially improved outcomes over standard open laminectomies [25, 26]. It is particularly useful in those with mainly leg/claudication symptoms due to stenosis in the setting of mild scoliosis or spondylolisthesis when one is trying to avoid a larger procedure or a fusion. In larger degenerative scoliosis curves, when using a unilateral approach, one should *approach on the curve convexity* if possible, as this leads to less destabilization of the spine and a lower chance of curve progression; unilateral approach and decompression at the apex on the concave side have a higher risk of curve progression and therefore should be carefully considered [27]. Additionally, in patients with significant lateral (rotatory) listhesis, higher rates of surgical revision may occur versus those without this deformity, when using an MIS approach for decompression [28]. Cumulatively, unilateral MIS decompression is an effective tool in those with minimal spinal deformity or instability. However, one must carefully consider the potential consequences of performing this decompression technique without fusion (particularly over multiple levels) in the face of instability, and this should risk should be discussed prior to intervention.

Discectomy

Discectomy for the treatment of herniated intervertebral disk has been well described using less invasive retractor systems. To date, open discectomy has been found to be more effective than nonsurgical management and has recently been found to be cost-effective compared with nonoperative treatment [29]. Several studies have documented the effectiveness of tubular

discectomies in lower-level studies [30, 31]. Based on physician assessment and patient-based responses in outcomes questionnaires, it has been shown that there are 80 % good to excellent results with endoscopic lumbar discectomy for radiculopathy secondary to a herniated disk [32]. Although not specifically looked at in the elderly population, Arts et al. performed a double-blinded randomized controlled trial and found no functional differences between tubular discectomy and conventional microdiscectomy for the treatment of leg pain at 2 years post-decompression [33]. However, the benefits of tubular decompression have been shown in elderly patients over the age of 70 years old through decreased blood loss and earlier ambulation after surgery, which are essential in this population to minimize risks of prolonged immobilization [34]. Despite these potential advantages versus open discectomy, some randomized trial data suggest the magnitude of muscle injury is no different in tubular discectomy when compared to conventional microdiscectomy, when measured by creatine phosphokinase (CPK) blood levels and cross-sectional area of multifidus postoperatively [35]. It is important to note that this is single-level surgery and clearly may not give the same result in multilevel posterior spine cases where open dissection is more extensive and case duration is longer. Considering the increased mobility and decreased blood loss, tubular decompression clearly has a role in the elderly population.

Lateral Lumbar Interbody Fusion

The open anterior approach to the lumbar spine is often a morbid procedure with relatively high complication rates including vascular injury, retrograde ejaculation, abdominal wall weakness, hernia and pseudo-hernia, ureteral injury, gastrointestinal injury, infection, and a 10 % increased cost association compared to a MIS lateral interbody fusion [36–39]. Additionally, the anterior approach frequently requires the use of an access surgeon. Several authors have reported decreased operative times, less blood loss, shorter hospital stays, lower rates of complications, and quicker recovery with direct lateral anterior interbody fusion compared to open ALIF [40]. Rodgers et al. specifically looked at octogenarians and compared LLIF versus posterior lumbar interbody fusions (PLIF). He found significantly higher complication rates in the open PLIF group, including increased blood loss requiring transfusion (70 % of PLIF versus 0 % of XLIF patients), increased infection rates (15 % in PLIF group versus 0 % in XLIF group), increased hospital length of stay (5.3 days versus 1.3 days), and higher postoperative care needs (100 % of PLIF group was discharged to skilled nursing facility versus 7.5 % of XLIF group). They also found an increased mortality rate in the PLIF group (30 %) compared to the XLIF group (2.5 %) [41]. Additionally, LLIF was shown has been shown to be safe and without increased risk in the elderly population when compared to a younger cohort [42]. Cumulatively, the risks associated with open anterior (or posterior) lumbar interbody fusion procedures (sympathetic dysfunction, blood loss, vascular injury, somatic neural injury, sexual dysfunction, and prolonged ileus) when compared to LLIFs occur at consistently higher rates and are often less tolerated than the complications associated with MIS lateral interbody fusion, such as transient hip pain and quadriceps weakness (0.7 %), blood loss, and increased surgical time during the learning curve. This may be especially true for the elderly population, in whom anterior approaches are often fraught with higher risks [14, 39, 43–45]. The specific complication rates of open versus MIS interbody fusion and the effect of age are shown below (see Table 34.1).

In addition to reducing operative risks and improving postoperative recovery potential in the elderly, anterior interbody fusions via LLIF approaches have specific biomechanical benefits. These may be most relevant and compelling in elderly patients, where bone quality is often poor and is an essential variable in surgical decision making—with osteoporosis being present in 86 % of women >75 years old and over two fifths of men over the same age [47]. Specifically, lateral interbody fusion provides a large channel discectomy during endplate preparation, leading to greater surface area contact with the interbody graft than in cases of TLIF or PLIF, and is comparable to ALIF graft areas without the surgical morbidity associated with an anterior approach. Additionally, seating of the interbody cage preferably occurs on the apophyseal ring, relying on this strongest native portion of vertebral bone, which limits direct loading of an appropriately sized implant on weaker osteoporotic endplate bone [48]. The inherent stability afforded by retaining the anterior and posterior longitudinal ligaments adds significantly to the biomechanical stability of that fused segment (i.e., >159 % that of ALIF in certain moments) and may decrease loading at the bone-implant interface [48, 49]. This may have implications for fusion rates and reduced need for revisions in cases of pseudoarthrosis. For example, one analysis of 85 patients undergoing LLIFs (88 total levels) found a 3.4 % pseudoarthrosis rate using 12-month CT scan follow-up (fusion rate of 96.6 %), with a few of the cases performed either as standalone or via transfacet fusions posteriorly. Notably, 89.4 % reported being satisfied or very satisfied, and no revisions were necessary for pseudoarthrosis [50].

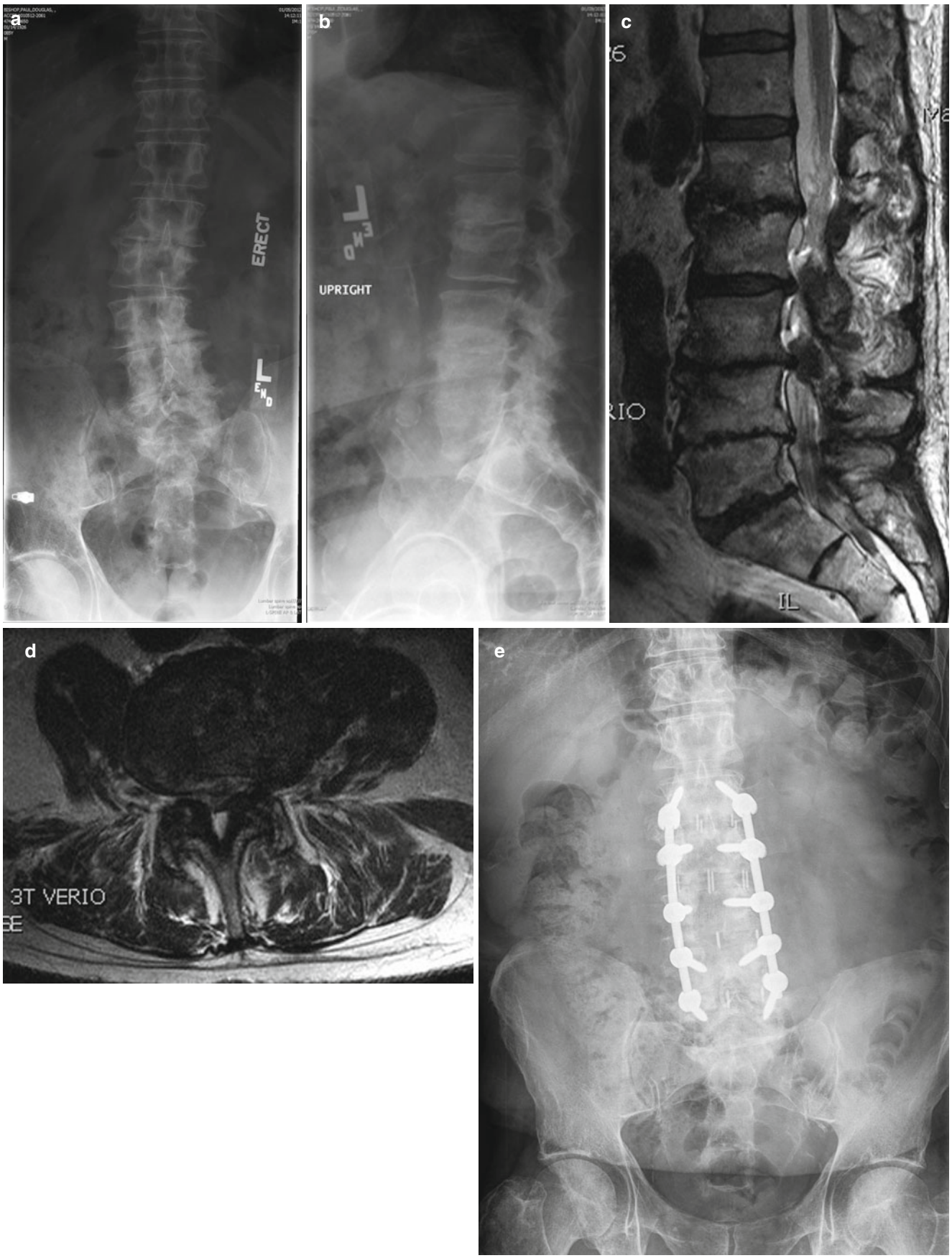
Using LLIF techniques in the elderly, an appropriate amount of deformity correction can be achieved. Lateral lumbar interbody fusion itself best corrects coronal deformity in degenerative scoliosis using LLIF grafts, as noted by radiographic correction of the central sacral vertical line preoperatively compared to postoperatively [51, 52]. It is imperative to recognize the ability to improve coronal imbalance

Table 34.1 Complication rates

Open anterior surgery complication rates	
Faciszewski et al. [39]	Open anterior approach complications for T- and L-spine surgery. Retrospective review of 1,223 patients. 11.5 % complication rate (9 % post-thoracotomy pain syndrome; 7 % Horner-Bernard Syndrome; 3 % pleural effusion; 1.8 % pneumothorax; 1.18 % abdominal hernia; 0.98 % superficial wound infection; 0.8 % impotence; 0.57 % deep wound infection; 0.54 % retrograde ejaculation). Complications were higher in patients over the age of 60 years
Flynn and Price [44]	Open anterior approach complications for various lumbar spine pathology. Retrospective review of 4,500 cases. 0.42 % rate of retrograde ejaculation. 0.44 % rate of impotence. Age not specifically evaluated
Rajarman et al. [45]	Open ALIF for various lumbar spine diagnoses. Retrospective review of 60 patients. 38.3 % overall complication rate (10 % sympathetic dysfunction; 6 % vascular injury; 5 % somatic neural injury; 5 % sexual dysfunction; 5 % prolonged ileus; 3.3 % wound dehiscence). Age was not specifically evaluated
Lateral lumbar interbody fusion complication rates	
Rodgers et al. [43]	Prospective analysis of 600 cases of extreme lateral interbody fusion. Overall complication rate 6.2 % (2.8 % in hospital medical events; 0 % wound infections; 0 % vascular injuries; 0 % intraoperative visceral injuries; 0.7 % transient neurologic deficits). Effect of age was not specifically evaluated
Knight et al.	Prospective, nonrandomized trial of 58 patients. Overall major complication rate was 8.6 % with approach-related complaints of nerve irritation nearing 3.4 %. EBL was less compared to open cohort. Age was not specifically evaluated
Isaacs et al. [46]	Prospective, nonrandomized, multicenter evaluation of 107 patients. 4.7 % of patients required blood transfusions; 2.8 % were admitted to ICU postoperatively. XLIF alone or percutaneous fixation had a major complication rate of 9 % compared to 20 % complication rate with open procedures
Posterior lumbar interbody fusion complication rates	
Park and Ha [14]	Prospective analysis of 61 patients who underwent PLIF via an MIS versus open approach. MIS group had statistically significant decrease in intraoperative blood loss, postoperative drainage, blood transfusion requirement, time needed before ambulation, VAS scores postoperatively, and hospital stay. The MIS group was noted to have increased surgical time however. Both groups had equivalent radiographic outcomes. Effect of age was not specifically evaluated
Kolchiro O et al.	Retrospective analysis of 148 consecutive PLIF patients. Ninety-one complications in 75 cases were noted. Eight percent transient neural palsy, 4 % dural tear rate, 2.7 % pedicle screw loosening, and 1.3 % deep infection rate were noted throughout the study. Age was not specifically evaluated
Humphreys C et al.	Prospective comparative study of 40 TLIFs and 34 PLIFs performed by two surgeons over 13 months. No significant difference was found between two groups in terms of EBL, operative time, and hospital stay when a single-level fusion was performed. However, when a two-level fusion was performed, there was significantly less blood loss using the TLIF approach compared to the PLIF approach. No effect of age was noted in this study

as a potential explanation for improvement in axial pain [52], but one must be careful not to overcorrect a balanced or compensated patient, as elderly patients may be stiff and unable to further compensate in longer fusions using LLIF techniques (Fig. 34.2). Specific to the elderly population, less sagittal or coronal plane correction may be acceptable to prevent failure of the construct or bone while still improving the patient's symptoms. Due to bone quality concerns in the elderly and in osteoporotic patients, stand-alone LLIF techniques are *not* recommended, particularly with cages that are 18 mm or less in width and/or do not sit on the apophyseal ring appropriately. This can lead to excessive subsidence, recreation of the deformity and limiting ability to correct deformity or maintain decompression.

In addition to deformity correction and treatment of axial pain, indirect foraminal decompression can be achieved with direct LLIF techniques [46, 53]. Improvement in foraminal volume has been shown for degenerative conditions and scoliosis, with lower complication rates than associated with open procedures. Specifically, it has been shown that the foraminal volume is increased with the LLIF grafts, which can reduce the symptoms (and improve outcome scores) associated with radiculopathy without associated open posterior decompression and may, in select patients, help avoid further and/or more extensive decompressive posterior surgery that clearly puts the elderly patient at higher perioperative risk [54, 55]. However, as discussed above, stand-alone LLIF in the elderly can be associated with graft subsidence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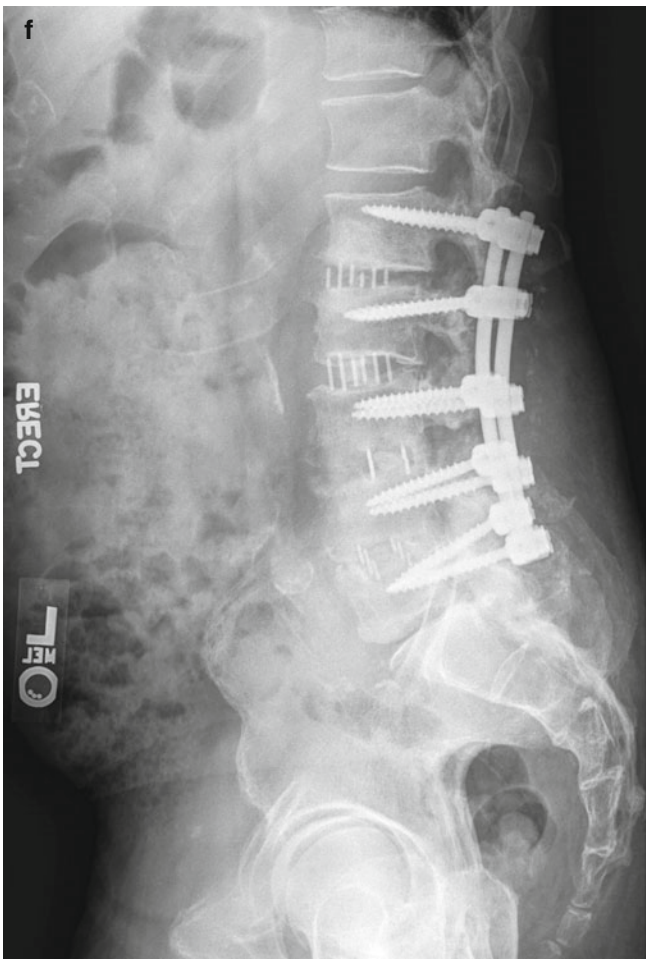

Fig. 34.2 (continued)

or vertebral fracture and one should strongly consider supplementary anterior or posterior fixation. Additionally, despite inferences in prior studies, it is unclear how much foraminal volume/area increase is needed to relieve symptoms and correlate with outcome improvements; or which patients and specific pathologies are ideal candidates for LLIF without decompression posteriorly.

MIS Transforaminal Lumbar Interbody Fusion (MIS TLIF)

Interbody fusion through a transforaminal approach using less invasive (or tubular) approaches is well described in the literature and increasing in popularity. This approach, commonly referred to as MIS TLIF, allows the surgeon access to the anterior spine for interbody fusion at essentially any level of the lumbar spine without the morbidity associated with an anterior approach or lateral approach as discussed earlier. Takahashi et al. looked at mini-open TLIF in patients aged 70–86 years with lumbar degenerative spondylolisthesis and radiculopathy or neurogenic claudication, who underwent one- or two-level fusions. The authors found mini-open TLIFs in this situation achieved clinically significant improvements in VAS, ODI, and Japanese Orthopaedic Association Scores [56]. They also found high rates of radiographic fusion success, although the clinical benefits were a bit less robust when compared with a younger cohort. This may be multifactorial, due at least in part to recovery potential, more significant preexisting foraminal narrowing and less ability to indirectly open the foramen in the elderly population due to smaller implant height given the limitations of implant placement and poorer bone quality. In select patients, however, these concepts may provide some evidence for LLIF in select patients. To date however, there are no randomized, controlled studies comparing MIS TLIF and lateral interbody fusion in terms of outcomes and complication rates to help define superiority or develop a patient selection algorithm.

Summary

The evolution of surgical technique and technology has in no other field been more relevant and profound than in spine surgery. The driving force and catalyst for the increasing use of MIS in spine surgery is the hope that MIS in spine may provide improved outcomes, faster recovery rates, and lower rates of complications, preferably with less revision surgeries. This

Fig. 34.2 Preoperative AP (**a**) and lateral (**b**) lumbar radiographs of an 82-year-old male with degenerative scoliosis, facet cysts, severe multilevel stenosis, and disk disease (highlighted on representative sagittal (**c**) and axial (**d**) T2 MRI images). He underwent an L1–5 LLIF (with XLIF, NuVasive Inc, San Diego, CA) with MIS posterior decompression, osteotomy, and instrumented fusion. Although curve correction was achieved, note on the *early* postoperative AP (**e**) and lateral (**f**) lumbar plain radiographs the mild coronal imbalance, seen clinically as well, to the right side. This is likely a combination of some coronal overcorrection, a stiff compensatory curve proximally, and inability to further compensate for this with an L1–5 fusion

potential MIS offering may have no greater impact than in the elderly patient with disabling, symptomatic, and often severe spine disease. The preservation of surrounding musculature and supporting ligamentous structures is an advantage that has consistently been defined in the literature and benefits both the younger and older patient populations. At this time, despite limited data, there are several literature-supported benefits for minimally invasive spine surgery compared to open alternatives for many of the pathologic conditions that afflict the elderly. These techniques include posterior MIS decompression of cervical and lumbar stenosis, MIS discectomy for herniated disks, and lumbar interbody fusions for various pathologies via either lateral lumbar approaches or posterior MIS transforaminal approaches. With an increasingly elderly population and the high risk of complications associated with open spine surgery in the elderly, MIS spine procedures are a valuable skill set to develop and apply to the elderly patient. These techniques may improve their function and quality of life, without the risk profiles associated with open spine procedures in the elderly population. Minimally invasive surgery is rapidly advancing and is likely to have a significant role, if not a primary role, in the future of spine surgery—particularly in the elderly population.

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Minimally Invasive Applications of Motion

35

Luiz Pimenta, Leonardo Oliveira, and Luis Marchi

Background

Motion at degenerated spine provokes pain [1]. Therefore, spinal fusion has become a popular option for severe degenerative disc conditions [2]. The lumbar degenerative disc disease has been treated over the years with methods of stabilization, and it has presented good results, but the completely loss of motion in a fused segment leads to overload of the adjacent segments, pseudarthrosis, and a long recovery time after surgery [3]. Total joint arthroplasty in other orthopedic subspecialties has prompted the spine community to seek a similar solution for the lumbar spine that both relieves pain and preserves physiologic motion [4]. Motion preservation options have been developed as an alternative for fusion to keep the range of motion of the spine in attempt to decrease the adjacent disc degeneration, prevent adjacent segment disease, protect the neural elements by reconstructing the spine level, and provide faster recovering period to patients [5].

Literature suggests a correlation between fusion and the development of adjacent segment degeneration (ASD) compared to arthroplasty (34 % versus 9 %) [6]. Meta-analysis data supports the use of arthroplasty to reduce ASD and disc degeneration compared to arthrodesis, and higher odds of ASD was associated with older patients, arthrodesis, and longer follow-up [6]. ASD is correlated with loss of motion; changes seem to occur in arthroplasty cases which had ankylosed and had limited motion [7, 8].

Nucleus Replacement

Nucleus replacement was developed as a less invasive technique in motion preservation spine surgery, and unlike spinal fusion, this technique would restore normal biomechanical function to the disc and patient's normal levels of activity with little or no pain. Additionally, due to its minimally invasive nature, reduced time spent in surgery and in hospital would beneficiate the patient.

In the late 1950s and early 1960s, the disc nucleus space was filled or replaced with polymethyl methacrylate, silicon, or stainless steel ball bearings [9]. These were the first recorded attempts at spinal motion preservation. Results from these early procedures were inconsistent and were not accepted during that time [10]. The Fernstrom ball attempted to preserve motion by replacing the nucleus with stainless steel ball bearings while retaining most of the annulus fibrosis. In most of the cases, major subsidence occurred, causing bad clinical outcomes [11].

Different nucleus replacement prostheses were then developed, including:

- Injectable polyurethane (Dascor)
- Injectable albumin (Biodisc)
- Injectable silicone (PNR)
- Injectable polyvinyl alcohol/polyvinyl pyrollidine copolymer (Hydrafil)
- Injectable silk/elastin copolymer (Nucor)
- Preformed hydrolyzed polyacrylonitrile (PDN)
- Preformed polyvinyl alcohol (Aquarelle)
- Preformed partially hydrolyzed acrylic copolymer (Neudisc)
- Mini PEEK ball-and-socket disc (Nubac)
- Pyrolytic carbon (Regain)

The present authors have reported their experience with three different modalities of nucleus replacement [12]: presacral injectable silicone (PNR), preformed hydrolyzed polyacrylonitrile (PDN), and mini PEEK ball-and-socket disc (Nubac). The studies were unsuccessful and retrieval/reoperation rates were very high (overall 48.8 %) due to various adverse events: posterior migration/expulsion (Fig. 35.1), prosthesis displacement, subsidence, and disc collapse.

Nucleus replacement technologies remain investigational, with very narrow indications and have not proven efficacious for the treatment of discogenic pain.

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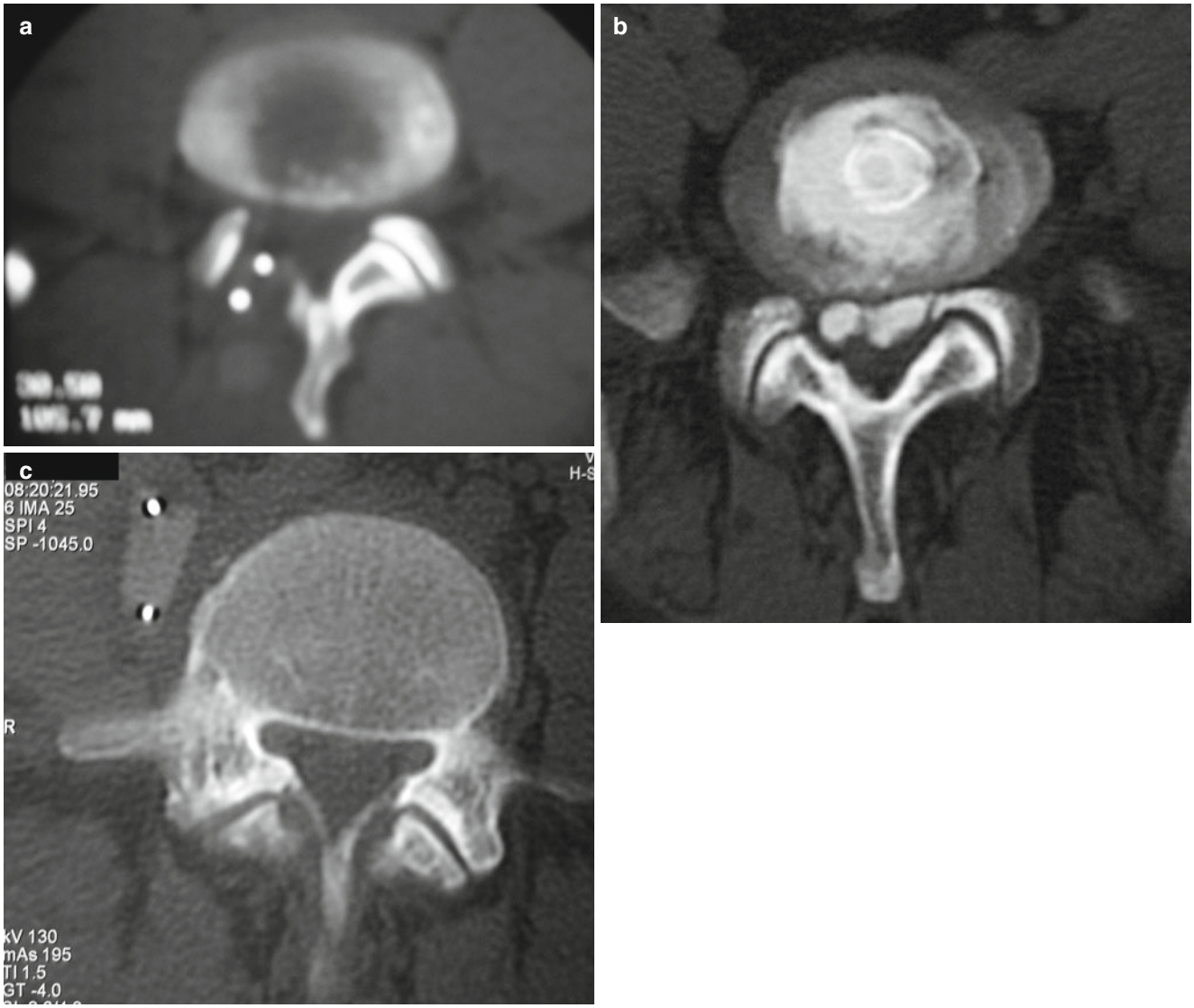


Fig. 35.1 Examples of complications with nucleus replacement devices. (**a**) PDN posterior migration in a posterior approach procedure. (**b**) Silicon posterior migration in PNR presacral procedure. (**c**) Nubac lateral extrusion and disc collapse

Total Disc Replacement

The total disc replacement aims to restore the physiologic characteristics of a human intervertebral disc. The functions assumed by it include the role of the nucleus pulposus and annulus fibrosis, preserving normal range of motion, while absorbing and transmitting loads to the adjacent levels. It also needs to indirectly decompress the neural structures while maintaining spinopelvic alignment [5].

Lumbar Anterior Approach

The standard technique for implantation of a lumbar TDR is the anterior approach. This access route has some inherent risks including the need to mobilize the great vessels above the level L5–S1. This technique also calls for resection of the anterior longitudinal ligament (ALL) [13], which plays an important role in lumbar spine stabilization [14].

There are several disc prostheses commercially available, mostly implanted by anterior approach with partial or total resection of the ALL [5]. The SB Charité was the first designed implants for lumbar total disc replacement in the early 1980s [15]. To date, more than 20,000 patients worldwide underwent total disc replacement using this prosthesis that, through its long follow-up evaluation, led to important conclusions regarding anterior total disc replacement [16].

One of the major contraindications for lumbar total disc replacement is scoliosis. The resection of ligaments

generates an unstable spine in comparison to intact, with abnormal increased mobility, more pronounced in multilevel reconstructions [17, 18]. McAfee et al. found an important number of patients with lumbar TDR that developed iatrogenic scoliosis, independently of prosthesis type [18], corroborating the importance of ALL in the lumbar spine stabilization. Cakir et al. [19] have concluded that the increased segmental lordosis after a disc replacement was mainly caused by the excision of the ALL.

Facet degeneration after a lumbar TDR is another important finding in a long-term follow-up evaluation [20]. Biomechanical and clinical studies found that preserving the ALL is required to maintain the spinal stiffness, thereby reducing loads within the facet joints [20, 21]. Also, the facet arthropathy leads to a significantly lower motion at the index level in comparison to treated levels without facet degeneration [22]. Indeed, considering the above circumstances, TDR may increase the incidence of adjacent level disease [23], negating one of the main indications for arthroplasty: preservation of the adjacent segments.

In our series [24], with 9 years' follow-up in six different prostheses models implanted by anterior approach, we found a high incidence of complications, most of them directly or indirectly related to the ALL resection during the implantation technique. Facet degeneration was found in 25 % of all patients, being the major complication in the postoperative period, followed by iatrogenic scoliosis, present in 8.5 % of all operated subjects. Overall, our complications were not related the prosthesis model, with no statistical difference in facet joint pain, subsidence, bad positioning, iatrogenic scoliosis, and heterotopic ossification (Fig. 35.2).

Future

Many of the existing artificial disc designs fail to restore native quality and quantity of motion to the functional spinal unit and in addition lack the ability to provide shock absorption. Altered load absorbance and distribution may be related to the nonphysiologic nature of the design of these disc prostheses [25–27], resulting in overload of the facet joints, pars, and pedicle at the index levels.

Elastomeric disc prostheses have been proposed to mimic physiologic biomechanical features (Fig. 35.3) [28–30]. Short-term clinical results are encouraging and even superior for the elastomeric device (Physio-L), compared to the Charite, ProDisc-L, and fusion (Fig. 35.4) [30]. Furthermore, there was no incidence of subsidence, migration, or expulsion for any of the implanted devices.

MIS Application

Although range of motion may remain similar with arthroplasty, this feature is not sufficient for the success of the procedure. Anterior approach lumbar disc replacement devices are thought to retain close to "normal" range of motion (ROM), but they also inherently cause iatrogenic instability due to resection of the anterior longitudinal ligament and annulus [31]. Although the motion can be restored, instability/laxity is manifested once the center of rotation is changed and neutral zone motion is increased [32].

Preservation of the anterior ligamentous and annular structures seems to be reasonable and promising in lumbar TDR. Biomechanical data with a lateral inserted artificial disc (XL-TDR, Fig. 35.5) points to a significant stabilizing effect with concurrent tensioning of the anterior and posterior longitudinal ligaments and remaining annulus (Figs. 35.6 and 35.7) [31]. And the stabilizing role of the ALL was proven once its resection increased ROM in all directions with respect to the disc with intact ALL and to other anteriorly placed prosthesis. This makes this strategy more stable than those delivered anteriorly and then probably less susceptible to some of the drawbacks observed in the literature. Additionally, the footprint of the lateral TDR device capitalizes on the biomechanical support of the ring apophysis. But the arthroplasty by the lateral approach is limited to discs above L5, once this technique cannot be performed at L5–S1 due to the iliac crest.

Short-term clinical results are encouraging with retention of natural ROM and minimal rate of prosthesis-related complications (Fig. 35.8) [33, 34]. Furthermore, the minimally invasive lateral transpsoas approach avoids anterior approach-related complications, avoiding mobilization of the great vessels and provides rapid patient mobilization (Fig. 35.9) [35, 36].

Conclusions

Our analyses can point out various lumbar arthroplasty aspects, including its pros:

- Better biomechanical results
- Good clinical results
- Restoration of global motion
- No bone graft needed

and its cons:

- Expensive technology
- Important adverse events in some prosthesis options
- Ideal prosthesis nonexistent or without long follow-up reports

MIS options for lumbar arthroplasty must take into consideration the lessons learned from previous experiences and aim to restore the quality and quantity of motion of the lumbar spine. Constant patient monitoring, data sharing, and concept and technology adaptation will be essential to achieve growing success.

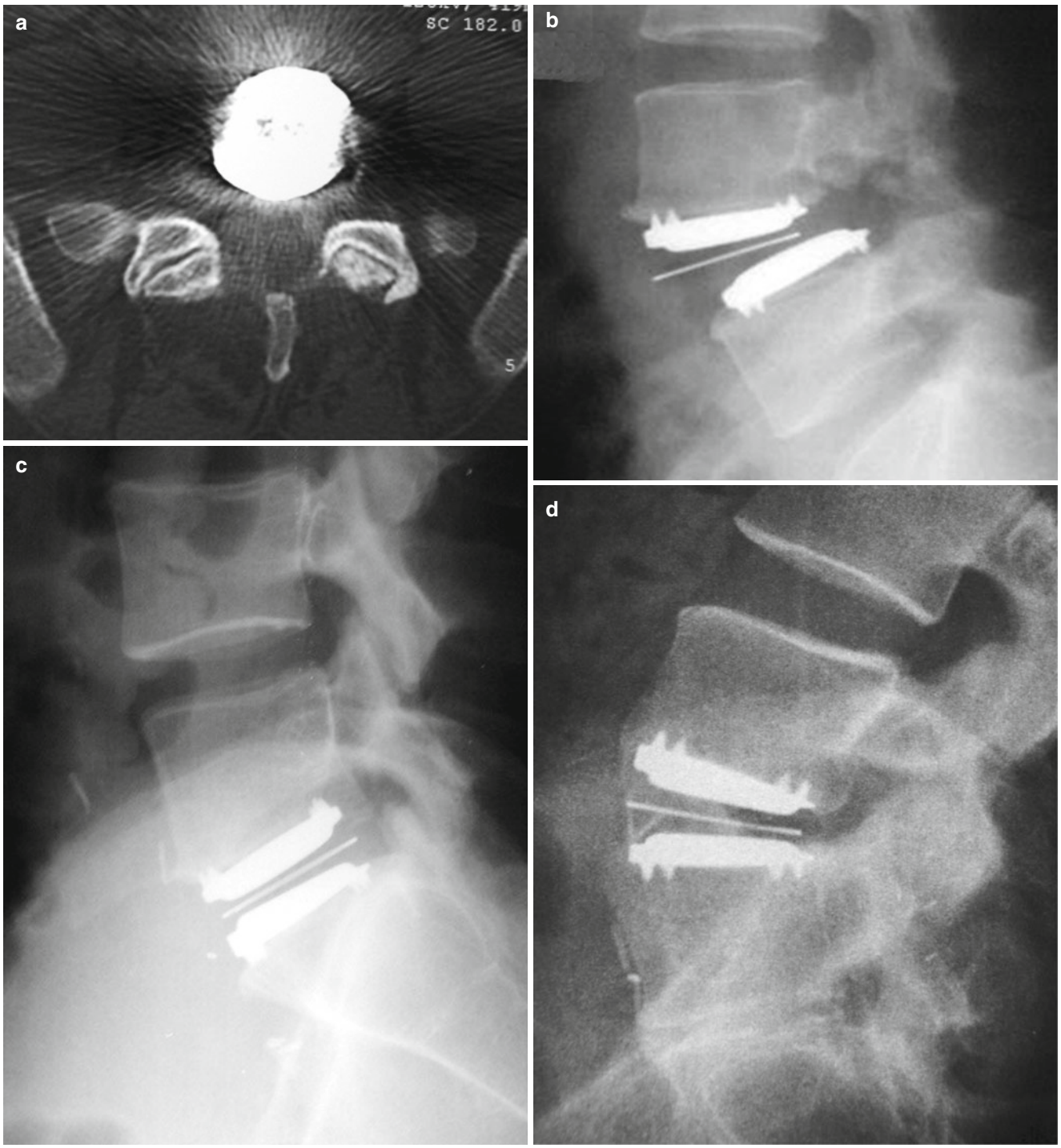
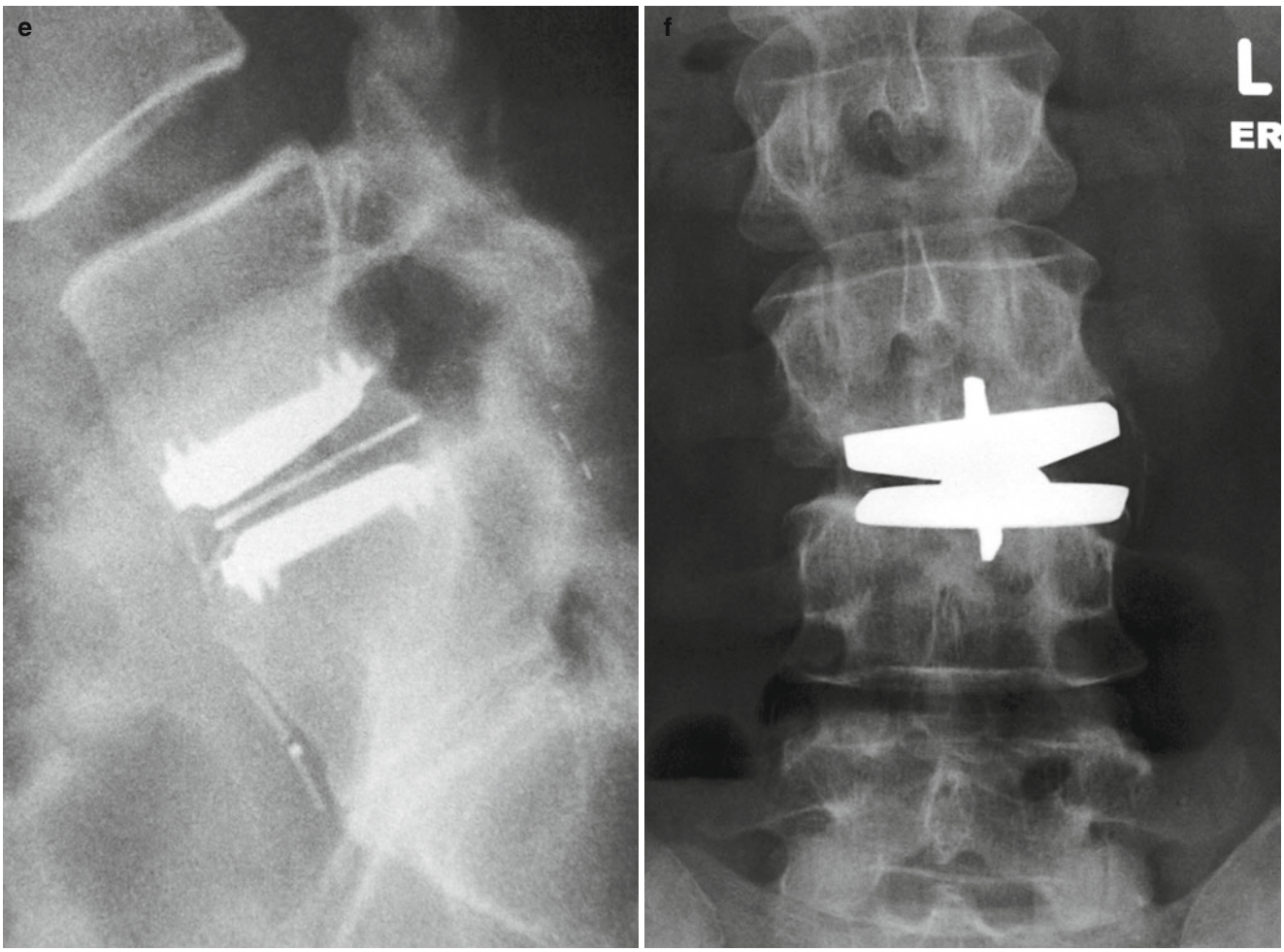


Fig. 35.2 (**a**) Facet degeneration after Charité total disc replacement. The image shows an incipient osteophyte in the left facet joint, peculiar to facet arthropathy. (**b**) Prosthesis displacement due to index level instability. (**c**) Prosthesis subsidence and consequent kyphotic angulation of the artificial disc. (**d**, **e**) Dynamic X-rays showing the increased motion at the operated level, corroborating with the importance of ALL in motion control. (**f**) Bad positioning of the prosthesis generating iatrogenic scoliosis



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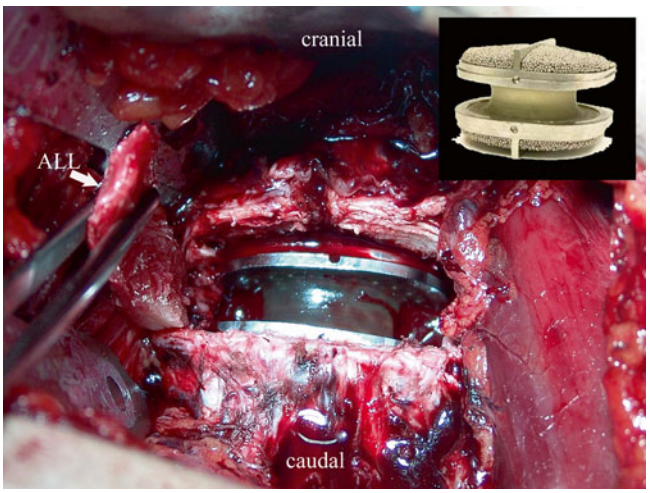

Fig. 35.3 Implantation of an elastomeric total disc replacement via anterior approach. Note the resection of the ALL, inherent of the anterior surgical technique. In detail, the prosthesis design is evidenced

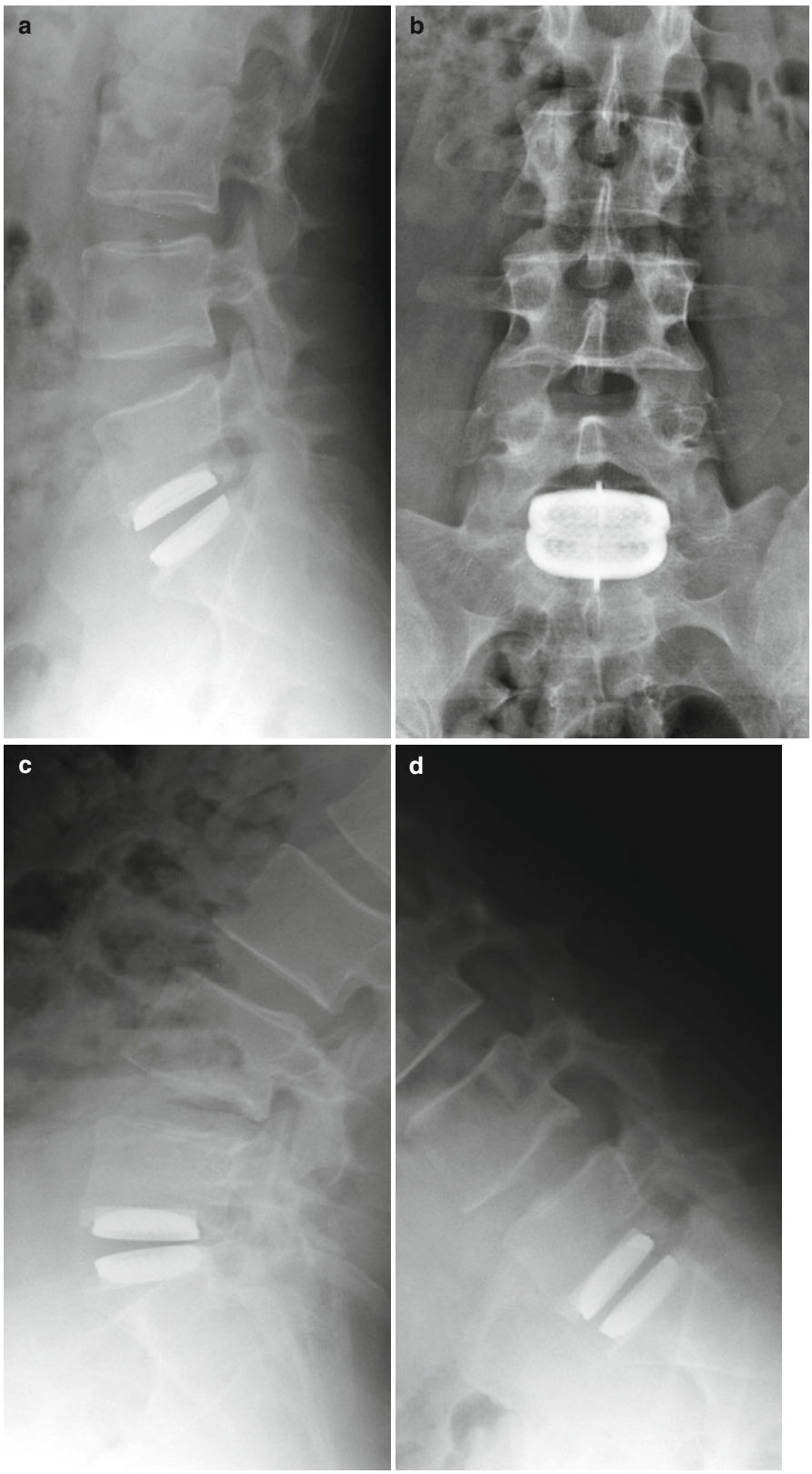

Fig. 35.4 Phisio-L case example. (**a**) Orthostatic lateral. (**b**) Orthostatic A/P. (**c**) Flexion. (**d**) Extension. The elastomeric material improves the retention of motion while enhancing the load distribution between vertebrae

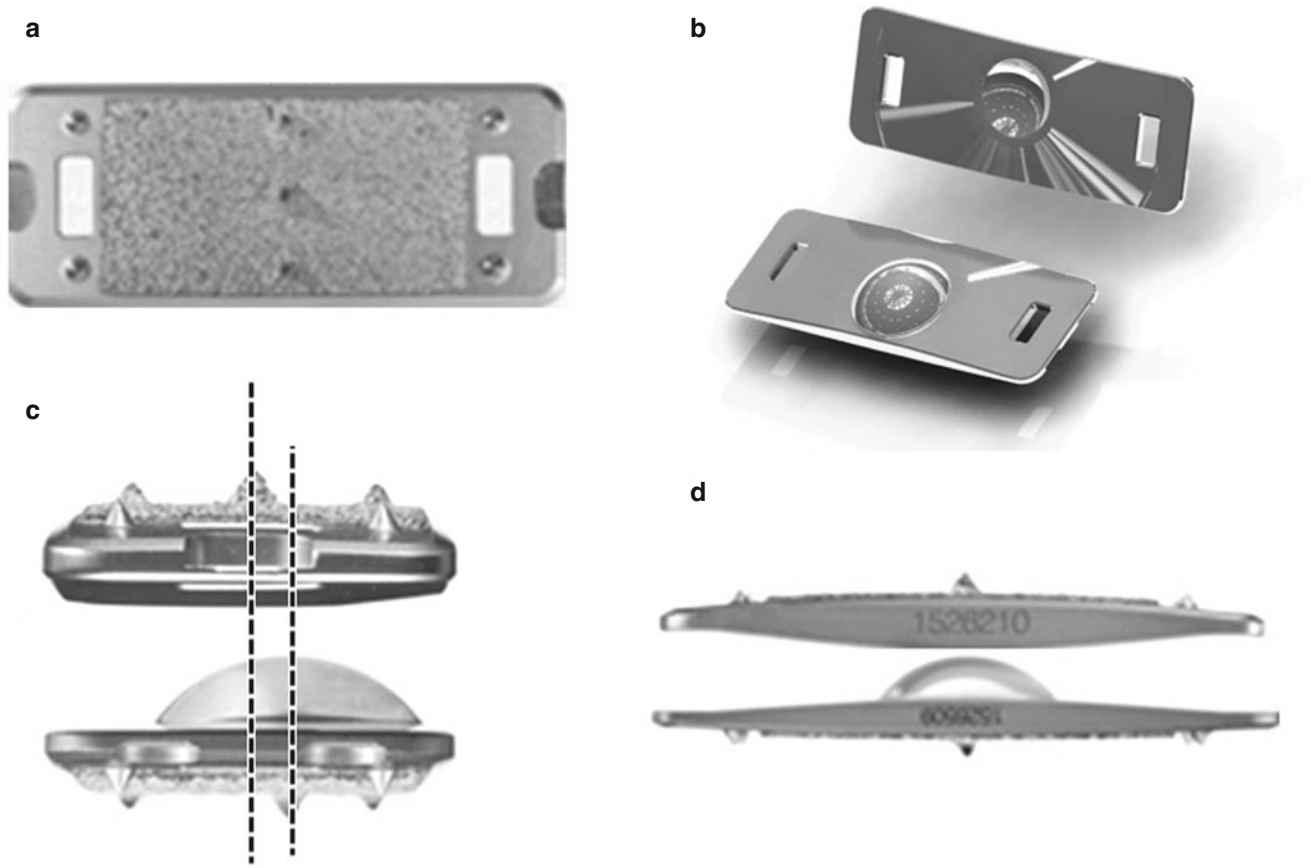

Fig. 35.5 XL-TDR prosthesis design. (**a**) Superior view, showing wide contact area that lies in apophyseal ring. The external endplate surfaces possess porous plasma spray coating. (**b**) The prosthesis is a ball-and-socked semi-constrained design. (**c**) Lateral view, evidencing markers. The medial superior marker must be positioned in the center of the vertebral body, while the medial inferior marker shows the positioning of the center of rotation of the prosthesis. (**d**) A/P view, showing a large contact surface with the vertebral body, preventing subsidence

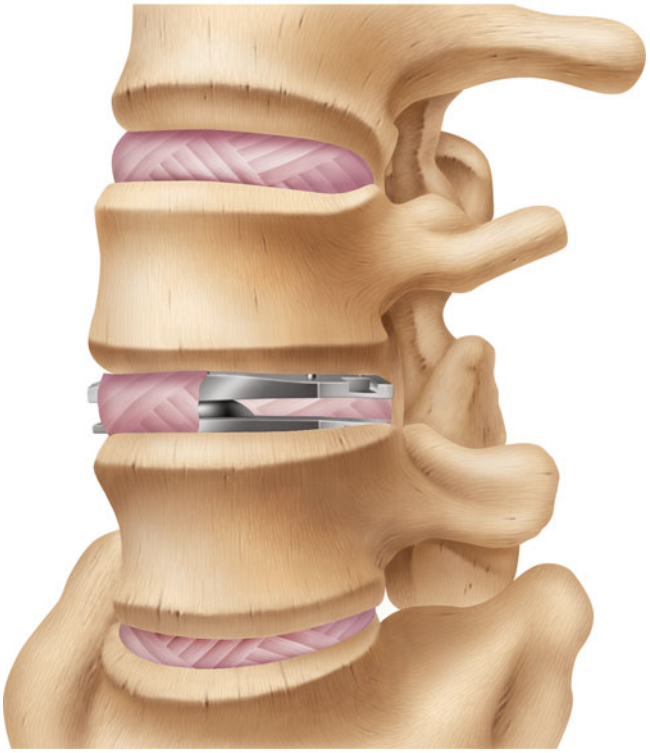

Fig. 35.6 Final position of the prosthesis. Oblique anterior view evidencing the maintenance of the ALL, while the prosthesis lies in the vertebral ring apophysis, generating biomechanical characteristics similar to intact disc (Copyright NuVasive, used with permission)

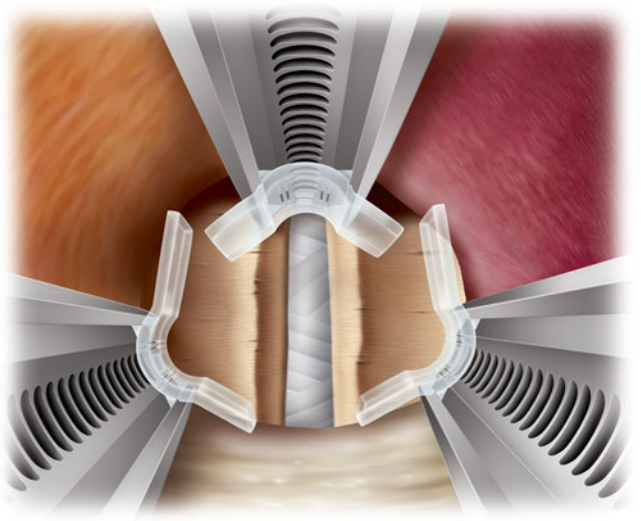

Fig. 35.7 Direct visualization of the disc by lateral approach. This technique allows lateral access to the index level, being possible to remove most of the intervertebral disc, maintaining the posterior and anterior parts of it, which contains the restraint ligaments (Copyright NuVasive, used with permission)

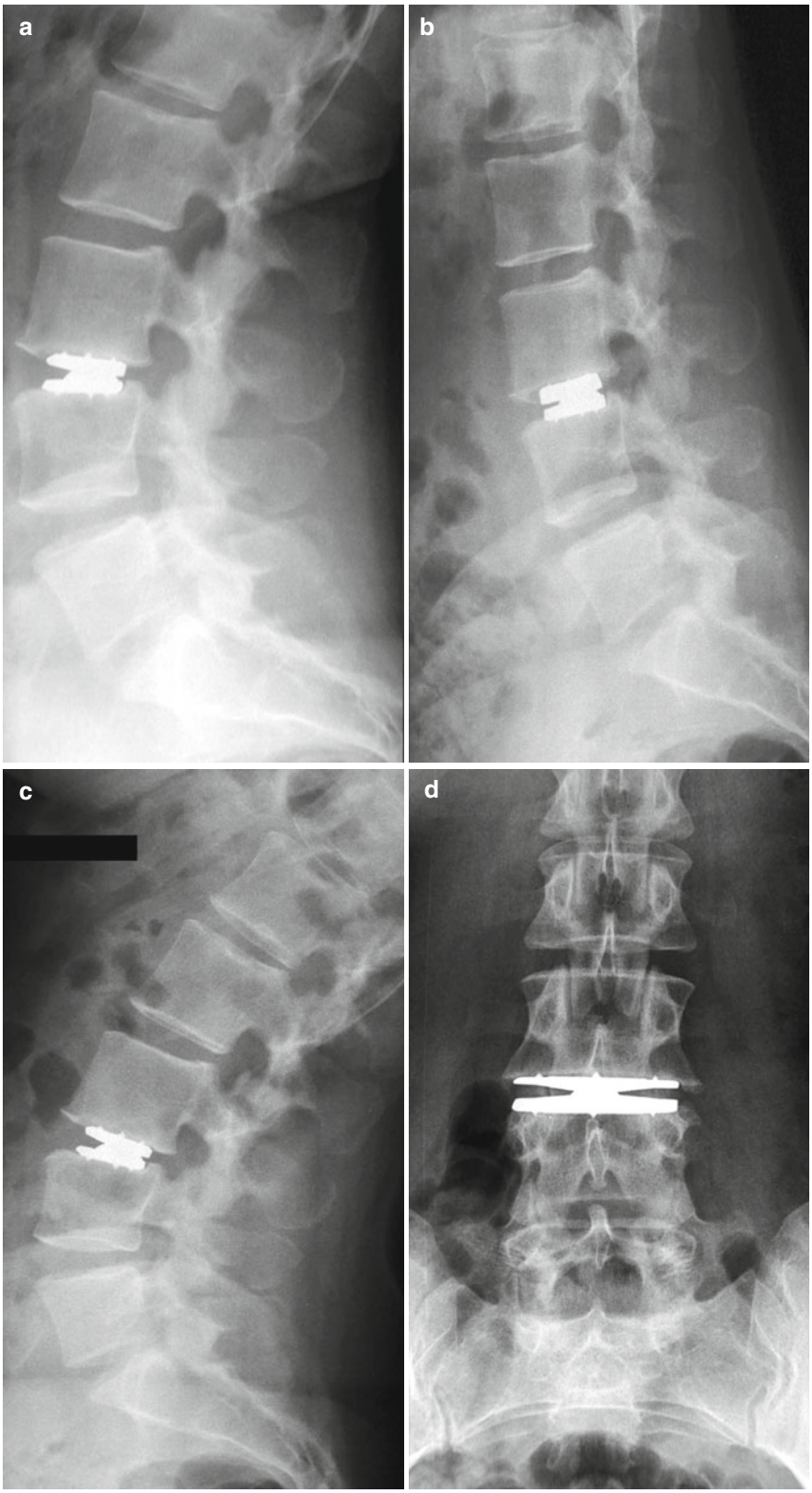

Fig. 35.8 XL-TDR prosthesis design. (**a**) Orthostatic lateral view. (**b**) Flexion. (**c**) Extension. (**d**) Orthostatic A/P view. The maintenance of ALL generates a more controlled motion at the index level. The markers lead to an easy and ideal implantation

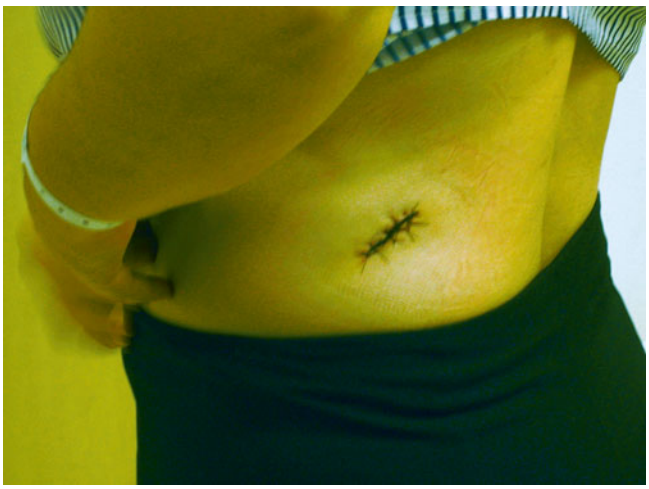

Fig. 35.9 Minimally invasive implantation of the prosthesis by lateral approach evidenced by the diminished incision required to generate a working portal to access the disc space

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Part VI

Minimally Invasive Spine Surgical Complications

Choice of Minimally Invasive Approaches: A Review of Unique Risks and Complications

36

Ngoc-Lam M. Nguyen and Alpesh A. Patel

Introduction

In the last two decades, spine surgery has witnessed an evolution of minimally invasive procedures. Despite established evidence of long-term efficacy, conventional open surgical approaches are associated with high morbidity that can sometimes mitigate clinical benefits. Complications such as vascular and neurologic injury, infection, incisional pain, muscular atrophy, abdominal hernias, and sexual dysfunction have been well documented in the literature [1–5]. On the other hand, minimally invasive surgical techniques are purported to minimize soft tissue trauma and, therefore, offer the advantages of decreased blood loss, reduced postoperative pain, shorter hospitalization, facilitate quicker recovery and rehabilitation, and delay progression of adjacent level degeneration and deformity.

Advances in minimally invasive technology as well as specialized access instruments and tissue retractors have allowed surgeons to reduce approach-related morbidities by focusing on the pathologic anatomy and preserving normal muscular, ligamentous, and bony structures. As more minimally invasive procedures are being performed, it is becoming evident that, with experienced surgeons and appropriate patient selection, outcomes can be as efficacious as traditional open surgeries [6–12]. However, surgeons who desire to master minimally invasive surgery must overcome a set of unique technical challenges. First, the limited tactile feedback from using long instruments in deep tubular retractors coupled with the loss of 3D appreciation and imperfect color representation associated with endoscopic optics can increase the risk of iatrogenic injury to important anatomic structures. Second, although many of the same complications associated with conventional open spine surgery can also occur in minimally invasive approaches, the decreased access inherent to operating through smaller surgical windows causes particular difficulty with managing intraoperative technical problems. Third, there is a steep learning curve for developing the appropriate surgical manual dexterity to master the specialized instruments necessary to perform minimally invasive spine surgery. There is some evidence showing an increased risk of complications and longer operative time for minimally invasive spine surgeries performed by surgeons who are inexperienced at these techniques [13, 14]. Finally, the use of fluoroscopic imaging is frequently increased as compared to traditional open surgeries, and, as such, the cumulative radiation exposure to surgeons, operative room staff, and patients becomes a greater concern. Therefore, careful vigilance and special precautions must be observed to minimize the risk of developing cataracts, thyroid cancer, lymphoma, breast cancer, and other conditions linked to occupational radiation exposure [15].

As minimally invasive procedures continue to grow, surgeons are also faced with a wide array of surgical approaches and techniques. It, therefore, is paramount that spine surgeons possess a clear understanding of the associated complications that can occur with each approach. More importantly, knowing how to avoid these possible complications and how to manage them is critical to performing safe and successful minimally invasive spine surgery.

Cervical Procedures

Anterior Cervical Foraminotomy

This technique was first described by Verbiest in the 1960s and later refined by Jho in 1996 [16–18] (Fig. 36.1). It has

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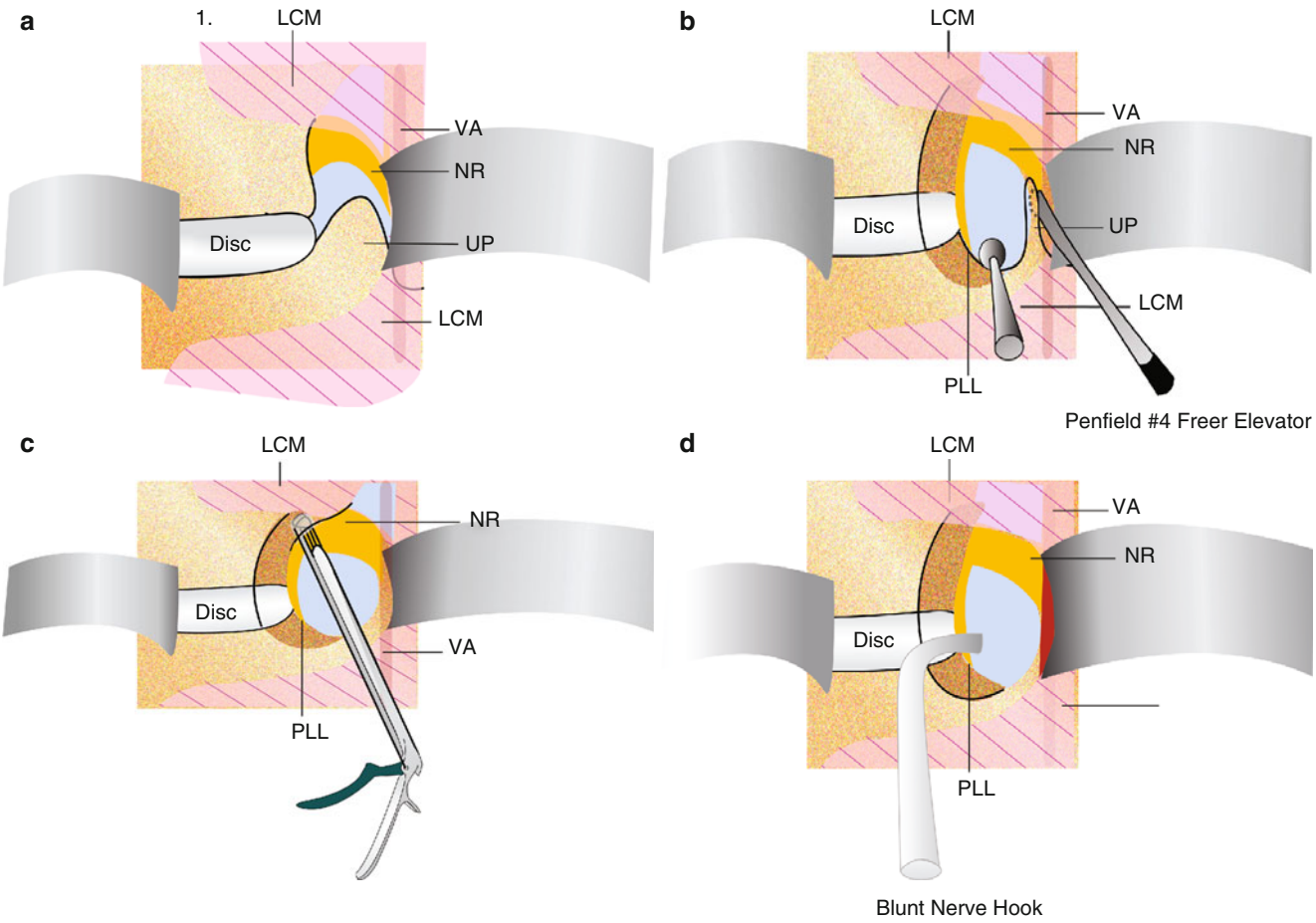

Fig. 36.1 Approach and technique for anterior cervical foraminotomy. (**a**) Demonstrates the surgical landmarks for the approach. (**b**) Illustrates creation of a 5–6 mm foraminotomy and the use of a Penfield #4 to protect the vertebral artery. (**c**) Depicts progression and completion of the foraminotomy and decompression. (**d**) Blunt nerve hook is used to ascertain complete decompression. *LCM* longus coli muscle, *VA* vertebral artery, *NR* nerve root, *UP* uncinate process, *PLL* posterior longitudinal ligament (From Celestre et al. [114])

been advocated for the treatment of unilateral radiculopathy associated with foraminal stenosis. This approach can be performed as an outpatient procedure and offers the advantage of preserving segmental motion by avoiding intervertebral body fusion. There are, however, several risks described for this procedure. Of greatest concern, the surgical window places the surgeon in very close proximity to the vertebral artery, which can be inadvertently injured during drilling of the uncovertebral joint. The vertebral artery is at particular risk of iatrogenic injury at three possible sites: at the level of C6–7, at the uncinate process, and at the foramen transversarium [16]. At the C6–7 level, the vertebral artery traverses between the transverse process of C7 and the longus colli muscle. Therefore, to avoid injuring this vessel, Jho recommends incising the longus colli at the level of the C6 transverse process. As the surgeon reflects the muscle stump caudally toward the C7 transverse process, the vertebral artery is seen directly beneath the longus colli muscle at that level. At the uncinate process, a thin layer of cortical bone should be retained, behind which lies the vertebral artery, when drilling down the uncovertebral joint. This layer of bone can then be more safely and carefully removed with a curette. Lastly, care should be taken to avoid violating the transverse foramen while drilling the uncovertebral joint. The presence of brisk venous bleeding suggests that the venous plexus that surrounds the vertebral artery is injured and the transverse foramen has been breached [19].

Vertebral artery injury during anterior cervical spine procedures is rare, with only sporadic reports published in the literature [20, 21]. Golfinos and colleagues recommend direct primary repair as a first choice for managing iatrogenic vertebral artery lacerations [20]. The rationale being that one cannot be sure of the status of the contralateral vertebral artery and its ability to provide adequate blood flow. However, primary repair is technically demanding and requires the appropriate technical and microsurgical capabilities. Recently, the use of endovascular interventional stenting has been reported with high success rates for treating iatrogenic vertebral artery injury [22–24]. When primary repair is not amenable, immediate consultation with the

interventional endovascular team may provide the best chance of preserving the patency of the vertebral artery. On the other hand, Smith et al. argue that direct exposure and hemostasis with electrocoagulation, ligation, or clipping can be safe, quick, and reliable [21]. The incidence of ischemic sequelae from vertebral artery ligation has been reported as high as 12 % [25]. Thus, prior to any ligation or clipping the competency of collateral circulation must be ascertained with angiography. Others prefer to pack the field with Gelfoam, muscle, or bone wax [26]. Due to reports of delayed complication associated with packing, such as vertebral artery dissection, arteriovenous fistulas, and aneurysm formation, it is prudent to obtain postoperative angiography and continued evaluation of these patients [27, 28].

Horner syndrome from inadvertent injury to the sympathetic chain is another potentially serious complication from anterior cervical foraminotomy. The sympathetic chain is located anterior to the longus colli muscle and lies approximately 11.6 ± 1.6 mm lateral to the medial edge of the longus colli muscle [29]. It is at risk during dissection of this muscle to expose the transverse process. The risk of injury may be minimized by adequate lateral retraction of the longus colli, ensuring the retractor blade is situated between the vertebral body and the longus colli muscle (not on top of the muscle), and limiting resection of the muscle to the most medial aspect [19].

Anterior Cervical Discectomy and Fusion

First introduced in 1958 by Cloward [30], open anterior cervical discectomy and fusion (ACDF) has been widely adopted for the treatment of cervical disc disorders causing radiculopathy and cervical myelopathy. The principal advantage of the anterior approach as compared to the traditional open posterior approach is the avoidance of extensive subperiosteal stripping of the paraspinal musculature, which can result in postoperative pain, spasm, and dysfunction. The clinical success rate for ACDF is very high with low associated morbidities [31]. More recently, inspired by Foley and Smith's use of microendoscopic and tubular retractor technology in the lumbar spine, surgeons are applying this minimally invasive technology to anterior cervical procedures with initial success [32–34]. The endoscopic approach is very similar to the traditional open approach, with the exception that tubular dilators and retractors are placed after the cervical bodies are identified via the standard open fascial window medial to the sternocleidomastoid muscle. As such, the same complications that occur with the traditional open approach can also occur with the endoscopic method.

In their review of the literature, Fountas et al. list the postoperative complications associated with this procedure: recurrent laryngeal nerve palsy, Horner syndrome, pharyngeal or esophageal injury, thoracic duct damage, pneumothorax, vertebral artery laceration, carotid artery or jugular vein injury, aneurysm formation, wound (superficial and deep) and epidural hematoma, epidural abscess, respiratory insufficiency, angioedema, superficial wound infection, spondylodiscitis, aseptic spondylodiscitis, seroma, dural laceration, CSF leakage, meningitis, spinal cord contusion, transient or permanent myelopathy, nerve root lesion, additional radicular symptoms, development of angular deformity, bone graft or instrumentation extrusion, and postoperative mechanical instability of the cervical spine [35]. Of these, dysphagia was found to be the most common postoperative complication, occurring in 9.5 % of patients. Although the exact mechanisms remain unknown, soft tissue edema and injury resulting from retraction, postoperative hematoma, adhesion formation, and implant irritation are postulated to be the underlying causes of postoperative development of dysphagia [36, 37]. The incidence of early postoperative dysphagia may be reduced by new improvements in low-profile interbody implants and thin-blade retractors. In their review of 1,015 patients undergoing ACDF who subsequently developed isolated postoperative dysphagia, Fountas et al. show that conservative treatment resulted in excellent outcome [35]. Postoperative hematoma is the second most common morbidity (5.6 %). The surgeon should be alerted to this complication in patients who develop an enlarging neck mass with associated dysphagia and respiratory distress. Early detection and urgent wound exploration and surgical evacuation of the hematoma remain the mainstay of management [35, 38]. Recurrent laryngeal nerve (RLN) palsy can manifest with hoarseness, dysphagia, vocal fatigue, persistent cough, aspiration, and airway obstruction. Fountas et al. found a 3.1 % incidence of clinically symptomatic RLN palsy in their series, but the true incidence remains unclear, with reports ranging from 0.9 to 24 % [35, 39, 40]. It has been suggested that the RLN is shorter and has a more oblique course on the right side of the neck and is therefore at an increased risk for traction injury during a right-sided approach [41]. Periodic release of tissue retractor may reduce the rate of RLN injury. The routine use of intraoperative indirect laryngoscopy or vocal cord EMG monitoring remains controversial, and their utility for decreasing RLN palsy has not been determined by prospective clinical studies [42, 43]. Their use may be more strongly considered for patients who are at higher risk of sustaining RLN palsy, such as those with a history of previous neck surgery or thyroid gland enlargement or those with preexisting hoarseness [39]. Fortunately, recurrent laryngeal nerve palsy spontaneously resolves within a few days [35, 39, 44]. Persistent hoarseness that does not resolve after 4 weeks should be evaluated by postoperative laryngoscopy to assess vocal cord function.

Injury to the larynx or esophagus can be fatal if not promptly identified and appropriately treated [35, 38, 40]. If there is a high clinical suspicion, performing intraoperative esophagoscopy can help the surgeon identify an injury. Others have

described using diluted indigo carmine to fill the esophagus before wound closure at the end of the case; lack of extravasation of dark blue color suggests an intact esophagus at the surgical site [45]. When identified intraoperatively, these injuries should be primarily repaired, followed by wound and nasogastric tube drainage. Unrecognized injury can result in development of mediastinitis and/or retropharyngeal abscesses, which can have dismal prognosis. When suspected postoperatively, obtaining plain radiographs or CT to look for subcutaneous emphysema, mediastinal widening and haziness, and fluid collections is imperative in the diagnostic workup. Timely consultation with our ENT and/or thoracic surgery specialists is of paramount importance. As these injuries typically result from improperly placed retractors, avoidance of overzealous retraction, mindful placement of tissue retractors, and careful sharp dissection are crucial techniques for reducing complication risk.

Posterior Cervical Laminoforaminotomy and Discectomy

The familiarity of the posterior approach to the cervical spine and the avoidance of anterior complications are appealing. Furthermore, by avoiding a fusion, the posterior procedure may minimize the risk of accelerated degeneration of adjacent motion segments. With the development of minimally invasive muscle-splitting techniques, the use of microendoscopes and tubular retractors may reduce the morbidities of tissue destruction and postoperative pain classically ascribed to traditional open posterior cervical approach. Initial reports have described favorable outcomes for microendoscopic posterior cervical laminoforaminotomy and discectomy [46–48].

Initially, this procedure was performed in the prone position, which led to bleeding that obscured the endoscopic portal and resulted in increased operative blood loss and time. To address this issue, Fessler and Khoo [46] describe a semi-sitting position with the head stabilized in the Mayfield head holder. The position not only leads to decreased operative blood loss by reducing epidural venous congestion but also improves the visualization of the surgical field by allowing blood to flow out of the tubular retractors. Although the theoretical risk of air embolism does exist, there have been no reports of such complication to date with the semi-sitting position. One potential serious complication with the endoscopic approach to the cervical spine is iatrogenic spinal cord injury that can occur with the initial docking of the K-wire and/or muscle dilators. Surgeons should be particularly mindful of this risk when performing revision cases in which dense scar tissue or altered muscle anatomy may increase the risk of inadvertent placement of instruments between the cervical lamina and into the canal if undue force is used. In order to minimize this risk, many authors recommend either avoiding the use of K-wires or gently advancing the K-wire under spot fluoroscopic guidance to ensure that it is docked on the bone [42, 46, 47]. It is also possible that with each subsequent passage of tubular dilators, the K-wire may be unintentionally plunged between the lamina or through a laminal defect and into the canal. Thus, it is more prudent to remove the K-wire after docking of the initial dilator [42]. As an extra precautionary step, it has been advised to only initially rest the dilators and final retractor at least 1 cm off the spine [42, 47]. Then, under direct visualization, a straight curette is utilized to separate the muscle fibers and palpate the bony facet complex. Once the target location is identified, the tissue retractor is safely advanced to its final docking position. AP and lateral fluoroscopic images are then used to confirm proper engagement on operative target. A far lateral final docking position greatly increases the risk of injury to the nerve root and vertebral artery.

When performing bony decompression, excessive resection of the facet complex should be avoided. Using a 25°-angled scope or starting in a lateral position can lead to excessive bony removal [49]. Based on biomechanical data, unilateral resection of less than 50 % of the facet complex will not induce iatrogenic instability [50]. In his review of 100 patients undergoing endoscopic posterior cervical laminoforaminotomy and discectomy, Adamson [51] reported only three complications (two cases of durotomies and one case of superficial wound infection). The two durotomies were treated with Gelfoam packing, and none of the patients developed long-term sequelae. Fessler and Khoo [46] reported 3 complications from their series of 25 patients, which included two cases of small cerebrospinal fluid (CSF) leakage and one case of partial thickness dural injury. The CSF leaks were treated with routine lumbar drainage without persistent issues. The key to avoiding incidental dural tears is good dissection of the underlying ligamentum flavum and dura from the bone. If identified intraoperatively, direct primary repair should be performed for large dural defects, which may require conversion to an open procedure. Small tears can be managed with packing adjuncts such as Gelfoam, dural grafts, and/or fibrin glue. Meticulous fascial closure is imperative to minimize the risk of delayed development of a pseudomeningocele. Finally, nerve root manipulation during foraminotomy must be limited to a minimum, particularly in revision cases where adhesions and scar tissue can tether the nerve roots and place them at higher risk of traction injury [42].

Thoracic Procedures

General Considerations for Thoracoscopic Spinal Surgery

More recently, studies have shown that thoracic spine pathology may have been underestimated in the past, with new evidence estimating a prevalence of 11–37 % for herniated

thoracic discs [52, 53]. While clinically symptomatic herniated thoracic discs are rare, those patients who are symptomatic can develop myelopathy and/or thoracic radiculopathy [54]. Traditionally, an anterior approach to the spine was performed via a lateral thoracotomy. However, with the advent of thoracoscopic technology in the 1990s, anterior thoracoscopic approach to the spine has reported a lower incidence of postoperative incisional pain, intercostal neuralgia, respiratory complications (i.e., pneumonia, effusion, atelectasis, scarring), and scapular dysfunction [55–61]. Nevertheless, reported complications include those related to anesthesia, port placement and access, manipulation of long instruments within the pleural space, and potential injury to the pulmonary parenchyma and vascular structures when performing thoracoscopic surgery.

Anesthesia-related complications in thoracoscopic spine surgery typically pertain to single-lung ventilation. Patients with baseline pulmonary disease are less likely to be able to tolerate the ventilation perfusion mismatch in single-lung ventilation. A thorough preoperative workup including pulmonary function testing, medical optimization, and smoking cessation is necessary to reduce the intraoperative and postoperative complication rates. Careful size selection and proper placement of endotracheal tubes can prevent dislodgement and ensure adequate deflation of the lung in the operative hemithorax. If the bronchial cuff is not appropriately inflated, pressure injury to the bronchus may occur (in the case of hyperinflation) or air may leak into the operative lung (in the case of underinflation) jeopardizing the operation [62, 63]. Carbon dioxide insufflation is seldom required to compress the lung in the operative side, especially when a double-lumen endotracheal tube is used. However, when used, gas insufflation to achieve lung compression can cause serious respiratory and hemodynamic changes that can clinically resemble a tension pneumothorax. These physiologic changes can occur with pressures as low as 5 mmHg, particularly in patients who are hypovolemic [62, 64]. Ensuring adequate hydration status and limiting the gas volume to 2 L/min and insufflating at a pressure below 5–10 mmHg will reduce the risk of a cardiac tamponade [57, 65]. One should also be aware of the risk of fatal CO_2 embolism if a vein or artery is injured during sustained positive pressure insufflations [66].

Prolonged changes in intra-arterial oxygenation and end-tidal CO_2 should alert the surgeon and anesthesiologist to potential complications that require immediate intervention. A sustained decrease in oxygenation saturation should precipitate an investigation with a fiberoptic bronchoscope to confirm the position of the endotracheal tube. Chest auscultation should be performed to evaluate for the presence of a spontaneous pneumothorax, which requires placement of a chest tube. Finally, prolonged deflation of the lung, particularly in longer surgeries, can result in excessive accumulation of secretions in the airways and lead to development of postoperative atelectasis and pneumonia. A variety of techniques can be instituted postoperatively to reduce this complication, including the use of incentive spirometry, early ambulation, and pulmonary percussion and postural drainage [65].

To reduce organ injury during port placement, it is recommended that all ports after the initial one should be placed under direct endoscopic monitoring. With the lung collapsed, the diaphragm and abdominal organs can elevate slightly toward the thorax and become prone to injury with placement of the lower ports. To reduce the risk of injury with blind placement of the initial port, one should pass the finger through the port site and sweep circumferentially to release any potential adhesions tethering the lung parenchyma to the thoracic wall [67]. If the surgeon is operating on the left thorax, extreme caution should be observed when placing the first port to avoid injuring the pericardium and the heart within [67]. Careless placement of ports can also lead to injury to the intercostal nerve and vessels. Injury to intercostal nerves can result in postoperative neuralgia; however, most of the cases of postoperative intercostal neuralgias associated with thoracoscopic surgery spontaneously resolve after a period of observation [55, 60]. Bleeding from port placements can typically be controlled with bipolar cautery. When cautery hemostasis fails, a Foley balloon may be inflated to tamponade the bleeding. The surgeon should not be reluctant to convert to an open thoracotomy to adequately visualize and control the bleeding source if indicated [68]. Catastrophic injuries to major vessels, the lung and heart, and diaphragm can also occur from injudicious manipulations of long instruments within the thoracic cavity. Tips to minimize complications include continuous visualization of instrument motion, making only small movements, keeping retractor jaws fully closed when not in use to avoid inadvertently clamping down on important structures, and not turning on sharp high-speed tools until it is properly positioned on the target [64].

Thoracoscopic Discectomy

With the introduction of thoracoscopic technology, minimally invasive thoracoscopic techniques have been used to approach the anterior spine in order to treat symptomatic thoracic herniated discs [55, 56, 60, 61]. Compared to the traditional thoracotomy, reports on thoracoscopic techniques cite a lower incidence of approach-related complications, such as intercostal neuralgia, postoperative respiratory compromise, and blood loss [60, 61, 69]. In their study, Rosenthal et al. showed that the incidence of postoperative intercostal neuralgia was 16 % for the thoracoscopic approach as compared to 50 % for the traditional open thoracotomy approach, and the incidence of postoperative pulmonary dysfunction (atelectasis, pleural effusion, pneumonia, etc.) was 7 % versus 33 % for the

thoracoscopic and thoracotomy approach, respectively [60]. The use of soft, flexible thoraports and avoidance of levering against the rib when manipulating instruments can help decrease the incidence of posteroperative intercostal neuralgia [55, 64]. Most cases of intercostal neuralgia spontaneously resolve within 1–2 weeks, but prolonged and/or severe cases may require the use of intercostal nerve blocks [55, 59, 60]. Other commonly reported complications include CSF leakage, chylothorax, pneumothorax, and hemothorax. As discussed earlier, durotomies can be managed with primary repair or packing. All reported CSF leaks resolved without long-term sequelae with treatment using lumbar spinal fluid drains or, rarely, lumboperitoneal shunt to prevent persistent leakage of CSF into the thorax [55, 60, 61, 67, 69]. Cases of chylothorax were treated with chest tube drainage and/or temporary total parenteral nutrition [67, 70, 71] or surgical evacuation [60]. Pleural effusions, pneumothorax, and hemothorax can be treated effectively with routine chest tube placement. In the setting of a CSF leak, the chest tube should be placed to gravity drainage, instead of wall suction, to prevent the development of a CSF pleural fistula [55]. The use of radionucleotide myeloscintography with In-111 diethylenetriamine pentaacetic acid (DTPA) has been shown to be useful for localizing a CSF pleural fistula in cases of unrecognized CSF leaks [72].

With the proper training and practice and appropriate patient selection, thoracoscopic spine surgery can be performed safely and effectively to remove symptomatic herniated thoracic discs. It provides a more complete visualization and access to the ventral spine and spinal cord while offering the benefits of decreased postoperative pain, less blood loss, shorter hospitalization, and fewer pulmonary complications.

Posterior Thoracic Microdiscectomy

Posterior and posterolateral approaches are popular given the familiarity of the approach for spinal surgeons and the ability to avoid intrathoracic complications. Minimally invasive techniques have been applied to the posterior approach for thoracic disc herniation. This has most commonly been reported in small, soft, and lateralized herniated discs resulting in thoracic radiculopathy. As with open procedures, wrong-level surgery is one of the more common complications. Adequate preoperative thoracic and lumbosacral plain films as well as intraoperative fluoroscopic visualization are paramount to correctly localize the level of pathology. Adjunctive methods of counting ribs or referencing from the sacrum can also aid in localization. Aberrant anatomy in 4–30 % of patients, such as the presence of extra ribs and lumbar mobile segments, can increase the risk of wrong site surgery and must be noted with appropriate preoperative and intraoperative imaging [73, 74]. Additionally, a careful assessment of preoperative imaging is prerequisite to determine how far lateral the incisions need to be in order to dock dilators and retractors with the appropriate degree of angular clearance on the facet complex. Similar to cervical spine endoscopic procedures, there is a risk of spinal cord injury associated with K-wire or retractor malpositioning, and great care should be exercised when docking the K-wire and dilators/retractors. To further reduce the risk of neurologic injury, the lateral aspect of the dura should be exposed and identified early to gain an appreciation of the orientation of the spinal cord. One can avoid manipulation of the cord by removing portions of the disc laterally first, creating more room within the disc space to push the more central herniated disc fragments away from the cord [42]. Bleeding from engorged epidural veins and incidental durotomies can be managed as described above.

Lumbar Procedures

Minimally Invasive Lumbar Microdiscectomy and Laminoforaminotomy

Minimally invasive lumbar decompression may be the most commonly performed and reported MIS approach in the literature. In 1997, Smith and Foley first introduced the microendoscopic discectomy (MED) system for performing decompression of symptomatic lumbar nerve roots via a tissue-sparing approach utilizing tubular retractors [75]. Guiot et al. later demonstrated the feasibility of performing adequate bilateral lumbar decompressions using only a unilateral approach [76].

Decompression and discectomy procedures are generally performed using sequential tubular dilators. Proper docking of K-wire on the laminofacet complex and careful advancement of the dilators and final retractor under fluoroscopic monitoring is critical to avoid injuring the spinal cord and nerve root. Multiple techniques have been described to reduce the risk of iatrogenic injury during the decompression. When performing decompression, a burr can be used to aid in bony resection. By maintaining the ligamentum flavum during the initial bony decompression, it can be used to as a barrier to protect against dural injury. Small angled curettes and Kerrison rongeurs may be used to carefully dissect the underlying ligamentum flavum and dura from the bone to reduce the risk of incidental durotomies [76]. Once satisfied with the ipsilateral decompression, the patient is tilted away from the surgeon by 5–10° and the tubular retractor angled to view the base of the spinous process. At this point, the contralateral spinous process and laminofacet complex may be undercut while protecting the neural elements. Once decompression is achieved, the ligamentum flavum can be excised. The ipsilateral ligamentum flavum is

removed first as this allows more room in the canal for the removal of the ligamentum on the contralateral side. It is during removal of the contralateral ligamentum flavum that most accidental durotomies occur [42]. Using a small upgoing curette to remove any dural adhesions and mobilize the underlying dura prior to removing the ligamentum flavum can reduce the incidence of dural tear. The literature reports this incidence to occur between 2 and 17 %, with most series reporting a rate of roughly 8 % (almost twice as high as the incidence reported for open procedures) [7, 11, 77–81]. Once a tear is identified, primary repair in the confined space of the tubular retractors may prove very difficult. Some authors have reported using a micropituitary rongeur or arthroscopic knot passers to aid in primary repair [82]. Fat, fascia, muscle, or using commercially available materials such as dural grafts or fibrin glue can aid in securing the repair. A tight, meticulous fascial closure is needed to reduce the risk of pseudomeningocele development. Although the rates of dural tear in minimally invasive surgery may be higher compared to conventional open approaches, it does appear that the preservation of soft tissues helps limit the potential space present after removal of tubular retractors and provide a protective effect against the development of symptomatic CSF leak, CSF fistulas, or pseudomeningocele [83].

Another important pitfall of minimally invasive posterior approach is the potential for performing an incomplete decompression. In their systematic review of the literature, Fourney et al. reported a reoperation rate of 9.2 % in the minimally invasive surgery cohorts as compared to 7.7 % in those who underwent convention open approach procedures [11]. Gebauer et al. offer tips for safeguarding against incomplete decompressions: (1) all preoperative imaging should be reviewed carefully and correlated to the patient's symptoms and presentation to identify areas of pathology that must be addressed during surgery, and (2) all areas of decompression should be probed with a blunt instrument to confirm there is adequate space for the neural elements [84]. Hussain et al. recommend using a long thin electric drill that does not obstruct the surgeon's view and can be smoothly operated with the push of a foot pedal and therefore allows for better visualization and access when performing the contralateral decompression [42]. Lastly, intraoperative fluoroscopic imaging can be utilized to confirm visualized landmarks (i.e., medial wall of the pedicles) and confirm appropriate resection.

Minimally Invasive Transforaminal and Posterior Lumbar Interbody Fusion

Cloward first described the posterior lumbar interbody fusion (PLIF) procedure in 1953 to achieve simultaneous nerve root decompression and interbody fusion in patients with herniated lumbar intervertebral discs [85]. As an alternative to PLIF, Harms and Rollinger introduced the transforaminal lumbar interbody fusion (TLIF) procedure in 1982 [86]. Both the PLIF and TLIF approach can now be performed with the use of muscle-splitting, tubular retractor devices. Complications of MIS interbody fusion procedures include many of the complications of traditional open techniques: nerve injury, incomplete decompression, durotomy, hardware malposition, and infection. The greatest concern with MIS procedures involves the adequacy of the interbody discectomy and fusion preparation.

Similar to open procedures, there are several key principals that must be observed during a minimally invasive approach in order to attain a solid fusion. The discectomy must be thorough while preserving the integrity of the anterior annulus and anterior longitudinal ligament. The endplate should be completely stripped of all disc material but not violated. Because the availability of local autologous bone graft stock may be limited with a minimally invasive technique, surgeons may have to rely on the use of bone morphogenetic protein-2 (BMP-2), autologous iliac crest, or other bone substitutes to secure a successful fusion. Some authors suggest burring the transverse processes and/or the contralateral facet to enhance fusion rate during minimally invasive approaches [84]. In a quantitative meta-analysis, Wu et al. found that the fusion rates were similar for open (90.9 %) and minimally invasive TLIF (94.8 %) but that the use of bone morphogenic protein 2 was more common in the minimally invasive technique (50 % of MIS procedures vs 12 % for open) [87]. Park and Ha have also described a high fusion rate (96.9 %) for the minimally invasive PLIF procedure that was statistically comparable to the open procedure cohort [88].

To date, there is a paucity of studies directly comparing the clinical outcome, fusion rate, and complication rate between minimally invasive endoscopic TLIF, PLIF, and their respective conventional open approaches. However, a multitude of available observational cohort studies have reported less blood loss and decreased need for blood transfusion, shorter length of hospitalization, decreased postoperative pain, and faster rehabilitation and recovery with the minimally invasive techniques [12, 88–90].

Minimally Invasive Transpsoas Interbody Fusion

The transposas interbody approach has increased over the past decade. This approach has been described across a variety of spinal conditions as an alternative to the traditional anterior lumbar or thoracolumbar approach. These approaches are typically used for lumbar interbody fusion above the L5–S1 level because the iliac crest limits access to the L5–S1 interspace.

Major unique complications that can occur with transpsoas approach include intraperitoneal entry, vascular injury, injury to the psoas muscle, and damage to the lumbar plexus [91–94]. To decrease the incidence of inadvertent entry into the peritoneal cavity, Ozgur et al. recommend using a second smaller incision to digitally palpate the retroperitoneal space in order to safely guide instruments prior to docking retractors [92]. To date, there have been no studies directly comparing the complication rates of bowel or vascular injury from endoscopic lateral lumbar interbody fusion techniques against the traditional open anterior or lateral transpsoas techniques. However, a review of the literature demonstrated only 1 case of cecum perforation during endoscopic lateral transpsoas approach to the lumbar spine [95]. When suspected, an emergent general surgery, vascular surgery, or urology consultation should be requested intraoperatively to address any bowel, vascular, or bladder/ureteral injury.

The psoas muscle contains the lumbosacral plexus posteriorly and genitofemoral nerve anteriorly, and these structures can be violated during placement of tubular dilators and retractors. Furthermore, the ilioinguinal, iliohypogastric, and lateral femoral cutaneous nerves all travel obliquely within the retroperitoneal space and are also at risk of injury. Injury to these structures can lead to development of postoperative thigh and/or groin pain, numbness, paresthesia, and weakness. Cadaveric studies have examined the safe working zones for the transpsoas approach [96–98]. The lumbar plexus courses more ventrally in the caudal segments and is most at risk at the L4–5 disc space, where it is located the most anteriorly on the lateral body wall [96–98]. To avoid causing injuries to these lumbar plexus structures, care should be observed to dock the tubular dilators and retractors in the middle third of the lateral vertebral body wall as one moves caudally. At the same time, avoiding placement of instrumentations in the anterior aspect of the vertebral body wall is crucial to minimize risk of injuring the genitofemoral nerve. The senior author (AP) advocates for directly visualizing the disc space and neural elements via a mini-open, blunt dissection through the psoas muscle prior to dilator placement. Additionally, the use of proprietary real-time neuromonitoring units attached to dilating/retracting instruments has significantly reduced the incidence of neural injury by allowing surgeons to detect nearby neural elements and reposition the instrument trajectory to avoid permanent neural injury. Ozgur reported that a stimulation threshold greater than 10 mA is considered safe to proceed with advancement of dilator instruments toward the target disc space [92]. In their initial report on 13 patients, Ozgur et al. reported no complications [92]. In their series, Knight et al. reported an overall complication rate of 22.4 %, with 10 % incidence of meralgia paresthetica, and 3 % incidence of L4 nerve root injury likely related to the inconsistent use of varied neural monitoring techniques in this series [91]. Bergey reported a 30 % occurrence of groin or thigh paresthesia likely from irritation of the genitofemoral nerve [99]. Moller described that 23–25 % of their patients reported medial thigh and groin pain and/or numbness [100]. Sofianos and colleagues found a 17.8 % incidence of anterior thigh numbness, 6.7 % of quadriceps weakness, and 2.2 % (1 patient) of foot drop [94]. The common theme of these series, however, was that the majority of patients experienced significant improvement or resolution of symptoms after 6 months [101]. Treatment with pregabalin (Neurontin) may provide symptomatic relief to those with dysesthetic pain.

Another common complication after transpsoas approach is hip flexion weakness and psoas muscle spasm, which occur in approximately 1–30 % of the time [94, 100–103]. It is theorized that this results from muscle damage during dilation and retraction and from postoperative edema causing dysfunction. Patients should be educated about this potential complication and that it typically resolves. Initiation of early postoperative therapy and rehabilitation exercises, such as gentle hip flexion and range of motion, can be very helpful. Overall, lateral transpsoas approach to the lumbar spine has multiple advantages over the traditional open approach, including avoidance of the need for an access surgeon, elimination of the need to retract or violate the peritoneum or mobilization of the great vessels, and preservation of the anterior and posterior longitudinal ligaments. However, these approaches do have unique complications related to splitting/retracting the psoas muscle, but the reported incidence of overall complication is low and falls within, if not lower than, the reported complication range following traditional open spine surgical procedures [4, 5, 104–106].

Presacral Approach/Axial Lumbar Interbody Fusion

In 2006, Marotta et al. describe a novel presacral approach to achieve L5–S1 interbody fusion [107]. This technique has expanded to the L4–5 interbody fusion as well [108, 109]. This technique takes advantage of the natural presacral fat pad plane (also called the retrorectal space) for percutaneous access to the anterior sacrum. A working channel is drilled through the S1 body to access to the intervertebral disc space. Specialized instruments are then passed through this working channel to prepare the interspace and distribute graft material. Finally, a metal screw/strut (axial rod) is inserted to provide rigid fixation.

The major unique complication associated with this approach is injury to the rectum due to its close proximity to the surgical corridor. In their case series, Tobler and colleagues identified no vascular, neurologic, urologic, or bowel injuries with a paracoccygeal transsacral procedure [110]. They reported a high overall fusion rate of 94 % and also

showed that the fusion rates did not differ with the use of bone morphogenetic protein [110]. Their fusion rate was similar to the 91 % fusion rate reported by Aryan et al. and Lindley et al. [109, 111]. The authors emphasized the importance of a thorough disc space preparation in obtaining a successful fusion. Botolin et al. recently reported an incidence of missed high rectal injury that manifested with postoperative development of melena, hypogastric pain, fevers, and nausea [112]. This patient had risk factors for rectal injury, including previous diverticulitis and pelvic inflammatory disease. Lindley et al. also presented 2 cases of rectal injury in their case series (2.9 % incidence), with one of the cases occurring in a patient with a history of pelvic inflammatory disease, diverticulitis, and prior anterior lumbar surgery [109]. Other complications reported by Lindley et al. include superficial infection (5.9 %), sacral fractures (2.9 %), pelvic hematoma (2.9 %), and S1 nerve root irritation (1.5 %) [109]. Patients with wound infection were treated with antibiotics and/or irrigation and debridement without long-term consequences.

Several strategies have been proposed to reduce this risk. First, all patients should undergo a bowel prep the night prior to surgery. Second, lateral radiographs of the coccyx should be inspected to ensure that the coccygeal curvature or hooking is not overly excessive and may impair the feasibility of the approach. Preoperative assessment of the presacral space is imperative to ensure adequate room for safe passage of instruments. A minimum safe size of 10 mm is recommended by the manufacturers. One study has reported that only 42 % of patients would meet this requirement [113]. Third, after the initial incision is made, blunt dissection should be employed to clear the bowel away from the anterior sacrum. Some surgeons consider it a contraindication when patients have medical conditions that cause excessive abdominal adhesion formation that could potentially prohibit adequate mobilization of the bowel, such as a history of pelvic inflammatory disease, prior abdominal surgeries, diverticulitis, or endometriosis [42, 84, 109, 112]. If bowel injury is suspected, patients should be placed on broad-spectrum antibiotics that include Gram negative coverage, and general surgery consultation should be obtained. A missed injury should be suspected when patients develop abdominal pain, blood per rectum, fevers/chills, nausea/vomiting, and prompt imaging workup with plain abdominal radiographs and CT imaging should be ordered.

Although the risk of vascular and neurologic injury does exist, it is not as high for presacral techniques as compared to other procedures [107, 109]. The anterior midline region of the sacrum is typically devoid of important vascular or nervous structures. The middle sacral arteries and veins are typically small and are located more rostral to the S1–2 junction where the working cannulas and pins are docked; therefore, the risk of bleeding is possible but very low [107]. Nevertheless, preoperative imaging should be carefully reviewed for the presence of aberrant anatomy. Neurologic injury can occur from erroneous placement of the screw or from graft extravasation into the epidural space, injuring the nerve roots. Lindley reported 1 case of S1 nerve root impingement from a misplaced screw that deviated off the midline to the right [109]. This complication can be avoided by the use of fluoroscopic imaging to ensure the proper trajectory and positioning of the screw. Overzealous impaction of graft material can potentially lead to extravasation through an annular weakness or defect and into the epidural space, causing irritation and radiculopathy. This risk can be minimized through gentle graft impaction, the use of radiopaque graft, and vigilant fluoroscopic monitoring [109].

Conclusion

Minimally invasive spine procedures can be performed effectively and safely in the cervical, thoracic, and lumbar spine. They offer distinct advantages over traditional open approaches, but at the cost of decreased visualization and increased technical difficulties. Although existing evidence suggests an equivalent or lower rate of complications with minimally invasive spine procedures as compared to convention open surgeries, our understanding of the unique complications is still developing with a lack of high-quality long-term, large-scale randomized prospective data. Minimizing the risk of complications of these minimally invasive spine techniques requires mastering the knowledge of surgical spine anatomy, technical prowess and manual dexterity in using equipment, and an understanding of the potential complications and strategies for avoiding and managing these complications. Many of these procedures have a steep learning curve and cadaveric practice with experienced surgeons before they can be safely applied. Balancing risks and benefits of each minimally invasive approach (and those of traditional approaches), as well as careful and proper patient selection is critical for reducing complications and improved clinical outcomes.

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Minimally Invasive Spine Surgery Complications with Implant Placement and Fixation

37

Justin B. Hohl, David C. Holt, and Darrel S. Brodke

Introduction

In a recent supplement dedicated to minimally invasive surgery (MIS) of the spine, McAfee and colleagues proposed a definition of minimally invasive spine surgery that was based on identifying the common goals and principles of the MIS approach.

> An MIS procedure is one that by virtue of the extent and means of surgical technique results in less collateral tissue damage, resulting in measurable decrease in morbidity and more rapid functional recovery than traditional exposures, without differentiation in the intended surgical goal. [1]

These authors then outlined four criteria that should be met in order to justify a procedure as minimally invasive:

- Decreased surgical damage to tissue
- Quantifiable clinical benefits such as reduced blood loss, reduced morbidity from the procedure, decreased pain, decreased length of stay, and early return to activities
- Clinical effectiveness
- Positive socioeconomic benefits [1]

Using this as a broad definition of minimally invasive spine surgery, this chapter will explore the safety profile of many of these techniques by evaluating the complications with minimally invasive implant placement and fixation.

Many of the minimally invasive techniques are relatively new in the field of spine surgery and, as with any new technique, require a period of learning and adoption. During this period, the reporting of complications is often a gradual process that takes a number of years with multiple studies. Initial reports of new minimally invasive techniques could potentially underreport complications, in part because they have been performed by experts who are skilled with minimally invasive techniques. Additionally, industry funding of the initial studies could result in bias with either minimization or underreporting of complications.

Thus, with the abundance of new minimally invasive techniques for spine surgery, reporting accurately on the complications with implant placement and fixation can be challenging. Very few papers focus exclusively on complications, and this data must be gleaned from papers that at times mention the complications almost as a side note. Nonetheless, the topic is paramount to the widespread adoption of minimally invasive techniques, because a safety profile that is similar to traditional open techniques must be established. This chapter therefore attempts to make these comparisons and provide a fair evaluation of the safety of MIS techniques compared to traditional open techniques.

Finding a uniform definition of complications can also be challenging, since some authors group all complications together and others divide them into major and minor complications. Additionally, there is a wide range of follow-up, and studies with less follow-up may not appropriately describe complications such as revision rates.

The summary statement from McAfee et al. highlights an example of this confusion over definitions and rates of reported complications in discussing postoperative thigh pain after lateral interbody fusions [1]. Although the extreme lateral approach to the lumbar spine appears to have less vascular complications than an anterior approach, there seems to be a higher rate of postoperative thigh pain and weakness following these procedures. The true incidence of thigh pain may be difficult to fully understand, however, because some authors may consider it an expected result of a transpsoas approach and not report it as a complication. Isaacs and colleagues reported all cases of postoperative thigh pain and weakness after extreme lateral interbody fusion (XLIF), but only the cases with significant or prolonged sensory or motor deficit were defined as complications [2]. While thigh pain or weakness may be expected following a transpsoas approach, not calling it a complication may not allow readers to fairly compare lateral, anterior, and posterior approaches for interbody fusion.

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This chapter will begin with a discussion of complications resulting from thoracoscopic, laparoscopic, and microendoscopic procedures. Minimally invasive decompression techniques, including interspinous spacers, will then be discussed. Methods for interbody fusion will be explored by comparing the complications associated with anterior, lateral, and posterior approaches. Posterior spinal fusion will be evaluated via minimally invasive approaches to cervical, thoracic, and lumbar fusion. Last of all, special situations will be discussed, including a focus on the learning curve associated with minimally invasive spine surgery.

Thoracoscopy

Minimally invasive spine surgery was largely born from the success of endoscopic techniques used in general surgery in the thoracic cavity and the abdomen. During the late 1980s and well into the 1990s, minimally invasive thoracoscopic spine surgery was gaining momentum with the thought that surgical morbidity could be reduced and patient recovery could be accelerated. Although there have been many positive reports in the literature, thoracoscopy has proven to be technically demanding and has declined in popularity during the most recent decade. Part of this decline may be due to the more recent popularity of posterior approaches, with the decreasing need for anterior releases and fusions. Improved pedicle screw constructs, as well as the posterior osteotomies, have allowed surgeons to manipulate the spine in a way that less often requires an anterior approach. Thus, the need for open thoracotomies, as well as thoracoscopy, has declined in the recent decade.

Thoracoscopic procedures have the inherent risk of injuries to the aorta, superior vena cava, or pulmonary vessels, either through direct injury or indirectly with malplacement of guidewires that might require conversion to an open procedure. The lung must also be handled carefully, being sure not to use continuous carbon dioxide insufflation and never going above 12 mm of Hg to avoid mediastinal shifts and rapid changes in cardiac output [3]. Postoperative intercostal neuralgia may be caused by trocars compressing the neurovascular bundle or monopolar cautery around the inferior portion of the rib. This neuralgia can be avoided by using flexible trocars less than 12 mm in diameter and avoiding monopolar cautery around the neurovascular bundle. In a report of the first 100 thoracoscopic cases, there were 6 instances of transient intercostal neuralgia, although all of these resolved completely with time [3].

In order to avoid visceral or diaphragmatic injury, once the first trocar is placed, subsequent ports should be placed under direct thoracoscopic visualization. Visualization of all instruments at all times is paramount to avoiding visceral injuries. The first trocar should be placed in the midaxillary line well above the hemidiaphragm.

Laparoscopy

Much like thoracoscopy, laparoscopic minimally invasive approaches to the spine have decreased in the recent decade. Not only has the use of the anterior approach declined (with the growing popularity of posterior, lateral, and transforaminal lumbar interbody fusions), but, like thoracoscopy, there is a steep learning curve and high technical demands with laparoscopic approaches.

Unlike thoracoscopy, laparoscopy is routinely performed with carbon dioxide insufflation. The same risks that apply to thoracoscopy, such as vascular or visceral injuries, also apply to laparoscopy, and great care must be taken with initial and subsequent trocar placement. The initial trocar should be placed after needle insufflation at the umbilicus, with the sharp tips pointed caudally to avoid bowel perforation. Maintaining the pneumoperitoneum requires careful insertion of the instruments (which can allow air to escape through the trocars), as well as careful suctioning. As with any open procedure, care should be taken around the L5–S1 disk space in order to avoid injury to the sympathetic plexus, which lies on the sacral promontory. Avoiding monopolar cautery in preference to bipolar cautery may help prevent transient or permanent retrograde ejaculation in males, which has a higher incidence with laparoscopic versus open procedures [4].

The most significant complication of laparoscopic spine procedures is vascular injury, which is commonly a tear of the iliac vein. This generally necessitates an emergent conversion to open surgery in order to gain control of the hemorrhage. Mobilizing the iliac vessels usually requires ligating the tethering branches and, in approaching L5–S1, often requires tying off the middle sacral artery.

Interbody fusions can be performed laparoscopically, although there is a steep learning curve, and the trend has shifted to performing these through a traditional or mini-open approach. The main issue with laparoscopic placement of an interbody cage or bone graft is limitations with exposure, visualization, and orientation. The limitations with visualization can lead to under- or overdistraction of the disk space with the possibility of overreaming the end plates with subsequent subsidence of the implant. It can also be challenging to appreciate where the midline of the disk space is located, leading to asymmetric placement of implants.

In a multicenter study comparing open verse laparoscopic anterior lumbar fusions, 250 consecutive patients at a single center had laparoscopic anterior lumbar fusions at either L4–5 or L5–S1 performed with a BAK cage. These were

compared with 591 patients with open BAK fusions at 19 different centers. The laparoscopic patients had a significantly shorter hospital stay and less blood loss, but the operative time was significantly longer. The complication profile was similar between open and laparoscopic cases, with the only significant difference being more disk herniations in the laparoscopic cohort [5]. However, there are numerous subsequent articles that discuss the increased incidence of complications with a laparoscopic approach [6, 7].

Microendoscopy

A herniated nucleus pulposus can be approached through a number of different minimally invasive techniques, including microscopic discectomy, tubular discectomy, and microendoscopic discectomy. The microendoscopic approach entails performing a discectomy through a tube under the visualization of an endoscope. Visualization can be challenging in this approach and poor visualization leads to most of the complications. Limited soft tissue retraction, bleeding, and orientation of the surgical field can all contribute to the risk of complications, which are similar to those of any discectomy: insufficient disk excision with recurrent herniation, incidental durotomy, and nerve root injury.

Microendoscopy has also been used in placing posterior interbody grafts. It can be challenging to understand the orientation and depth to which the grafts are inserted, and there is the potential that poorly placed cages can result in radiculitis or graft dislodgement. Reports on microendoscopic insertion of posterior interbody grafts can be found in the literature but are quite limited, and this procedure has not been widely adopted.

MIS Decompression

Minimally invasive techniques for lumbar decompression include laminotomy and foraminotomy with use of tubular retractors and microendoscopic laminotomy. These procedures have a complication profile that appears to be similar or in some cases better than that of open decompression. In the recent Scoliosis Research Society (SRS) report on the morbidity of first-time surgery for lumbar spinal stenosis based on the database of 10,000 cases, patients who had minimally invasive procedures had a complication rate of 5.8 % versus 7.6 % for traditional open procedures ($p=0.01$) [8]. The authors noted that this difference may have been due to the severity of stenosis or number of levels decompressed. Additionally, the SRS database is based on self-reported complications of its members, which may underestimate the true rate of complications.

Podichetty and colleagues reported on 220 patients with symptomatic neurogenic claudication from lumbar spinal stenosis who underwent microscopic or microendoscopic decompression [9]. There were 24 minor complications and 14 major complications, including an incidental durotomy rate of 4.5 % and a readmission rate of 2.3 % within the first month, 4 of which were for medical complications. Although the comparison is not equivalent because the populations and studies are different, the recent SPORT trial data revealed an incidental durotomy rate of 9 % for patients with lumbar stenosis. The SPORT trial included patients who had an open decompression with or without fusion, although they reported that there was no significant difference in rate of durotomy when a fusion was performed [10].

Many spine surgery studies report on short-term follow-up (2 year or less), and it can be difficult to gauge mid- and long-term success and revision rates. Oertel and colleagues reported on patients who underwent unilateral laminotomy for bilateral decompression for lumbar spinal stenosis with a 4-year minimum follow-up and 5.6-year mean follow-up [11]. A total of 102 out of 133 (76.7 %) consecutive patients were available for follow-up at a mean of 5.6 years, and 85.3 % had an excellent to fair result. The overall reoperation rate was 11.8 %, 7 of which were for restenosis and 2 of which were for spinal instability, with an overall complication rate of 9.8 %.

Interspinous Spacer

In the last several years, the use of interspinous spacers has gained popularity, with the thought that distracting the interspinous space indirectly decompresses lumbar spinal stenosis. Although there were promising short-term results about the success and potential longevity of these devices, more recent studies have suggested that the revision rate may be higher than originally expected.

The original randomized trial reported a 75 % magnitude improvement in symptoms and physical function at 1-year follow-up [12]. In another prospective observational cohort of 40 patients, 26 of which returned questionnaires at 12-month follow-up, 54 % reported improved symptoms, 33 % reported improved physical function, and 71 % expressed satisfaction with the procedure. In addition, 29 % of patients required epidural steroid injections after 12 months for recurrent symptoms of neurogenic claudication.

Tuschel et al. retrospectively evaluated 46 patients who underwent implantation of the X-STOP interspinous spacer for neurogenic claudication [13]. After a mean follow-up of 40 months, the revision rate was 30.4 %. They found that lack of improvement at 6 weeks correlated well with subsequent revision surgery and that most revisions occurred within 12 months of the index procedure. They concluded

that clinical outcomes after X-STOP implantation may be less favorable than previously reported and that patient selection may be a reason for early revision surgery.

Spinous process fractures have also been reported after interspinous spacer implantation by Kim et al. [14]. Fifty interspinous process devices were placed in 38 patients and followed for 1 year. Postoperative CT scans revealed 11 spinous process fractures in 11 patients (28.9 %) without trauma and not identified on plain radiographs. Three patients underwent revision with removal of the device and laminectomy. The clinical significance of fractures detected on CT only is not yet fully understood, however.

In addition to these implants causing spinous process fractures, there is also at least one case report of an extruded device. An interspinous process spacer was inserted in an 84-year-old patient with a grade 1 L4–5 spondylolisthesis and stenosis, resulting in bilateral foot drop. Three months later, the device extruded and was removed, followed by decompression and fusion 9 months later with partial resolution of the foot drop [15].

Minimally Invasive Anterior Lumbar Interbody Fusion

The mini-open retroperitoneal approach for anterior lumbar interbody fusion has a relatively low complication profile, although there is the potential for life-threatening vascular injury. One of the largest series to report on detailed complications with this approach was the paper written by Brau in 2002 [16]. The author described his mini-open retroperitoneal approach with great descriptive and diagrammatic detail, retrospectively reviewing 684 patients and reporting an overall major complication rate of 3.8 % in the 6-month perioperative period. There were 6 arterial injuries (0.8 %), 6 venous injuries (0.8 %), and one instance of retrograde ejaculation (0.1 %). Seven patients developed DVT (1.0 %), 4 patients had more than 3 days of ileus (0.6 %), and there were 3 wound infections above the fascia (0.4 %), 2 hernias, and 2 compartment syndromes. Brau concluded that with a well-planned incision that is muscle preserving, this approach could be performed safely, although he noted a steep learning curve even for experienced surgeons.

Brau's extensive ALIF experience and low complication rate may not be applicable to surgeons who do not have this level of experience and volume. Mini-open ALIF approaches have been reported elsewhere to have higher complication rates. For example, Kaiser and colleagues reported an immediate postoperative complication rate of 17.6 %. In this study the authors retrospectively compared 51 patients who had a mini-open ALIF versus 47 patients who had a laparoscopic approach. While the mini-open group had a 17.6 % complication rate and the laparoscopic group had a 4.3 % complication rate ($p<0.05$), the rate of retrograde ejaculation was much lower in the mini-open group than the laparoscopic group, 6 % versus 45 %, respectively ($p<0.05$) [6].

These complications may be on the high side, however, when compared with the prospective comparison by Zdeblick et al. of 25 patients who had a laparoscopic L4–5 ALIF versus 25 patients who had a mini-open procedure. The complication rate was 20 % in the laparoscopic group compared to 4 % in the mini-open group. The laparoscopic group had one case of each of the following complications: retrograde ejaculation, ureteral injury, DVT, disk herniation, and iliac vein laceration requiring repair. On the other hand, the mini-open group only had one complication of ileus [7].

Minimally Invasive Transforaminal Lumbar Interbody Fusion

Advocates of a minimally invasive approach to a transforaminal lumbar interbody fusion cite improved clinical outcomes, decreased blood loss with lower transfusion rates, shorter hospital length of stay, and less postoperative pain as reasons to consider an MIS TLIF. The complication data appears somewhat mixed, however, with some studies reporting notably fewer complications and other studies reporting increased complication rates.

Villavicencio and colleagues retrospectively compared 63 patients who underwent open TLIF versus 76 patients who had minimally invasive TLIF [17]. Patients in the MIS TLIF group had almost double the number of complications (although not statistically significant), with an 18.4 % major complication rate compared to a 9.5 % major complication in the open TLIF group. They found a total rate of neurological deficit in the MIS TLIF group of 10.5 %, compared to 1.6 % in the open group ($P=0.02$). Their conclusion was that although MIS TLIF may offer similar long-term clinical outcomes with potential short-term benefits, this must be weighed against the increased rate of nerve injury that they associated with a steep learning curve.

Figure 37.1 demonstrates a complication following MIS TLIF of a cage displacing posteriorly into the spinal canal. Cage displacement may result in neurological injury such as that reported in the series by Villavicencio.

However, cage migration has not appeared to be a significant problem with MIS TLIF's, according to the literature. One study reported an 8.7 % rate of asymptomatic cage migration in open cases with a rate of 5.8 % in MIS cases ($p<.05$) [18].

Additionally, the difference in nerve injury in MIS versus open TLIFs has not been replicated to the extent that Villavicencio reported. In fact, other groups have reported higher complication rates for open versus MIS TLIF. Peng and colleagues prospectively compared open versus MIS TLIF and found a fusion rate of 80 % in the MIS group and 86.7 % in the

open group ($p=.164$) [19]. The overall complication rate for the MIS group was 13.8 % versus 6.9 % for the open group ($p<0.05$). However, these were not complications involving nerve injury or revision surgery for misplaced hardware. The MIS group had two iliac crest site superficial infections that were taken to the operating room for irrigation and debridement, while the open group had one case of atelectasis, two urinary tract infections, and one wound infection in a diabetic patient that was treated with intravenous antibiotics.

Dhall retrospectively compared 21 patients who had open TLIF and 21 patients who had mini-open TLIF, with the mini-open group having more complications, as seen in Table 37.1, Complications of mini-open TLIF versus open TLIF [20]. The authors concluded that the mini-open approach is a viable option for TLIF with shorter length of stay and less blood loss but higher rates of hardware complications.

While there are reports of increased complications with MIS TLIF versus open TLIF, there is not sufficient quality

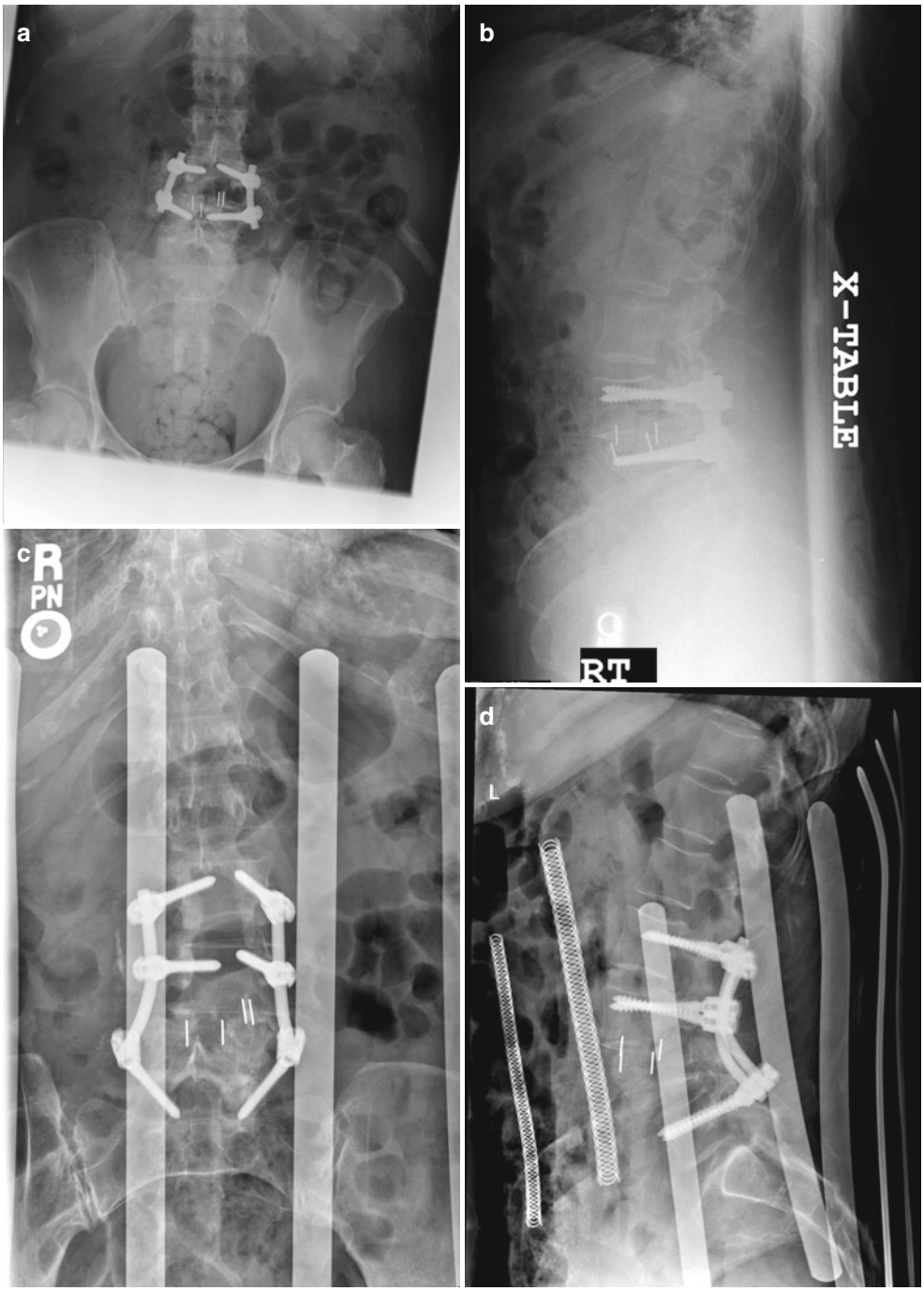

Fig. 37.1 Postoperative AP (**a**) and lateral (**b**) imaging of a 72-year-old female after MIS TLIF placed with MIS instrumentation as her index procedure. The TLIF cage fractured through the vertebral end plates, and the patient developed bilateral lower extremity weakness. AP (**c**) and lateral (**d**) imaging after the initial surgeon revised the failed TLIF by extending decompression and fusion. The patient presented to our facility with continued bilateral lower extremity weakness and extensive bone loss as shown on sagittal CT imaging (**e**). The patient then underwent staged revision at our facility with posterior decompression and fusion from L1 to the pelvis, removal of the fracture fragments, and placement of iliac bolts during Stage 1. Stage 2 involved L3–L4 anterior corpectomy and fusion with an expandable cage placement. Final AP (**f**) and lateral (**g**) imaging after two-stage revision

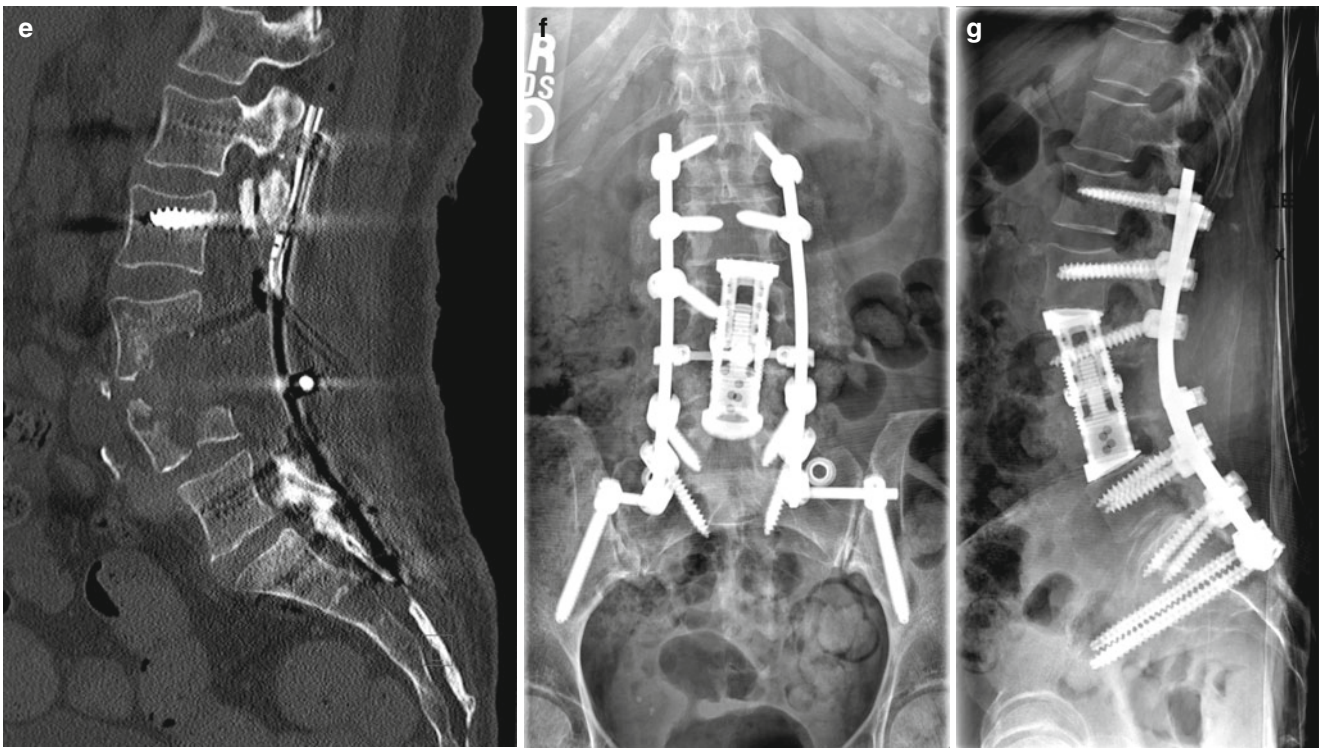

Fig. 37.1 (continued)

Table 37.1 Complications of mini-open TLIF versus open TLIF [18]

Complication	Mini-open	Open
Transient L5 sensory loss	2	0
Misplaced screw requiring revision	1	1
Cage migration requiring revision	1	0
Radiculitis	0	1
Pseudarthrosis requiring reoperation	1	0
Total	5	2

and quantity of evidence to definitively conclude that MIS approaches have more complications. Furthermore, because of the steep learning curve with certain MIS cases, the rate of complications may decrease with increased experience.

Figure 37.2 represents another example of a complication with MIS TLIF in which the end plates are violated leading to an iatrogenic L4 burst fracture, which necessitated subsequent revision. It may be that minimal access can lead to poor placement of cages, although this has not been demonstrated in the literature.

Far Lateral Approach Interbody Fusions

Isaacs et al. studied the use of extreme lateral approach interbody fusions (XLIF) in 107 patients with degenerative scoliosis, with or without supplemental posterior fusion and instrumentation [2]. A mean of 4.4 levels were treated with interbody devices, and 75.7 % of patients had supplemental posterior instrumentation and fusion. Major complications occurred in 13 patients (12.1 %), including 2 medical complications and 12 surgical complications. Three patients had posterior wound infections, one had a kidney laceration, one had a deep vein thrombosis, and seven had postoperative motor deficits. The patients with motor deficits defined as a major complication had weakness lasting greater than 6 months of weakness that was decreased by two grades at any time point. However, there were 36 (33.6 %) patients overall who had postoperative lower extremity weakness (mostly hip flexor weakness thought to be due to passage of retractors through the psoas). In most of these patients, this weakness was transient and the authors considered it an expected consequence of surgery and thus did not label it as a complication. This definition of complications appears somewhat arbitrary, and it is important to note that, although transient, one third of patients had postoperative weakness following XLIF for degenerative scoliosis.

A retrospective review of 600 XLIFs by Rodgers and colleagues for degenerative spinal conditions revealed an overall perioperative complication rate of 6.2 % (including intraoperative and up to 6 weeks postoperative) [21]. In this report, there were only four (0.7 %) transient postoperative neurologic deficits, with no wound infections, vascular injuries, or intraoperative visceral injuries. There were 9 (1.5 %) in-hospital surgery-related events with 17 (2.8 %) in-hospital medical events. Eleven events (1.8 %) required a return to the operating room for additional procedures.

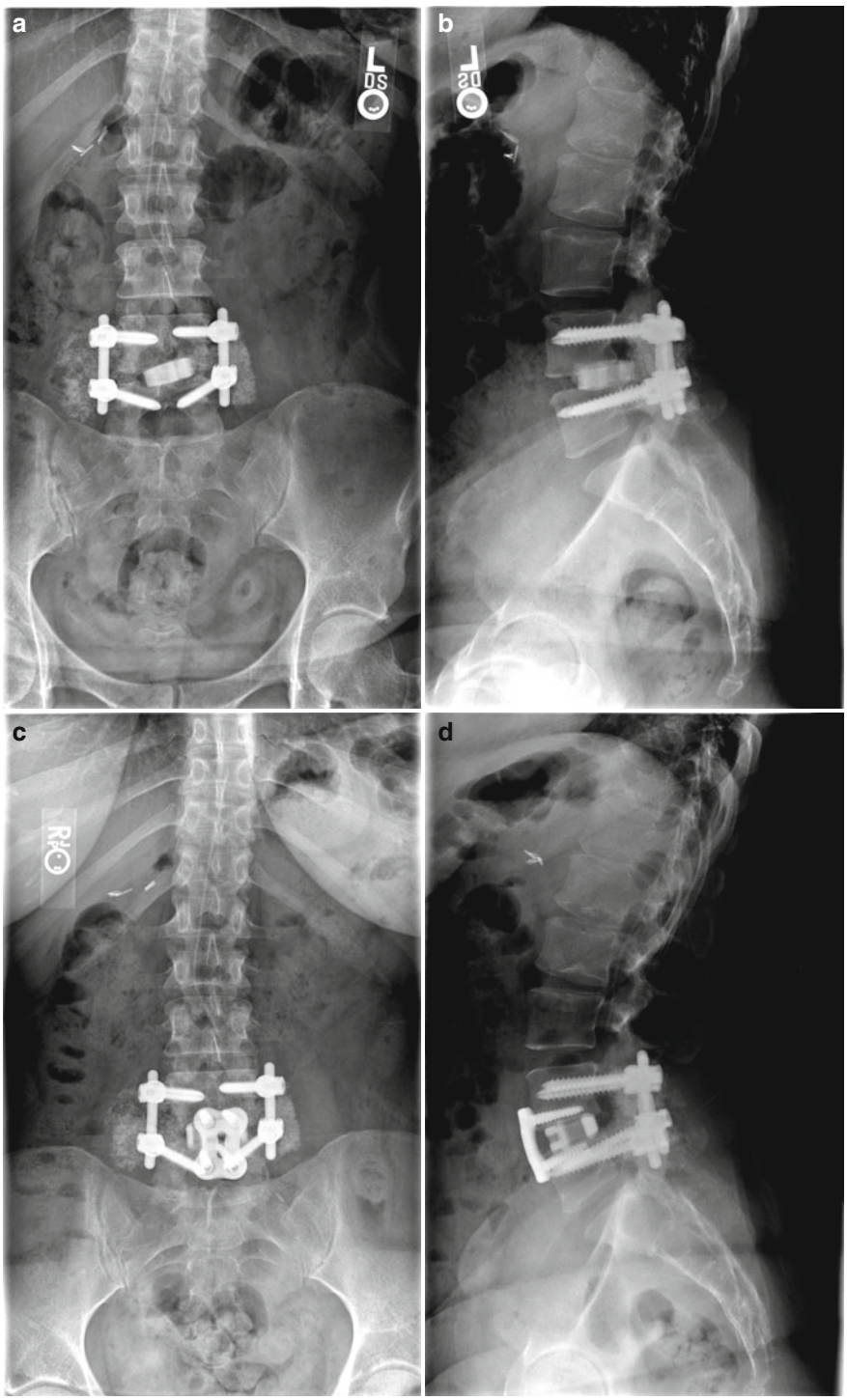

Fig. 37.2 A 29-year-old female who underwent L4–L5 decompression and posterior arthrodesis with TLIF placement for recurrent L4–L5 disk herniation after previous failed decompression attempts. AP (**a**) and lateral (**b**) imaging of migration of TLIF postoperatively. The patient then underwent removal of TLIF, placement of anterior interbody device, and anterior decompression and fusion. Final postoperative AP (**c**) and lateral (**d**) imaging

Daffner and Wang reported a case with lateral migration of a far lateral cage that caused leg pain and required revision surgery. The cage was revised with what they termed a mini-open lateral approach, in which the cage was replaced and a lateral plate was used to buttress the cage. The authors felt that in cases of coronal deformity or lateral listhesis, a buttress plate should be considered [22].

Transacral Interbody Fusions

One of the newer techniques for interbody fusion at L5–S1 is the transacral interbody fusion, which utilizes an approach via the presacral space with an interbody implant that is placed in a plane perpendicular to traditional anterior or posterior interbody spacers.

Table 37.2 Complications of AxiaLIF

Complication	Percent of patients
Pseudarthrosis	8.8 %
Superficial infection	5.9 %
Sacral fracture	2.9 %
Pelvic hematoma	2.9 %
Failure of wound closure	1.5 %
Transient nerve root irritation	1.5 %
Rectal perforation	2.9 %
Total	26.5 %

From Lindley et al. [20]

Lindley and colleagues reported specifically on the complications associated with 68 transsacral interbody fusions [23]. They had a total of 18 complications (26.5 %) in 16 patients (23.5 %), the details of which are listed in Table 37.2, Complications of transsacral interbody fusion. The 2 cases of rectal perforation were repaired emergently by a general surgeon, one being identified intraoperatively and the other found 4 days after the index procedure.

Tobler and colleagues reported on 156 patients with 2-year follow-up who underwent transsacral interbody fusion for low back pain [24]. They reported a 94 % fusion rate with no vascular, neural, urologic, or bowel injuries. There were no revisions reported over the 2 years and no other complications noted.

One year later, a similar group of authors including Tobler reported on 26 patients who had AxiaLIF for grade I and II isthmic spondylolisthesis at 2 years, augmented with percutaneous posterior instrumentation without direct decompression [25]. They reported a 100 % fusion rate without any perioperative complications (no infection or bowel perforations). However, they did report that four patients (15.4 %) returned to the operating room for recurrent radiculitis (two patients) or screw-related pain (two patients). There were no other complications reported.

Posterior Cervical Fusion

Posterior cervical fusion is applied to a variety of pathologies but is most often used in patients with cervical spondylotic myelopathy. Traditionally, a posterior approach is indicated in myelopathic patients requiring fusion at greater than 3 levels with preserved sagittal alignment [26]. High rates of fusion and neurologic improvement, with relatively low complication rates, have been demonstrated [26]. Posterior cervical fusion involves creating a midline incision and placement of pedicle and/or lateral mass screws. This approach necessitates significant muscle dissection and soft tissue stripping to achieve adequate exposure. While the overall rate and natural history is unknown, a significant number of patients continue to complain of neck pain and spasm after a posterior cervical approach. These symptoms are believed to arise at least in part from the extensive soft tissue dissection required by this approach and, for this reason, minimally invasive approaches have been investigated.

A variety of techniques for minimally invasive discectomy and decompression have been described in the cervical spine. However, to our knowledge, there is very limited data available with regard to minimally invasive posterior cervical fusion.

Wang et al. [27] described their experience with minimally invasive lateral mass screw placement in 18 patients undergoing attempted posterior cervical fusion. The authors used a series of tubular dilators and retractors to place lateral mass screws and then pack the facet joints with autograft bone. Two patients required conversion to a standard open approach due to inability to obtain adequate fluoroscopic images. The authors noted one superficial wound complication and successful fusion in all patients with no hardware failure at 2-year follow-up. There was no report of implant misplacement or failure. Overall, the authors felt minimally invasive lateral mass screw placement was safe for instrumentation from C3 to C7, with the potential for fusion of up to 3 levels through a single 1.5 cm incision. However, with such a low number of patients included, it is difficult to make substantial conclusions applicable to the approach in general.

While minimally invasive posterior cervical fusion offers the possibility of decreased muscle dissection and postoperative neck pain and spasm, at this point, there is not enough literature to make recommendations regarding its indications and complication rate. Further research is warranted to fully vet any proposed technique prior to widespread adoption.

Posterior Thoracic Fusion

Posterior thoracic spinal fusion has traditionally been accomplished via a standard midline approach. Posterior fusion is indicated in the treatment of a wide range of thoracic spinal pathology including trauma, tumor, deformity, and degeneration. As with other posterior approaches, significant muscle trauma and ischemia arises from the soft tissue dissection and retraction necessary to produce adequate visualization. This can lead to prolonged morbidity, including muscle atrophy, scarring, and chronic postoperative pain [28]. Theoretically, minimally invasive, muscle-sparing approaches to the thoracic spine should reduce the morbidity associated with a standard posterior approach.

Minimally invasive techniques have been applied to pedicle screw implantation in the thoracic spine; however, the majority of current data discusses these techniques as applied to patients with traumatic injury or spinal deformity. Therefore, that data will be reviewed in those sections.

Ringel et al. [29] reviewed their experience with percutaneous pedicle screw placement in 104 patients for a variety of indications, including trauma, deformity, and degeneration. According to the authors, no intraoperative complications occurred and no patient required conversion to an open approach. Based on their self-defined categories, out of 488 pedicle screws placed, only 15 (3 %) were deemed unacceptable. However, a total of 11 patients (10.6 %) required immediate, intraoperative surgical revision for screw repositioning. This rate of revision for screw malposition is higher than the rate generally considered for open thoracic screw placement. A systematic review reported a revision rate of 0.66 % for screw malposition in 1,666 patients who underwent pedicle screw placement for scoliosis surgery [30].

Posterior Lumbar Fusion

Traditional posterior lumbar fusion has been successfully used to treat a variety of degenerative conditions. However, despite advancements in technique and instrumentation, an open posterior approach to the lumbar spine is associated with damage to the surrounding soft tissues and paraspinal muscles, due to both soft tissue stripping and prolonged retraction that are generally necessary for an adequate exposure. As previously discussed, minimally invasive techniques for posterior lumbar decompression and discectomy have been developed and are increasingly being implemented. Recently, attention has been turned towards developing similar methods for posterior lumbar fusion via a minimally invasive approach to potentially decrease some of the attendant complications of an open approach.

MIS posterior lumbar fusion can refer to a variety of specific techniques. In general, an attempt is made to decrease the wide muscle dissection and soft tissue stripping associated with a standard midline posterior lumbar approach. Minimally invasive lumbar fusion can involve the use of percutaneous pedicle screw fixation, posterior interbody fusion, or posterolateral fusion.

Proponents believe that minimally invasive lumbar fusion can lead to improved clinical outcomes with shorter hospital length of stay, decreased postoperative pain and narcotic use, and overall lower rate of complications. However, these claims are not fully validated in the literature, and the number of complications can vary significantly and may be underreported.

Wang et al. [31] retrospectively reviewed 74 patients treated with either a standard posterior lumbar fusion via a midline approach or a minimally invasive approach. Patients were included with a variety of degenerative conditions and had complaints of both axial back pain and lumbar nerve root compression. For patients in the MIS group, a tubular retractor system was inserted through a paramedian approach and used to visualize the facet joint. The facet joint and disk were removed, and then an interbody cage was placed. Pedicle screws were inserted percutaneously. The authors noted significant differences in blood loss, length of stay, and hospital charges preferentially for MIS. Lower rates of dural tear, deep infection, neurologic deficit, and cardiopulmonary complications were also noted in the MIS groups, without comment on whether these values were statistically significant. In addition, only patients with unilateral complaints were treated with MIS, possibly justifying some of the higher complication rates in patients treated with a standard fusion necessitating a bilateral approach.

In a technique defined as "less invasive" posterior lumbar fusion, Kasis et al. [32] evaluated their experience with 333 patients followed prospectively and treated with either a standard posterior lumbar interbody fusion (ST-PLIF) or a less invasive posterior lumbar interbody fusion (LI-PLIF). A standard midline posterior lumbar approach with superiosteal elevation of the paraspinal musculature to the lateral border of the facet joints was used with the LI-PLIF. A bilateral facetectomy was performed and a novel method was developed for determining pedicle screw entry point based off the mamillary process, obviating the need for far lateral dissection over the transverse process. In addition, the posterior elements were all maintained for the LI-PLIF.

With an LI-PLIF, significantly greater improvements in ODI and VAS scores were found at follow-up as compared to ST-PLIF. In addition, fusion rates were found to be similar. The authors noted a 19.7 % complication rate with ST-PLIF versus 6.7 % with LI-PLIF. However, with a ST-PLIF technique, an iliac crest autograft was obtained. After removing the complications associated with graft donor site morbidity, the complication rate of ST-PLIF approached that of LI-PLIF. In the patients undergoing LI-PLIF, 14 complications were noted with 2 deep infections (1 %), 6 dural tears (3.94 %), and 6 neurological complications (3.94 %), which were not further elucidated. This study is unique in showing improved clinical outcomes and a lower complication rate with a "less invasive" approach when compared directly to the standard posterior lumbar interbody fusion, though again this is largely due to the complications associated with iliac crest donor site morbidity.

While low complication rates are often reported with minimally invasive lumbar fusion, it is difficult to extrapolate this data to a greater number of patients. The majority of these studies are observational and retrospective. Only Wang et al. and Kasis et al. compared minimally invasive (or, "less invasive") techniques directly to traditional open approaches. Both studies did demonstrate lower complication rates with minimally invasive surgery; however, neither represents Level I evidence. While the data suggests that minimally invasive posterior lumbar spinal fusion may have a lower

Table 37.3 Complications associated with XLIF for correction of spinal deformity [33]

	Absolute no. of complications				Absolute no. of patients		
	Medical complications		Surgical complications		Major complication	Minor complication	Any complication
	Major	Minor	Major	Minor			
Entire cohort ($n=107$)	2 (1.9 %)	14 (13.1 %)	12 (11.2 %)	9 (8.4 %)	13 (12.1 %)	17 (15.9 %)	26 (24.3 %)
XLIF with open posterior instrumentation ($n=29$)	0 (0.0 %)	3 (10.3 %)	6 (20.7 %)	3 (10.3 %)	6 (20.7 %)	6 (20.7 %)	11 (37.9 %)
XLIF with MIS posterior instrumentation ($n=52$)	0 (0.0 %)	6 (11.5 %)	4 (7.7 %)	2 (3.8 %)	3 (5.8 %)	6 (11.5 %)	8 (15.4 %)

complication rate compared to a standard open approach, prospective, randomized trials will be needed before this can be shown definitively.

Deformity

Complication rates in open surgery for deformity correction vary considerably, with lower complication rates in pediatric deformity and, in some studies, an extremely high complication rate, from 25 to 80 % with a posterior approach and up to 40 % with an anterior approach [33]. These complications generally arise from the prolonged operative times and blood loss due to the extensive approach and dissection necessary for multilevel deformity correction. This complication rate is particularly worse in the studies on adult deformity, noting that many patients with symptomatic spinal deformity are elderly and may have significant medical comorbidities, with a decreased tolerance for prolonged operative times and blood loss.

With this in mind, developing safe and effective minimally invasive techniques for spinal deformity correction may be advantageous. Recently, Wang et al. [34] reviewed their experience in 23 consecutive patients undergoing a combined anterior and posterior approach for correction of thoracolumbar spinal deformity. The anterior procedure was performed via a minimally invasive, "mini-open" direct lateral exposure, and posterior pedicle screws were inserted percutaneously. The authors noted no complications at the time of operation, no complications related to pedicle screw placement, and no deep or superficial infections. Four perioperative complications (17.4 %) were noted including two pneumothoraces, one persistent CSF leak requiring reoperation, and one patient with new-onset atrial fibrillation. In addition, seven patients (30.4 %) developed thigh numbness, pain, or weakness related to the anterior approach. Taken in sum, 11 patients (47.8 %) suffered a complication, though all were noted to have resolved at the time of follow-up aside from one patient with continued sensory and motor changes, which ultimately required the use of an assistive device for ambulation.

Anand et al. [35] used percutaneous pedicle screw instrumentation combined with various anterior and lateral interbody fusion techniques to correct lumbar deformity in 12 consecutive patients. The authors noted no technical issues or surgical complications. No infections were noted. Three patients did develop thigh dysesthesias related to a transpsoas approach that ultimately resolved. In their follow-up study of the same patients [35], they did note one patient developed a renal hematoma, which did not require reoperation, and an unrelated cerebellar hemorrhage. Including all complications noted, an overall rate of 41.7 % (5/12) is present.

In the article by Isaacs et al. [2] that evaluated XLIF, they also reported on the difference in complications between patients having MIS posterior instrumentation versus open instrumentation. There was a significantly lower complication rate in patients treated with XLIF and percutaneous pedicle screw implantation as compared to XLIF combined with an open posterior approach (15.4 % vs. 37.9 %). See Table 37.3.

Newton et al. have described a technique for minimally invasive correction of thoracic deformity in idiopathic, congenital, and adolescent scoliosis [36]. Their technique involves the use of thoracoscopic anterior arthrodesis. They reviewed their experience with their first 41 patients, and at 5-year follow-up, the authors noted a low complication rate, with no postoperative deep infections and no clinically relevant neurovascular or pulmonary complications. They did note implant failure in 3 patients, with a total of 3 patients (7 %) requiring revision posterior arthrodesis (implant failure, pseudarthrosis, and progression of deformity) [36]. However, in their surgical technique manuscript published after their initial 5-year follow-up, the authors claimed that they no longer use anterior thoracoscopic deformity correction in favor of a traditional posterior arthrodesis, due to concerns over higher rates of implant failure and less correction attained with an anterior approach [37].

With a limited number of patients and studies currently available, it is difficult to make a summary statement on the complication rate of minimally invasive correction of adult spinal deformity. The available literature presents complications inconsistently, so one cannot easily combine the data to

definitely claim an overall complication rate. Analyzing the results of Isaacs et al, it appears that XLIF combined with percutaneous pedicle screw instrumentation may afford a significantly lower complication rate compared to standard open procedures. However, further research is warranted, and randomized, controlled trials with a larger number of patients would be of benefit.

Tumor

Traditionally, spinal tumors have been approached anteriorly when surgical treatment is required, as most metastatic lesions are located within or near the vertebral body. A standard thoracotomy is associated with major complications in up to 79 % of patients [38]. Recently, there has been a resurgence of interest in treating spinal tumors via a posterior approach to avoid the morbidity associated with an anterior approach. However, a standard open approach requires extensive dissection with significant soft tissue disruption blood loss. Regardless of the approach, the goals of operative treatment generally involve palliation, stabilization, and preservation of ambulatory function.

To lessen the morbidity of an open approach, minimally invasive techniques are being applied to surgical treatment of spinal tumors. Uribe et al. [38] retrospectively reviewed 21 consecutive patients who underwent a minimally invasive lateral approach to the thoracic spine for tumor resection. The authors performed tumor resection, neural decompression, and stabilization as necessary through an expandable retractor system. In this series, only one perioperative complication was noted (postoperative pneumonia). No intraoperative complications, infection, or hardware failure occurred.

Haji et al. [39] retrospectively reviewed their experience with 20 patients with spinal tumors treated with a minimally invasive posterior approach for decompression. A one-level hemilaminectomy was performed through a unilateral muscle-splitting approach accessed by a series of sequential tubular dilators. According to the authors, no patient required conversion to an open technique, and no wound infections were noted. Two patients did develop perioperative complication, including one patient with a persistent CSF leak requiring reoperation and a second patient with a foot drop and urinary retention that incompletely resolved.

Both of these studies involve a limited number of patients and likely suffer from selection bias based on tumor type and pattern. However, given the overall low complication rate noted, minimally invasive techniques may be of benefit in select patients and pathologies, possibly mitigating the morbidity associated with a standard open approach.

Trauma

Surgical treatment of spinal fractures traditionally involves an open approach with wide dissection, instrumentation, and arthrodesis. In general, the goals of operative intervention for spinal fractures include regaining spinal stability and protecting neurologic function. Depending on the location and pattern of injury, spinal fractures have been variably managed with both anterior and posterior approaches. Traditional open procedures are associated with significant blood loss and infection rates as high as 10 % [40].

Minimally invasive techniques for spinal stabilization have been developed and are increasingly being applied for acute spinal trauma. Similar to the treatment goals of nontraumatic spinal conditions, the aim of minimally invasive surgery in spinal trauma is to mitigate the approach-related morbidity associated with open techniques. In some cases, percutaneous pedicle screw stabilization of fractures is performed without fusion, with the thought that once the fractures have healed the instrumentation can be removed without the risk of adjacent segment disease.

In a review article by Rampersaud et al. [41], the authors describe the use of anterior endoscopic decompression and stabilization for thoracolumbar fractures. They report overall low complication rates, with reduced blood loss, pain, and time to mobilization in patients treated endoscopically as compared to a standard open approach.

Khoo et al. [42] used an anterior, thoracoscopically assisted approach for stabilization and fusion of thoracolumbar fractures in 371 patients. This was combined with posterior percutaneous pedicle screw instrumentation in 65 % of included patients. This is one of the largest series of patients treated with minimally invasive techniques for spinal trauma, and the authors noted decreased operative times and blood loss as implant design improved and surgeons gained experience. An overall complication rate of approximately 10 % was noted, with approach-related complications (pleural effusion, pneumothorax, intercostal neuralgia) occurring in 5.4 % and all other complications (splenic injury from chest tube placement, infection) occurring in 4.3 % of patients. The authors stated only a single patient suffered neurologic deterioration postoperatively. The authors' experience compares favorably to complications rates as high as 24 % reported with an open transthoracic approach [43]; however, they do caution that a significant learning curve exists.

A mini-open, lateral approach was described by Smith et al. [44] to treat thoracolumbar fractures. A corpectomy was combined with either anterolateral plating or posterior pedicle fixation. The authors had an overall complication rate of 13.5 %. No reoperations were needed, and no patients experienced neurologic decline.

Percutaneous pedicle screw implantation may be used for reduction and stabilization of thoracolumbar fractures and

Table 37.4 Demonstration of learning curve: complications from the first 50 cases of MIS decompression versus the last 50 cases [43]

Complication	First 50 cases	Recent 50 cases
Dural tear	18 % (9)	8 % (4)
Percutaneous CSF leak postoperative	0	0
Conversion to open surgery	2 % (1)	0
Required blood transfusions	0	0
Wound infection		
Deep	0	0
Superficial	0	0
Need for further surgery		
Inadequate decompression	2 % (1)	0
Postop spondylolisthesis requiring fixation	2 % (1)	2 % (1)
Severe back pain	2 % (1)	0

theoretically may be associated with lower morbidity compared to an open approach.

Palmisani et al. [45] treated 51 patients with thoracolumbar fractures via a percutaneous pedicle fixation technique. Only four complications (7.8 %) were noted, with one malpositioned screw, one infection requiring reoperation, and two failures of the construct.

One critique of percutaneous pedicle screw instrumentation is that certain minimally invasive implant systems are limited in the number of vertebral levels that can be treated. However, it has been shown possible to percutaneously place long constructs when additional stability is warranted. Logroscino et al. [46] used a long implant fixation system to percutaneously stabilize thoracolumbar fractures and tumors in nine patients. While this is a very limited sample size, the authors noted no complications related to surgical technique.

Minimally invasive techniques for stabilization after spinal trauma present a compelling possibility for decreasing the significant morbidity associated with an open approach. As detailed above, several studies have suggested relatively low complication rate with a variety of techniques. While the reasoning behind minimally invasive surgery in spinal trauma is sound, at this point it would be premature to make broad conclusion on its complication rate. As with other, similar techniques, additional research—ideally with randomized, comparative studies—is needed to fully elucidate this topic.

Learning Curve

One of the issues that can confound a review of complications from minimally invasive surgery is the possibility that there is a steep learning curve with certain procedures. As a result, the first series of cases performed could potentially have a higher rate of complications while the technique is learned and refined. For example, Villavicencio and colleagues reported a significantly higher rate of neurological deficits for MIS TLIF (10.5 %) versus open TLIF (1.6 %) but attributed this to the steep learning curve [17]. In a total of 76 MIS cases, 6 out of the 8 neurological deficits occurred within the first 15 procedures performed, which they concluded were due to the learning curve [17].

Another example of the learning curve is Mannion and colleagues' retrospective comparison of the first 50 and most recent 50 cases of MIS decompression via a tubular paramedian muscle-splitting approach [47]. These authors compared the complications of the early versus more recent MIS decompression, although they did not provide details about the most recent 50 cases, and it is unclear how many cases they did in the interval between the first 50 cases and the most recent 50 cases. The difference in complications is detailed in Table 37.4 and showed a trend towards more complications in the first 50 cases, although this was not significantly different. The difference in the rate of dural tears was 18 % for the first 50 cases and 8 % for the last 50 cases, although this too was not significantly different ($p=0.24$).

Obesity

Although little has been written regarding the complication profile of performing MIS surgery on obese patients, it is generally well accepted that there are more complications in open spine surgery in the obese population. By limiting the size of the exposure with MIS spine surgery, it is possible that these complications may also be limited. On the other hand, when tubular retractors are used, it is more challenging to operate through a longer tube and therefore this may potentially lead to more complications.

Park and colleagues retrospectively reviewed 56 patients with a BMI greater than 25 and 22 patients with a BMI less than 25 who underwent lumbar MIS discectomy, laminotomy for stenosis, and fusion [48]. They reported a complication rate of 14.3 % (8/56) in the group with a BMI greater than 25 and a rate of 14.3 % (3/22) in the group with a BMI less than 25. Their conclusion was that there does not appear to be an increased risk of complications in overweight or

obese patients who have MIS surgery. However, the cutoff of a BMI of 25 (normal to overweight) may confound this data, given the fact that a 6′2″ muscular male who weighs 196 lb and has minimal subcutaneous adipose tissue on his lower back has a BMI of 25.1 and would have been categorized as overweight. Additionally, the authors performed open procedures when fluoroscopic visualization was challenging because of abundant soft tissue, potentially resulting in selection bias. It would be premature to conclude that MIS surgery in obese (BMI >30) and morbidly obese (BMI >40) patients results in a complication profile that is similar to patients with a normal BMI.

Conclusion

While it remains challenging to glean an accurate representation of complications from the literature regarding minimally invasive spine surgery, it appears that in general, complications of MIS spine surgery are comparable to open surgery. However, there may be a steep learning curve with certain procedures, during which time the complication rate may be higher than open procedures.

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Neural and Dural Injury

38

Scott L. Blumenthal and Donna D. Ohnmeiss

Introduction

Minimally invasive approaches to spine surgery have been described since the 1970s [1, 2]. During the 1990s, laparoscopic discectomy and anterior lumbar interbody fusion were described [3, 4]. More recent years have brought the development of numerous minimally invasive spine surgery (MIS) techniques for performing traditional surgeries such as discectomy, decompression, fusion, and treatment for vertebral body fractures. The overall strategy of MIS is to accomplish the same operative benefit, but to do so with reduced tissue trauma, possibly resulting in reduced recovery time. The basics of MIS surgery are the same as open techniques, and therefore, the types of complications encountered may be the same, but the incidence and treatment options may vary. One possible complication is the risk of injury to the dura/or and to neural structures. The origins of neural and dural injuries arising from MIS are similar to traditional approaches but they may also carry greater or additional risks due to limited visualization, use of retractor tubes, distraction instruments, etc. As with traditional open spine surgery, the risk of dural/neural injury may be greater in previously operated patients due to scarring, adhesions, and altered anatomical landmarks. In this chapter we will describe the types of dural and neural injuries occurring with various MIS procedures with a focus on the anatomy encountered with the surgical approaches and ending with a discussion for strategies to reduce the incidence of these complications.

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Transpsoas Approaches

Anatomy

Gaining access to the intervertebral disc space through a transpsoas approach avoids the potential for direct contact with the spinal cord, cauda equina, and dorsal root ganglia with the added benefit of avoiding the vascular structures encountered with anterior approaches as well as the need for an anterior access surgeon. With the transpsoas approach, there is little chance of a dural tear. However, one of the more frequently discussed complications of MIS is the postoperative onset of new thigh symptoms described as numbness, paresthesias, and/or muscle weakness associated with this approach. These complications are thought to arise due to psoas muscle trauma or injury to the lumbar plexus as it passes through the psoas muscle. There is a chance of surgical instruments directly injuring neural structures as they are advanced through the psoas muscle toward the disc space. However, there is likely a greater chance of nerve injury through an indirect means by retractors, dilators, or other instruments passing through the psoas deflecting and stretching the nerves which can increase the pressure on the nerves as they course from the spinal column to the lower extremities.

Both sensory and motor symptoms have been reported in multiple publications. The sensory symptoms reported are most commonly pain, numbness, or paresthesias in the anterior thigh and/or groin regions [5–9]. The motor deficits most commonly reported include weakness of the iliopsoas, hip flexors, and quadriceps [5–9]. Stemming from the first reports of the onset of these sensory and motor complications related to the transpsoas approach, there have been several studies investigating the anatomy of this region to try to determine the cause of the problem and to develop strategies for its prevention [10–15]. The neural structures at greatest risk of injury are the genitofemoral nerve and nerves of the lumbar plexus. Injury to the genitofemoral nerve is most likely to be associated with pain and/or numbness in the thigh or groin area.

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The lumbosacral plexus is most posteriorly positioned at L1–L2 and migrates anteriorly at each lower lumbar level [13]. This relative change in position may, at least in part, explain the increased risk of injury with surgery involving the L4–L5 disc level when attempting to position a retractor or dilator in the posterior aspect of the disc space. Avoiding this pathway may conflict with the intuitive desire to place fusion cages more posteriorly in the disc space to allow use of longer cages than is possible when placing implants more anteriorly due to the roundness of the ventral portion of the disc.

The reported occurrence of postoperative symptoms following transpsoas approaches has ranged from 0.7 to 63 % [5–7, 9, 16, 17]. It cannot be determined how much of this variation is attributable to variation in surgical technique versus methodology used to evaluate and report postoperative symptoms. This most commonly occurs with fusion at the L4–L5 level, although they are also associated with fusion at L3–L4 [16]. Fortunately, the literature indicates that the new symptoms usually resolve [5–7, 16]. The thigh symptoms resolve in at least 50 % of patients in 3–6 months and 90 % of patients in 12 months [16]. However, other reports have less favorable recovery rates such as Sofianos et al. who reported that among eight patients with postoperative anterior thigh hypoesthesia, seven failed to recover at an average of 9 months [9].

Another less frequent neural complication of the retroperitoneal transpsoas approach to interbody fusion is abdominal paresis characterized by bulging of the abdominal wall [18]. Dakwar et al. reported this problem in 1.8 % of 568 patients. Similarly, this complication generally resolves within 6 months. The authors attributed the complication to approach-related injury to motor nerves supplying the muscles of the abdominal wall [18]. Also rarely described is the postoperative onset of symptoms on the side contralateral to the XLIF approach [19]. This was noted in 2 of 32 patients and attributed to a displaced endplate fragment in one patient and a far lateral disc herniation in the other. The authors suggested awareness of the possibility of breaking off osteophytes on the side opposite of the approach which may irritate the nerve roots on that side and also cautioned about placing interbody cages very posteriorly or diagonally toward the foramen. Factors related to the onset of neural injury symptoms following transpsoas fusion techniques include operative time and female gender [7]. The relationship between operative time and postoperative symptoms may be related to several factors including if there was difficulty accessing the disc space and/or extended compression of the nerves due to the retractors being in use for a longer period. The reported relationship of female gender to a greater incidence of postoperative symptoms is not clear but may possibly be related to females typically being smaller in size which may increase the risk of neural compression in the smaller muscle by the dilators. Obesity was not found to be related to a greater of neural injury with XLIF [20].

Total Disc Replacement (TDR)

Traditionally TDRs have been implanted from the same anterior retroperitoneal approach as has long been used for anterior lumbar interbody fusion (ALIF). The size of the TDR devices has precluded their use from a posterior approach. TDR accomplished via a lateral approach has been reported [21]. Just as with fusion performed using this approach, there were occurrences of psoas weakness, anterior thigh numbness, lower extremity weakness, and one patient had quadriceps hypertrophy on the side contralateral to the approach.

One unique use of the lateral surgical approach is to remove lumbar TDRs implanted above the lumbosacral junction [22, 23]. The rationale for this procedure is to avoid the potential complications of repeat anterior approach surgery in which injury to the vessels may be greater due to skewed anatomical landmarks and in particular scarring. Only a small number of these cases have been reported and no complications have been associated with it. Although certainly the risk of postoperative symptoms reported for any of the lateral approaches does exist.

Transforaminal Fusion

Transforaminal lumbar interbody fusion (TLIF) performed using MIS techniques has gained much popularity in recent years. If offers access to the intervertebral disc space through a posterior approach with less risk of spinal cord injury or irritation than traditional posterior lumbar interbody fusion (PLIF). The most common causes of neural injury during MIS TLIF are neural compression due to retraction and malpositioned pedicle screws [24]. No large-scale prospective studies were identified to determine a reasonable estimate for the occurrence and types of neurological injuries associated with minimally invasive TLIF.

Care must be taken during insertion of the bone graft or fusion cages so to not put unduly retraction of the nerves. It has been suggested that a greater amount of facet resection may be needed to accomplish this [25]. The authors also noted the use of expandable cages which may help to reduce the amount of facet removal needed to place the cage without excessive nerve retraction. Neural injury can also occur as a result of displaced bone graft or implants [24]. A review study comparing open TLIF with minimally invasive TLIF found that the MIS technique may be associated with a higher rate of postoperative neurological deficits [26]. One relatively uncommon neural complication of TLIF performed using BMP is nerve compression due to ectopic bone formation. Crandall et al. reported an incidence of 0.6 % of this complication with the ectopic bone forming along the trajectory of the TLIF cage [27]. Joseph et al. reported a higher rate of

bone formation in the epidural space with the use of BMP in TLIF procedures [28]. No clinical symptoms were found to be associated with this heterotopic bone formation.

Bindal et al. supported the use of intraoperative neuromonitoring in MIS TLIF cases to help avoid neural injury [29]. However, it should be noted that the suggestion was due to avoid malpositioned pedicle screws. As noted by Archavlis et al., if a conjoined nerve root is identified, the surgeon may want to opt to approach the disc from the side opposite of the conjoined root to reduce the chance of nerve root injury [30].

Pedicle Screw Placement

Several years ago, percutaneous pedicle screws systems became available. These carry a potential for neural injury through malpositioning of the screws causing direct injury to the nerve roots. Although there are frequent reports of pedicle screws breaching the pedicle, most studies report no or very few cases of neural injury [31, 32]. In a recent comprehensive review article that included a variety of surgical techniques, the rate of malpositioned screws was reported to be 7.8 %, ranging from 0.7 to 32.2 % in a total of 35,630 screws placed in the thoracolumbar spine [33]. Nerve root irritation was reported to occur in 0.19 % per pedicle screw (ranging from 0.0 to 4.0 %). Although the occurrence is low, the possibility of nerve injury should not be overlooked. Discussed later are strategies to reduce the incidence of malpositioned pedicle screws including intraoperative monitoring and guidance systems.

When placing pedicle screws, one concern is the risk of neurological injury. The risk may be higher with minimally invasive techniques than with open placement. Intraoperative neuromonitoring may be helpful in reducing the incidence of malpositioned pedicle screws, but the use of this technology is not a guarantee to prevent problems. The system does not always warn or screw outside of the pedicle, and similarly there may be changes in readings when there are no breaches. Additionally, the threshold reading at which the surgeon should reposition the screw due to breaching the pedicle wall is not clear. Parker et al. concluded that with intraoperative monitoring using EMG during pedicle screw placement, readings of positive stimulation below 5.0 mA warranted investigation for screw malpositioning, but responses at higher thresholds were less reliably related to a breach [34].

Discectomy

Minimally invasive discectomy was introduced decades ago [1, 2], and a wide variety of techniques have been described incorporating mechanical removal of tissue, laser ablation, IDET, tubular retractor systems, endoscopes, and combinations of these methods. Performing MIS discectomy has been gaining popularity. Unfortunately, there is relatively little high quality data published for many of these methods with most papers reporting on relatively few patients, making the evaluation of complications challenging.

One randomized study randomized 112 patients to open discectomy or microendoscopic discectomy performed through a paraspinal approach [35]. Postoperative neurological problems were low in both groups with one foot drop in the open group and two patients in the endoscopic group having a transient S1 dermatomal neuralgia.

In a study comparing complications of various discectomy procedures, microendoscopic procedures had the greatest rate of root injury when compared with microdiscectomy or open techniques [36].

Decompression

There is risk of neural injury with various MIS decompression procedures; however, there is much less information available on decompression than for discectomy or fusion. One series reported a 10.5 % rate of transient neurological complications with no significant nerve injury following MIS decompression [37].

Dural Tears

There is little in the literature on the topic of dural tears during MIS procedures, either on the incidence or strategies on how to address these complications. Dealing with dural tears in MIS is generally more challenging than in open cases due to difficulty identifying the problem as it occurs and trying to repair a tear working through a cannula when it is thought that the tear may be too large to repair with an adhesive product. No studies were identified discussing when it may be preferable to convert to an open procedure to repair a dural tear.

Discectomy and Decompression

In a large series of patients undergoing microendoscopic discectomy, Wu et al. reported an overall dural tear rate of 1.6 % [38]. The rate was 3.6 % in the first 220 patients, decreasing to only 0.9 % in the subsequent 653 procedures. In a prospective, randomized study, it was found that the dural tear rate was significantly greater among patients undergoing microendoscopic discectomy (8.7 %) compared with microdiscectomy (2.7 %) or open discectomy (3.0 %) [36]. The authors did not attribute the differences to a learning curve, as they had much previous experience with all three techniques.

In a randomized study comparing lumbar discectomy performed by a microendoscopic technique, a microdiscectomy,

or open surgery, the dural tear rate was greatest in the endoscopic groups at 8.7 % compared to approximately 3 % in the other two groups [36]. The authors noted that a possible reason for the greater dural tear incidence with the endoscopic technique may be poor depth perceptions, although the surgeons involved with the study had experience with the procedure.

In a large series of patients undergoing percutaneous endoscopic discectomy (performed using a transforaminal approach removing disc fragments with endoscopic forceps and Holmium-YAG laser), a dural tear rate of 1.1 % was reported [39]. In three of the nine cases, the tear was recognized intraoperatively, and the surgery converted to an open approach to repair the tear. In the remaining six cases, the tear was not recognized until 1–7 days after surgery. All six cases had repeat surgery to repair the tear. Of note, two patients had nerve roots herniated through the dural tears. One resulted in a foot drop and the other in ankle weakness; both had significant pain even after the repair surgery.

Fourney et al. reviewed and compared multiple randomized and nonrandomized MIS versus open discectomy and decompression studies [40]. They found that in randomized studies the dural tear rate for MIS was 9.2 % compared with 7.7 % for open procedures. Interestingly, the rates reported in nonrandomized studies were much lower at 2.0 % in MIS cases and 0.0 % for open.

In a large consecutive series of patients, primarily lumbar cases, undergoing MIS decompression or fusion using tubular dilators, Ruban and O'Tolle reported a dural tear rate of 9.4 % [41]. The primary risk factor for a durotomy was previous surgery at the same level.

Other studies have also reported the rate of dural tears in MIS discectomy and decompression procedures to range from 5.3 to 10.2 % [37, 42].

Fusion

It has been well published that the risk of dural tears is greater in patients undergoing repeat surgery. There is little information published on the role of MIS TLIF specifically in patient who have previously undergone discectomy and decompression. In a study comparing open and MIS TLIF in a relatively small number of such patients, Wang et al. found a 12 % dural tear rate in MIS compared with 20 % in the open group [43]. None required reintervention for repair.

Dural Tear Repair

An algorithm for dural tear repair in MIS has been described [41]. In their series of patients undergoing MIS performed through tubular dilators, the authors suggested that for partial-thickness tears, fibrin glue may be used for repair. For full-thickness tears, they advocated suturing when possible using a commercially available repair kit, then applying fibrin glue over the repair. For tears not amenable to direct suturing repair, the authors placed a small piece of blood-soaked Gelfoam over the defect with fibrin glue applied over it. All dural tear patients were on strict bed rest overnight. With this approach, the authors reported that use of a drain was not needed and no patient developed a pseudomeningocele or complained of persistent headaches.

Chou et al. described a method of using a readily available micropituitary rongeur (used as a needle driver), suture, and a laparoscopic knot pusher to stitch close a dural tear through a tube during an MIS discectomy procedure [44].

Another strategy described for the repair of dural tears in MIS decompression performed through a tubular retractor system involved the use of one or more self-closing u-clips which form a closed loop to pull the dura close [45]. A piece of synthetic dural collagen matrix was placed over the repair with fibrin glue applied. In a small group of seven patients, the authors found this repair method to be viable and effective.

Reducing the Risk of Injury

The ultimate goal is to reduce the risk of neural and/or dural injury during surgery. Several strategies can be used toward this endeavor. Perhaps the greatest is a thorough understanding of the neural anatomy in the operative area. The large anatomical variation between individuals makes this task more challenging for each patient.

Safe Working Zone

The best strategy for avoiding neural complications with MIS is to review and understand the anatomy on the preoperative imaging studies. The key to safe surgery and manipulation of the vital structures is to identify the pars interarticularis when working outside the canal and identify the pedicle when working inside the canal. Identifying these structures aligns the surgeon to where the nerves and thecal sac lie.

In the early years of percutaneous discectomy, Kambin described a zone through which to pass instruments [1]. This was later termed "Kambin's triangle," which is a right triangular region with the superior end plate of the lower vertebral body being the base, the perpendicular margin being a line from the outer edge of the base up to the traversing nerve root, and the exiting nerve root serving as the hypotenuse. This provided a safe passageway to access the intervertebral disc outside of the foramen. Several studies have investigated the anatomy with respect to deriving the safest approach to each of the lumbar levels for various MIS procedures. Although a strong understanding of the anatomy

encountered during each technique is paramount, it is also important to review imaging studies to become aware of any anatomical variation within an individual patient which may increase the risk of injury and derive a plan for modifying the approach as needed.

Intraoperative Neuromonitoring

In recent years the use of intraoperative neuromonitoring has increased with a goal of reducing the risk of neural injury. It should be noted, as with open surgery, that the use of intraoperative neurophysiological monitoring in MIS surgery is not 100 % reliable. There are situations where nerve injury occurs with no alerts from the monitoring systems [16, 46]. In a review article, it was suggested that the use of EMG monitoring during transpsoas approaches to the spine could reduce the complication rate from 30 % to less than 1 % [47]. Cummock et al. reported that despite the use of real-time intraoperative EMG monitoring, postoperative motor deficits occurred in 24 % of patients undergoing fusion through a transpsoas approach [16]. The authors noted that the motor deficits may have been related to direct psoas injury occurring during the dissection that would not be detected by the monitoring or possibly due to compressive neuropathy occurring during muscle dilation. Also, there are several methods of neuromonitoring available for use during spine surgery. Which particular method may be best for surgery at particular disc levels or approaches has not been defined.

Robotics, Navigation, and Imaging

One tool available is the use of image-guided or robotic-guided technologies. These systems were initially developed years ago. However, challenges with the registration systems limited interest in their use. As with any computer-based technology, improvements have been made continuously and many challenges with the registration have been overcome. These systems will likely play an increasing role in the evolution of MIS spine surgery and increase the safety of percutaneous pedicle screw placement and other procedures [48, 49]. A review article reported that the use of a navigation system was associated with a higher rate of accurate pedicle screw placement of 95.1 % versus 90.3 % when this type of system was not used [50]. In a recent comparative study, it was reported that using 2-dimensional fluoroscopic guidance system for percutaneous pedicle screw placement was associated with a 3.0 % pedicle breaches compared with 7.2 % occurring with traditional fluoroscopic imaging [51]. The authors reported that none of the breaches resulted in neurological complications or required revision surgery.

Other Strategies to Reduce Risks

For transpsoas fusion approaches, Park et al. briefly discussed a potential benefit of positioning the patient with the hip in flexion [12]. With this positioning, the intrapsoas nerves migrate anteriorly where they may be at less risk of injury, as well as allowing the nerves to be more mobile for retraction.

Summary

MIS may offer potential benefits over traditional open spine surgery techniques. However, with respect to neural and dural injuries, many of the same challenges exist, as well as some new ones. The two most basic items are a strong understanding of the anatomy and patient positioning on the operating table. There should also be a solid appreciation for the significant anatomical variation between individuals. One technology that has been suggested to be used for fusion procedures is intraoperative monitoring. To reach the potential of this technology, there must be a good understanding of the thresholds that are significant and those that are not. Also, surgeons should be cautious not to be overly reliant on this technology as there are false-negatives. Another strategy for reducing neural injury during MIS procedures is the use of imaged-based navigation or robotic guidance systems. These systems, similar to intraoperative monitoring, may help to reduce the incidence of neural injury. However, they require time to learn to use effectively, may be expensive, and are also not failproof.

In several studies, the incidence of new postoperative symptoms in the lower extremities is approximately 25–30 % of patients undergoing fusion using a transpsoas approach. Fortunately, most cases resolve within 6 months. However, this can be painful and frustrating to patients. Surgeons using lateral approaches for interbody fusion must educate patients about the risk of this complication.

As with any procedure, each surgeon has a learning curve for each MIS approach. Also, there is somewhat of a cumulative effect as surgeons have problems and devise solutions to share with others to avoid past problems. Also, instruments are continually designed to address challenges encountered with the various approaches. These small changes in technique and instruments can have an overall cumulative effect in reducing the risk of neural and dural complications.

In the case of transpsoas approaches to the spine, it is very important to inform patients preoperatively about the chance of the postoperative onset of new symptoms. They can be reassured that this is not a rare problem and that in most patients it resolved over the course of several months. However, they should also be informed that in some cases, the symptoms persist long term. It is important to remember

what are the common and routine problems surgeons encounter that is likely much more significant to patients experiencing the problems. This was studied recently by Mannion et al. who found that postoperative complications, many of which were pain or weakness onset, are quite bothersome to patients [52].

There is much interest in the MIS approaches to spinal surgery and the promise of reduced tissue damage and recovery time. What should not be overlooked in the enthusiasm is the inherent risk of complications, including neural and dural injury. Reducing the rates of these complications will probably occur in incremental steps as experience with the procedures increases and small improvements in techniques are made and shared with other surgeons, as well as an ongoing series of small improvements in instruments and implants.

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Pseudarthrosis

39

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Introduction

Minimally invasive spine fusion surgery has many commonly described potential benefits, including soft tissue preservation, decreased operative time, decreased blood loss, and shortened length of hospitalization. In considering the adaptation of minimally invasive spine fusion techniques, the goals of the surgical intervention must be clearly identified and not compromised. The indications for minimally invasive lumbar spinal fusion are identical to those of traditional, open techniques. Modern lumbar arthrodesis with instrumentation is used to treat symptomatic motion segments and spinal instability resulting from infectious, neoplastic, traumatic, developmental, and primarily degenerative lumbar spinal conditions. The increased surgical treatment of degenerative lumbar disorders has resulted in a direct increase in the number of instrumented lumbar spinal fusions performed. There have been multiple minimally invasive techniques developed in an attempt to improve on the outcomes of this common procedure, but the ultimate goal is the same in each case: adequate decompression of the neural elements and stable, asymptomatic fusion of the lumbar spine. One of the most common and challenging complications of attempted fusion is the development of pseudarthrosis. Pseudarthrosis is not unique to minimally invasive fusion techniques, but certainly must be considered when choosing the optimal surgical treatment of lumbar spinal disorders. Despite technological advances in the treatments designed to improve fusion, lumbar pseudarthrosis can result in significant back pain and disability and is a major cause of failed spinal surgery.

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Background

The prevention and treatment of pseudarthrosis begins with an intimate understanding of the fusion process. The complexities of this process are ultimately beyond the scope of this chapter. Generally, lumbar arthrodesis requires manipulation of the intended fusion site, maintaining local vascularization and applying stable internal fixation while facilitating osteoinduction and osteoconduction, adding to the local osteogenic potential [1]. The addition of autograft and allograft bone, graft extenders, and osteoinduction-signaling molecules will effect each of these properties to varying degrees and are often implanted as adjuvants to the fusion procedure. Union is achieved when the cells involved in the osteogenic response fully incorporate, replacing grafted bone with a new, mechanically rigid matrix. This requires a low-strain mechanical environment, often facilitated by the use of segmental instrumentation. Further remodeling must occur in order to produce lamellar bone oriented along normal lines of stress to withstand physiologic loads. This is a time-dependent phenomenon, with arthrodesis typically occurring between 6 months and 2 years following the index procedure. Failure of any part of this process can result in pseudarthrosis.

Histologically, the area of pseudarthrosis has been shown to be comprised of dense fibroblastic tissue with signs of local fibrocartilaginous metaplasia [2]. A recent histologic analysis of a pseudarthrosis following attempted interbody fusion with rhBMP-2 demonstrated abundant osteoclasts and osteoblasts on reactive bone fragments. This is indicative of active remodeling, typical of the normal reparative response to bony injury [3].

Pseudarthroses have been described by four distinct morphologic categories: atrophic, transverse, shingle, and complex [4]. In the simplest of terms, these different morphologies describe the absence of bridging bone across one or more motion segments. Atrophic pseudarthrosis involves the partial or complete resorption of the graft material. Transverse pseudarthrosis has some maturation and incorporation of the

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graft material, but there remains a transverse or horizontal area of discontinuity at the motion segment. Shingle pseudarthrosis is characterized by overlapping areas of maturing graft separated by a sagittally orientated, oblique area of graft discontinuity. Finally, complex pseudarthroses are a combination of the above. This classification system can be useful in guiding the surgeon in establishing the diagnosis and in optimizing treatment.

In their critical analysis of spinal fusion procedures, Bono and Lee [5] performed an extensive review of the literature in order to determine whether the technologic advances of the 1990s improved fusion rates and outcomes. Through this analysis, they found that the fusion rates were marginally improved with circumferential fusion and the use of autograft with an interbody fusion device. The overall fusion rate in this study was 87–84 % in those undergoing uninstrumented fusions and 90 % in those with instrumentation using traditional open techniques. This analysis provides an important framework and comparison when evaluating newer, minimally invasive fusion techniques.

Stand-alone percutaneous pedicle screw fusion has been performed in conjunction with minimally invasive decompression for lumbar spinal stenosis and degenerative spondylolisthesis. Kotani et al. [6] evaluated 80 patients who underwent either traditional open decompression and posterolateral lumbar fusion with pedicle screw instrumentation or minimally invasive decompression and percutaneous pedicle screw placement for stenosis with degenerative spondylolisthesis. Midterm results showed fusion rates of 98 % in the minimally invasive group versus 100 % in the traditional open group.

The transforaminal lumbar interbody fusion (TLIF) allows for a relatively safe circumferential fusion from a posterior-only approach. The open technique originally described by Harms and Rolinger [7] has been readily adapted into a minimally invasive technique. Although there are no randomized controlled trials comparing open and minimally invasive TLIF, Wu et al. [8] performed a large meta-analysis to evaluate the two techniques. Because direct studies comparing the two techniques are limited, this was primarily done using a quantitative analysis of observational studies. There were 23 class III studies meeting the criteria for review comprising a total of 1,028 patients, 716 who underwent an open technique and 312 who underwent a minimally invasive technique. Both techniques used a unilaterally placed interbody device and pedicle screw instrumentation. After making adjustments for publication bias, the authors determined the fusion rates to be 90.9 % for open TLIF and 93.9 % for minimally invasive TLIF. Another important distinction is made between the two groups in that the minimally invasive technique used both rhBMP (50 % vs. 12.2 %) and structural allograft (54.4 % vs. 13.8 %) more frequently than the open techniques. Subsequent studies comparing the two techniques yielded similar results, with fusion rates for MIS TLIF from 95 to 100 % [9, 10].

Additional minimally invasive fusion techniques have also been studied. When compared to the open technique, minimally invasive posterior lumbar interbody fusion (miPLIF) has shown no statistically significant difference in fusion rates [11]. In addition, miPLIF with percutaneous pedicle screws has been shown to provide excellent arthrodesis rates in multilevel fusions with no demonstrable pseudarthroses [12]. However, in a small study of obese patients undergoing miPLIF, fusion rates were somewhat lower ranging from 67 % in patients with BMI >35–84 % in patients with a BMI of 30–34.9 [13].

Minimally invasive anterior lumbar interbody fusion (miALIF) has been performed as both a stand-alone technique and in conjunction with minimally invasive pedicle screws. In comparing the stand-alone techniques of miALIF to traditional open ALIF, there has been a reported fusion rate of 84 and 92 %, respectively [14]. Other studies have shown that the addition of minimally invasive pedicle screw constructs improves the fusion rates from 96.3 to 100 % [15, 16]. The reported fusion rate for two level miALIF and percutaneous pedicle screws has also been high at 88 % [17].

Lateral transpsoas techniques (i.e., XLIF (NuVasive, San Diego, CA) and DLIF (Medtronic, Minneapolis, MN) have yielded fusion rates of 80 % in multilevel fusions for degenerative lumbar scoliosis [18]. Newer techniques such as AxiaLIF (TranS1 Inc., Wilmington, NC) attempt to achieve an interbody fusion without placement of an interbody cage, but instead an interbody device is placed through the adjacent end plates of the vertebral bodies to be fused. Utilizing this technique along with percutaneously placed pedicle screws has a reported fusion rate of 96 % [19].

While the aforementioned techniques all provide a sufficiently stable environment for the arthrodesis, the choice of graft and graft extenders can certainly influence the fusion rate. The gold standard of iliac crest autograft has historically been used in lumbar fusion; however, it has been gradually replaced by alternatives due to the associated complications. Alternatives include local autograft from decompression and decortication, allograft, commercially available ceramics, demineralized bone matrix, and rhBMP. Different combinations of these grafts and graft extenders used in conjunction with the fusion techniques above have yielded fusion rates similar to that of traditional techniques with iliac crest autograft [20–25].

Diagnosis

The typical presentation of a patient with pseudarthrosis is that of persistent or more importantly worsening axial back pain and sometimes leg pain referable to the area of the

attempted fusion. Sufficient time should be given after the index procedure before the diagnosis is made; typically this is at least 1 year. Once suspected, additional laboratory and imaging studies are indicated.

The most commonly available initial study of choice is the plain radiographic series with dynamic views. They are easy to obtain, cost-effective, and have relatively low doses of radiation. Most importantly, the diagnosis can often be made without reliance on more advanced imaging [26]. The typical series is comprised of standard AP, lateral, flexion, and extension views. Any lucency surrounding the hardware, discrete failure of the hardware, or segmental motion in the area of the attempted fusion would be indicative of pseudarthrosis. The flexion-extension films have been shown to have the highest level of sensitivity, but have a relatively low specificity when compared to surgical exploration [27]. As such, the presence of motion on flexion and extension views is indicative of pseudarthrosis, but the absence of motion does not rule it out.

Currently, the thin-cut CT scan with sagittal and coronal reconstructions is the modality of choice in establishing the diagnosis of pseudarthrosis not evidenced on plain radiographs. The ideal protocol for making the diagnosis has not been established; however, 0.9 mm slices with 50 % overlap have been shown to marginally improve the sensitivity and specificity of CT scan in making the diagnosis of pseudarthrosis [28]. This allows for the most discrete characterization of the osseous detail in the area of the bone grafting, interbody space, and facet joints to assess for bridging bone. Additionally, careful evaluation of the bone-screw interface will allow for assessment of any hardware loosening that may not be readily apparent on radiographs. The previously discussed morphologic patterns can cue the surgeon in on the typical areas expected for the development of pseudarthrosis.

Other modalities such as radionucleotide scans and MRI provide minimal additional information in the establishment of the diagnosis of pseudarthrosis and are not routinely recommended. If an underlying infection is suspected, an Indium-99 bone scan may be warranted along with basic laboratory studies including inflammatory markers.

Treatment

Once the diagnosis of pseudarthrosis is established, different conservative and surgical treatment options can be considered. The treatment selected should be based both on the radiographic findings and the patient's symptoms. If a patient with the diagnosis of pseudarthrosis is symptomatic, it is important to establish the pseudarthrosis as the source of the patient's symptoms. Just as there are many patients with asymptomatic pseudarthroses, there are many patients with significant persistent back pain despite evidence of complete fusion. This obviously can create an extremely difficult diagnostic dilemma for the clinician.

A completely asymptomatic patient should be educated about their condition and provided with appropriate precautions. This should include a discussion of the risks of potential hardware failure, instability, and development of a symptomatic pseudarthrosis. Emphasis on core conditioning and cardiovascular exercises in order to maintain optimal spine health should be given. Patients should additionally be encouraged to make prudent choices about their recreational and professional activities in order to limit risks of development of a symptomatic or unstable pseudarthrosis. Patients who smoke should be referred for cessation as smoking has shown to be an independent risk factor for nonunion [29].

Ultimately treatment goals are to ensure spinal stability and relieve the patient's symptoms in order to allow the patient to safely return to their activities of daily living. Initial treatments should be conservative in most cases. A combination of activity modification and physical therapy can be effective in addressing some symptoms, particularly if a patient wishes to avoid revision surgery and there is no specific evidence of hardware loosening, spinal instability, or progressive neurologic deficit.

If a delayed union is suspected, pulsed electromagnetic fields have shown success in some cases. Simmons et al. [30] studied 100 patients in whom symptomatic pseudarthrosis was established at a minimum of 9 months following the index procedure for lumbar spinal fusion. All patients were treated with a pulsed electromagnetic field device worn consistently for at least 2 h a day for 90 days. They found that solid fusion was achieved in 62.5 % of primary fusion cases and in 76.8 % of revision fusion cases for an overall fusion rate of 67 %. Given that the treatment was initiated at a minimum of 9 months following the procedure, it is difficult to determine if the fusion is a direct result of the pulsed electromagnetic field or if these patients were eventually going to fuse spontaneously if given more time. A trial of this conservative modality may be reasonable in the symptomatic patient with a stable spine and intact hardware. Some surgeons also prefer to institute this treatment modality immediately following revision surgery in order to maximize the potential for fusion.

Surgical treatment can be considered in patients with symptomatic pseudarthrosis who have failed conservative treatment and in those with evidence of hardware failure or spinal instability. Careful evaluation of the previous procedure, spinal balance, patient risk factors, hardware stability, and pseudarthrosis morphology will help to determine the most appropriate revision strategy. General principles of adult spinal deformity should help dictate the treatment plan

and should not be compromised in order to maximize the success of revision surgery.

Optimization of coronal and particularly sagittal balance has been shown to significantly improve clinical outcomes [31] and fusion rates, particularly at the thoracolumbar and lumbosacral junctions [32]. Evaluation of sagittal and coronal balance is best assessed through the use of full-length, standing PA and lateral spine films. These should be performed using a 36 in. cassette, such that the hip joints and entirety of the cervical spine can be completely visualized on a single film. If there is any significant sagittal or coronal plane imbalance, consideration for local or global deformity correction should be given. If local deformity correction is necessary, a minimally invasive option involving combined extreme lateral interbody and posterior approaches has shown feasibility [33].

The strategies for revision of minimally invasive spinal fusion are similar to the traditional open procedures, in that revision focuses on improving the biology and potential stability for fusion to occur. Assessment of both the morphologic patterns described above and the stability of the hardware will guide the surgical plan.

If there is a component of atrophic pseudarthrosis, the revision strategy will require improving the biology of the fusion process, typically using an alternative grafting technique. Autograft techniques have the advantage of providing osteogenic, osteoinductive, and osteoconductive capabilities. Autograft is typically harvested either locally or from the iliac crest. Posterior iliac crest graft is most commonly used for lumbar fusion procedures. It is easily accessed in the surgical field and can be harvest using a traditional open or minimally invasive technique [34]. The harvest of posterior iliac crest autograft has historically been associated with complications of hematoma formation, wound infection, paresthesias, iliac fracture, and most commonly, prolonged donor site pain [35]. This persistent pain has been found to be a significant cause of long-term morbidity, contributing to patient-reported disability and functional limitations [36, 37]. Other authors have found that patients have a difficult time distinguishing posterior iliac crest pain from persistent low back pain, which could result in an overestimation of graft harvest-related complications [38, 39]. If posterior iliac crest graft is selected, this potential complication should be explicitly discussed with the patient preoperatively, as it could profoundly affect the ultimate outcome of the symptomatic pseudarthrosis patient.

Many graft substitutes have also been used as alternatives to iliac crest autograft with good success rates [20–25]. Alternative osteoinductive graft options include rhBMP, bone marrow aspirate, and demineralized bone matrix, along with an osteoconductive substrate in the form of local autograft, allograft, or ceramics. There has been an increased debate as to the ideal graft option as each carries a unique set of risks and benefits. Ultimately, the graft choice should be made in consultation with the patient, such that a discrete understanding of the unique risks and benefits of each option will be weighed appropriately. This will hopefully allow selection of the option that will best maximize the surgical outcome for each individual.

If the morphologic pattern is transverse, shingle, or complex, the implication is that there is some element of graft consolidation, but the final bridging of the callous failed to occur. This can be indicative of some residual instability. Revision requires taking down the area of fibrous tissue in order to expose healthy bleeding bone and repeat grafting of the pseudarthrosis. If there is hardware loosening, this should also be addressed. Loose pedicle screws can be revised by upsizing the screws by a minimum of 0.5 mm in diameter. The entirety of the revision may be performed through minimally invasive techniques if the area of pseudarthrosis can be adequately taken down using a tubular retraction system and the hardware system used is amenable to removal and reinsertion [40]. Loose interbody devices can also be revised through revision of mini-open approaches [41]. The surgeon should have a low threshold for converting to traditional open techniques, as the approaches chosen should never limit the goals of the procedure.

If the hardware is stable and the index procedure consisted of a stand-alone interbody fusion or posterolateral fusion, completion of the 360° fusion can be a reasonable option (See Figs. 39.1 and 39.2). This provides not only a biomechanically rigid construct but also has the distinct advantage of utilizing a primary approach. If the previous surgery involved a posterolateral construct with stable hardware, the preferred less invasive options are a mini-open retroperitoneal approach or transpsoas approach and subsequent interbody fusion. Similarly, if the index procedure involved a stand-alone interbody fusion, the addition of percutaneous pedicle screws and rods with posterolateral fusion is a good option [16].

Ultimately, pseudarthrosis remains a challenging problem that is best avoided with meticulous surgical indications and techniques. Current minimally invasive techniques fortunately have high fusion rates in the lumbar spine. Further technological and biomedical advances should strive for continued improvement of these fusion rates, ultimately preventing the occurrence of pseudarthrosis.

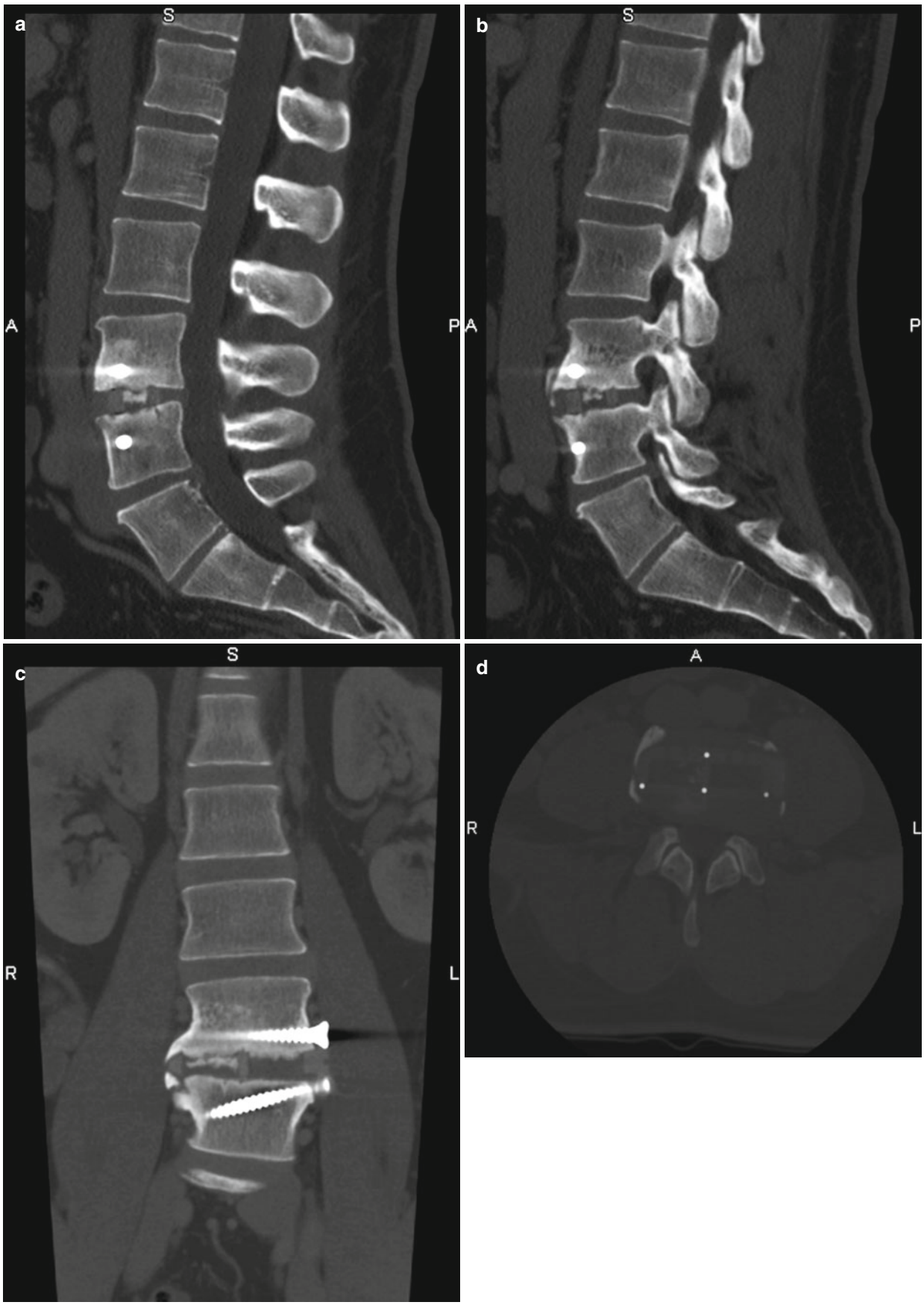

Fig. 39.1 A 38-year-old male smoker who underwent previous XLIF 13 months prior with use of rhBMP. Patient had good relief of symptoms for 4 months and then began to experience increasing axial back pain. (**a**–**d**) CT scan with sagittal and coronal reconstructions demonstrates stable hardware in good position, but absence of bridging bone through the interbody device

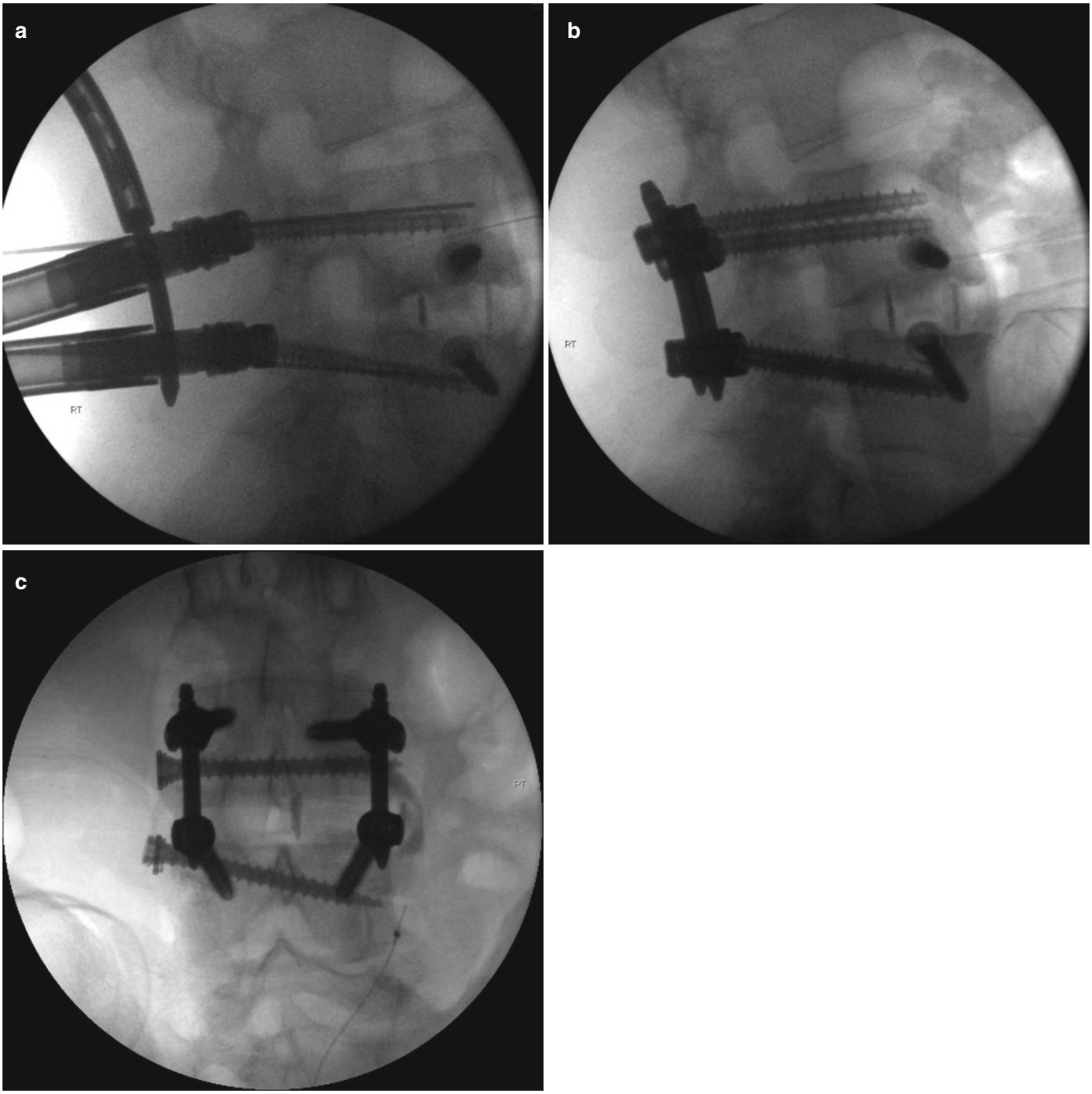

Fig. 39.2 (**a**–**c**) Intraoperative fluoroscopic images of percutaneous pedicle screw instrumentation for lumbar pseudarthrosis following XLIF. Patient underwent concomitant posterolateral fusion with allograft and rhBMP. He had good relief of his preoperative symptoms following this procedure

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Index

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