Posterior Approaches to the Thoracolumbar Spine: Open Versus MISS

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Abstract

The traditional open approach to the thoracolumbar spine remains one of the most powerful and widely practiced approaches in all of spine surgery. Over the past 2 decades or so, minimally invasive options have gained increasing traction and have been associated with reduced blood loss, paraspinal musculature disruption, infection rates, and length of stay, as well as hospitalization costs, without compromising clinical outcomes or radiographic fusion rates. The minimally invasive approach is not necessarily appropriate for all patients and pathologies, and the two approaches are not mutually exclusive. Currently an array of open and minimally invasive options exist for posterior thoracolumbar fusion, including midline and paramedian approaches, conventional and tubular retractors, posterior and transforaminal interbody as well as posterolateral fusion options, static and expandable cages, and various fixation systems, including pedicle (both open and percutaneous) and cortical bone trajectory screws. More recently, endoscopic spine surgery has garnered growing attention as an ultra minimally invasive alternative and may yet play a significant role in neural decompression and spinal fusion. Furthermore, advances in navigation, robotics, osteobiologics, and perioperative protocols will hopefully translate into increased safety, efficacy, and reproducibility for posterior thoracolumbar fusion procedures.

Keywords

Thoracolumbar fusion · Open · Minimally invasive · Posterior lumbar interbody fusion · Transforaminal lumbar interbody fusion · Tubular retractor · Percutaneous pedicle screw · Cortical bone trajectory screw · Endoscopy

Introduction

The posterior approach to the thoracolumbar spine is one of the most powerful tools in the spine surgeon's armamentarium. This approach is the oldest, and most widely practiced and accepted technique in all spinal surgery (Knoeller and Seifried 2000). It affords the surgeon access to all three columns of the spine through a single stand-alone approach, obviating the need for patient repositioning and staged procedures. It enables direct decompression of the common thecal sac and nerve roots and provides an avenue for fixation and fusion and therefore correction of instability and deformity.

Despite these advantages, the traditional open approach to the thoracolumbar spine is associated with significant iatrogenic disruption of normal surrounding tissue, in particular collateral damage to the paraspinal musculature, leading to devascularization, pain, atrophy, and disability (Fan et al. 2010; Kim et al. 2005). Minimally invasive spine surgery (MISS) has gained much popularity in recent years owing to the reductions in patient morbidity, length of hospital stay, and costs. This has been supported by advances in technology, including access, instrumentation, neuromonitoring, biologics, navigation, and robotics (Yoon and Wang 2019).

In this chapter, we will address the history of lumbar instrumentation and fusion, and the increasing adoption of minimally invasive techniques. We will also address current trends in spinal procedures performed in Australia and outline the common indications for lumbar fusion, including reviewing the most contemporaneous literature on the subject. Rather than exhaustively detailing each step involved in common thoracolumbar fusion operations, we will endeavor to share with our reader specific nuances accumulated through our surgical experience.

Brief History of Open and Minimally Invasive Spinal Fusion

Harrington in the 1950s is credited with the birth of spinal instrumentation (Harrington 1962). He revolutionized the treatment of pediatric scoliosis with his stainless-steel rod construct. While these were effective in correcting coronal deformities, it created a generation of patients with flat back deformities. The next major revolution in instrumentation came in the form of segmental transpedicular screw fixation, and while described a few decades earlier (Knoeller and Seifried 2000), Roy Camille is often credited with their popularization in the 1970s (Roy-Camille et al. 1976). While Hibbs had harvested iliac crest bone graft in the 1910s for posterolateral graft (Hibbs 1911), Cloward in the 1940s was the first to describe its placement in the interbody space (Cloward 1952), now considered the first iteration of the posterior lumbar interbody fusion (PLIF). To mitigate the forceful retraction applied to the traversing nerve root and thecal sac, Harms (Harms and Rolinger 1982) modified this technique in the 1980s to a more lateral approach, now termed transforaminal lumbar interbody fusion (TLIF) involving total facetectomy and entrance through a corridor referred to as Kambin's triangle (Kambin and Zhou 1996), formed by the obliquely oriented exiting nerve as its hypotenuse, the longitudinally oriented traversing nerve root medially, and the transversely oriented disc space and vertebral endplates inferiorly. Following the lead of our general surgical colleagues and their widespread adoption of laparoscopic techniques over traditional open laparotomies, the search for less invasive approaches to the spine had started to gain momentum. Magerl's percutaneous adaptation of the pedicle screw in the 1980s (Magerl 1982) and Foley's introduction of the tubular retractor[7] a decade later are often considered two of the most significant landmarks in MISS. Kambin, in addition to his eponymous anatomical triangle, is also credited with the development of percutaneous and later endoscopic approaches to the intervertebral space (Kambin and Zhou 1996), and thus spinal endoscopy was born.

Regional and Global Trends in Spinal Fusion

The World Health Organization estimated that low back pain (LBP) affects approximately two-thirds of people in industrialized countries at some point in their lives (Duthey 2013). Epidemiological studies have ranked LBP as the second commonest cause of disability in adults (Prevalence and most common causes 2009), and number one in Years Lived with Disability (Hoy et al. 2014). In parallel to the growing disability incurred by spinal pathology, the number of spinal surgeries performed has also increased, particularly fusion procedures. In Australia, where we practice, the number of simple spinal fusion procedures doubled between 2003 and 2013, while complex fusion procedures quadrupled (Machado et al. 2017). Similar trends have been demonstrated in the United States, with the fastest increases seen in the over 65 age group (Martin et al. 2019). Over a similar epoch, MISS has also gained increasing traction. According to a recent global survey of nearly 300 spinal surgeons, most respondents (71%) regarded MISS as mainstream, while the majority (86%) practiced some form of

MISS (Lewandrowski et al. 2020). In parallel with this trend, based on patient surveys, most patients (80%) prefer MIS over open surgery, provided that long-term outcomes and complication risk are comparable (Narain et al. 2018).

Selected Indications and Evidence for Spinal Fusion

Most spine surgeons would support the addition of fixation and fusion in patients with evidence of instability, classically manifesting as spondylolisthesis with abnormal movement on dynamic radiographs, although indirect signs such as sagittally oriented facets, intra-articular effusions, and synovial cysts may sway a surgeon toward fusion out of concern for creating iatrogenic instability following decompression (Blumenthal et al. 2013). Furthermore, the predominance of mechanical LBP in patients with neurogenic claudication or radiculopathy significantly reduces probability of improvement following decompression alone and may provide further impetus to fusion (Pearson et al. 2011). More recently, our growing understanding of spinal deformity and the negative impact of sagittal imbalance and spinopelvic mismatch on outcomes following spine surgery (Glassman et al. 2005; Schwab et al. 2013) has contemporized our understanding of the longitudinal impact of segmental fusion upon regional and global spinal alignment, as well as the potential benefits and pitfalls of long segment fusion, strategic placement of interbody devices and osteotomies, and deformity correction.

Spondylolisthesis

The rate of *fusions* around the world has more than doubled from the start of the twenty-first century and is only continuing to *increase* from *year* to *year* (Makanji et al. 2018). Despite this, evidence from large randomized controlled trials remains either lacking or conflicting. Certainly, the as-treated results from the spondylolisthesis arm of the Spine Patient Outcomes Research Trial (SPORT) supported surgery over conservative management for patients with degenerative spondylolisthesis (Abdu et al. 2018). However, the significant crossover rate mitigated the benefits of randomization, and the heterogeneity in surgical methods prevented any firm conclusions regarding whether fusion afforded additional benefit to decompression alone.

The two recent randomized controlled trials published in the New England Journal of Medicine addressing whether the addition of fusion to decompression in patients with low-grade degenerative spondylolisthesis raised more questions than they answered. The Swedish study (SSSS) randomized more patients (Försth et al. 2016), around 250, but only half had spondylolisthesis, and important patient characteristics such as dynamic instability and relative contributions of mechanical LBP versus leg pain were not addressed. They concluded that fusion was no better than laminectomy alone in all outcome measures and resulted in longer length of stay and higher costs. The North American study (SLIP) compared the addition of fusion to laminectomy alone in approximately 60 patients (Ghogawala et al. 2016). Patients with mechanical LBP and dynamic instability, generally considered relative indications for fusion, were excluded, potentially reducing the applicability of their patient population to real-world practice. Their results suggested a small but statistically significant improvement in the physical component of the 36-item Short Form Health Survey (SF-36). Neither trial was able to explore the nuances in decision-making spine surgeons face every day in this diverse patient population, and both largely used a surgical strategy, instrumented posterolateral fusion with autologous iliac crest bone graft without interbody that some would consider outdated today. Certainly, no minimally invasive techniques were utilized. Some evidence does also exist supporting the use of interbody over posterolateral fusion with respect to fusion and reoperation rates (Liu et al. 2014). Furthermore, interbody graft provides additional potential benefits of anterior column support and load sharing, fusion under compression and over a shorter distance, as well as indirect foraminal decompression and restoration of segmental lordosis.

Axial Back Pain

Fusion specifically for LBP has remained a subject of contention for many years. The reduced efficacy of surgery in patients with back-pain predominant symptomatology (Pearson et al. 2011), coupled with difficulties in localizing a specific pain generator in these patients (Brusko et al. 2019), who often possess significant psychological overlay and covert secondary gain, has made this field one of the most controversial in all of spine surgery. The initially positive Swedish trial (Fritzell et al. 2001) on fusion for intractable LBP was later rebutted by the Norwegian trial (Brox et al. 2003), which showed no benefit for fusion over rehabilitation with a cognitive behavioral component. True structured rehabilitation is, however, a scarce commodity in a lot of countries, including Australia, often with lengthy wait times. The latest American Association of Neurological Surgeons (AANS) and Congress of Neurological Surgeons (CNS) guidelines support at least consideration for fusion surgery in the setting of persistent mechanical LBP once all reasonable conservative alternatives have been exhausted (Eck et al. 2014).

Thoracolumbar Burst Fractures

Trials on surgery versus nonoperative management for thoracolumbar burst fractures in neurologically intact patients have shown similarly conflicting results (Abudou et al. 2013), although contemporary minimally invasive methods have not yet been rigorously studied. Certainly, patients with unstable thoracolumbar fractures without need for direct decompression may serve as an ideal cohort for percutaneous fixation to facilitate pain control, mobilization, and fracture union, with minimal collateral soft tissue disruption (Court and Vincent 2012). The instrumentation can often be removed following fracture union to remobilize the involved segment of the spine and prevent long-term adjacent segment issues (Court and Vincent 2012). Similarly, percutaneous instrumentation has an established role in providing supplemental fixation in the context of interbody fusion approached via a lateral route (Alvi et al. 2018) and holds promise in the realm of spinal infection (Deininger et al. 2009), with minimization of communication with infected tissue, and preservation of paraspinal musculovasculature and viability.

MISS Fusion

With an aging population and associated frailty, coupled with increasing emphasis on healthcare economics, there is growing demand for less invasive surgical options. The benefits of MISS have been clearly demonstrated in other subspecialties, such as laparoscopic abdominal surgery and endovascular neurosurgery. There is now a growing body of evidence that MISS fusion provides similar outcomes and fusion rates as traditional open methods. Our meta-analysis on MISS TLIF versus open TLIF showed less blood loss and lower incidence of infection with at least comparable clinical outcomes with regard to axial pain and disability (Phan et al. 2015a). Other studies have consistently shown shorter length of stay (Goldstein et al. 2014), reduced complications (Khan et al. 2015), less disruption of paraspinal musculature (Fan et al. 2010; Kim et al. 2005), less postoperative narcotic use, and earlier return to work (Adogwa et al. 2011), as well as decreased overall costs (Wang et al. 2012). Concerns around increased fluoroscopic exposure to the surgical team (Khan et al. 2015) have been counteracted by advances in navigation and robotic technology, which have also resulted in improved fixation accuracy (Kosmopoulos and Schizas 2007). The initial steep learning curve has been overcome to some extent by widespread dissemination of techniques, and opportunities to learn and practice at cadaveric workshops. The unique challenges raised by patients at risk for nonunion, including osteoporosis (Benglis et al. 2008), have led to strategies such as augmenting pedicle screws with cement to increase pull-out strength, and bone morphogenetic protein (BMP) to improve fusion (Mccoy et al. 2019). Understanding the dose-dependent properties of BMP, and risks of radiculitis, heterotopic ossification, and osteolysis (Fu et al. 2013), has led to more controlled application of smaller doses in carefully selected patients without malignancy to areas without exposed dura or nerve root, or endplate violation.

The classic tenets of MISS involving small incisions and tubular retractors have shifted toward an overarching paradigm of minimizing collateral tissue disruption to reduce disability, and a greater appreciation for the importance of multidisciplinary teams in enhancing recovery after surgery (ERAS). (Dietz et al. 2019) Patient selection remains key, and while indications for minimally invasive approaches have expanded, there remain pathologies, including but not limited to severe adult spinal deformity, especially if concomitantly rigid, which may be better suited to an open approach (Mummaneni et al. 2019).

Open Lumbar Fusion

There are several variations on the traditional open PLIF technique. We prefer to decompress then instrument to allow us to palpate and visualize the pedicular walls, although the opposite sequence is equally valid. This guides our pedicle screw trajectory both in the craniocaudal as well as medio-lateral planes, thereby minimizing risk of breaching. We also remove most if not the entire facet, comparable to a traditional Ponte osteotomy or Schwab grade 2 osteotomy (Schwab et al. 2014) and affording a similar lateral trajectory as TLIF. Not only does this minimize the amount of nerve root retraction necessary, it also increases the amount of autologous bone available for fusion, and mobilizes the spine to facilitate interbody insertion, foraminal height restoration, spondylolisthesis reduction, and deformity correction. Topical hemostatic agents such as thrombin and gelatin are essential to minimize blood loss, and cell saver technology should be considered if available. Retractors are intermittently released throughout the case to minimize muscle ischemic time. In closing, the muscle is approximated to obliterate dead space, but not so tightly as to risk ischemia. The fascia is closed tightly, particularly if there has been incidental durotomy. We prefer to do this is in an interrupted fashion so that suture line integrity is not reliant on a single knot at each end. We often place an epidural catheter for narcotic infusion (Klatt et al. 2013) postoperatively in addition to a wound drain. There is also some evidence to suggest that topical vancomycin placed in the wound may reduce the incidence of postoperative infection, particularly following instrumentation (Khan et al. 2014). Loupe magnification with headlight illumination is used to enhance visualization.

Positioning

Following appropriate timeout, intravenous antibiosis, and application of mechanical lower limb antithrombotic devices, the patient is positioned prone on the operating table. Particular emphasis is paid to the position of the arms to avoid undue traction on the brachial plexus, padding of all potential pressure areas, sufficient room for the abdomen so as to not impede venous return, and slight reverse Trendelenburg position and avoidance of any direct pressure on the globes to prevent ischemic optic neuropathy.

Laminectomy

In exposing the spine, it is critical to avoid, if possible, violating the capsules of the facet joints of uninvolved levels, particularly at the upper-instrumented vertebra, to minimize acceleration of adjacent segment disease (ASD). Furthermore, clear delineation of bone and bony edges is paramount and facilitates surgeon orientation, particularly in revision cases where the anatomy may be distorted. Laminectomy is performed with a combination of Leksell bone nibblers, high-speed drill, and Kerrison punches. There is usually a deficiency in the midline where ligamentum flavum attaches to the undersurface of the lamina, where epidural fat is encountered, heralding entrance into the spinal canal. The thinner the bone is egg-shelled, the easier it is to enter the canal with rongeurs. Significant dural adhesions may be encountered, especially in revision cases, which require careful separation with blunt dissectors such as curettes. Not all epidural adhesions or scar tissue require excision, provided the necessary neural elements have been detethered and decompressed.

Facetectomy

Following laminectomy, attention is turned to the facetectomy. The inferior articular process (IAP) is disarticulated by drilling or osteotomizing across the pars interarticularis, allowing it to be removed en bloc and saved as graft. Care must be taken to avoid violating the superior pedicle. The naked articular surface of the superior articular process (SAP) is then exposed. The SAP can be similarly removed en bloc by first palpating the superior border of the inferior pedicle with a blunt dissecting instrument such as the Woodson elevator. This defines the inferior limit of drilling or osteotomy (Fig. 1). The pars artery (Macnab and Dall 1971) is often encountered during these maneuvers and must be secured for hemostasis. In excising both the IAP and SAP en bloc, it is important that bony leverage occurs in the upward direction to avoid neural injury. Alternatively, Kerrison punches can be used to skeletonize the medial and superior borders of the inferior pedicle until sufficient space is created for interbody insertion. Care is taken superiorly and laterally in the foramen to avoid injury to the exiting nerve root. Foraminal ligament can be preserved as a protective barrier over the exiting nerve root if satisfactory direct and indirect decompression has otherwise been achieved.

Interbody

The epidural veins are cauterized with the bipolar tips parallel to the traversing nerve root to avoid inadvertent thermal injury, and divided to avoid neural traction. In cases where the disc is severely collapsed, it may be difficult to gain entrance into the disc space with traditional interbody instruments. It may be effective in these situations to enter the space with a smaller blunt tipped instrument, such as a pedicle probe, under lateral fluoroscopic guidance. Gradual distraction can then be achieved by sequentially upsizing spacers placed contralateral to the side that discectomy and endplate preparation is occurring if bilateral interbody devices are planned. Alternatively, laminar spreaders or ones anchored to pedicle screw heads can be used. Aggressive distraction must be avoided in the latter instance to avoid pedicular fracture, particularly in patients with osteoporosis.

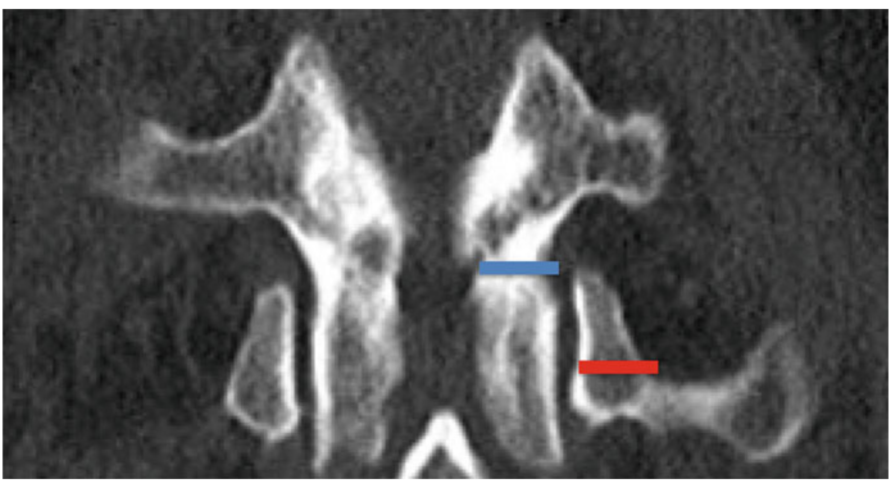

Fig. 1 Coronal lumbar spine computed tomography (CT) demonstrating the relationship of the IAP and SAP. The osteotomies performed are indicated by the blue (IAP) and red (SAP) lines, taking care not to violate the cranial and caudal pedicles

Similarly, care must be taken to avoid violating the bony endplate with forceful use of oversized shavers. The final implant is then inserted and impacted as ventrally as possible to take advantage of the strong apophyseal ring as well as maximize segmental lordosis. However, care must be taken to avoid breaching the anterior longitudinal ligament, as ventrally displaced cages are notoriously difficult to retrieve (Murase et al. 2017). Autogenous bone, supplemental allograft and BMP, if necessary, is packed into the disc space to enhance fusion (ventral to the implant in the case of BMP to prevent predural seroma and radiculitis), as implants themselves often contain very little space to accommodate graft. Traditionally, polyetheretherketone (PEEK) cages have been used, although titanium technologies are gaining popularity due to their osteo-integrative potential (Rao et al. 2014), at the cost of possibly increased risk of subsidence due to higher modulus of elasticity (Seaman et al. 2017), radio-opacity, and difficulties visualizing fusion mass. Insert and rotate devices (Sears 2005), as well as expandable cages (Fig. 2), offer further options in disc height and segmental lordosis restoration (Boktor et al. 2018). Autologous iliac crest bone graft, the gold standard to which other interbody devices and biologics have historically been compared, has been used with decreasing frequency due to the morbidity associated with its procurement (Banwart et al. 1995).

Pedicle Screw Placement

There are several methods for placing pedicle screws, including free hand and fluoroscopic techniques. Advances in navigation and robotics have improved placement accuracy (Kosmopoulos and Schizas 2007). We do not routinely use neuromonitoring due to its expense, lack of availability at our institution, and lack of substantive evidence demonstrating efficacy in preventing neurological harm outside of deformity, lateral transpsoas, and intramedullary tumor surgery (Fehlings et al. 2010). The safety of the freehand method is enhanced by intimate understanding of anatomy, visualization and palpation of the pedicular walls, tactile feedback, and subtle adjustments made based on detailed study of

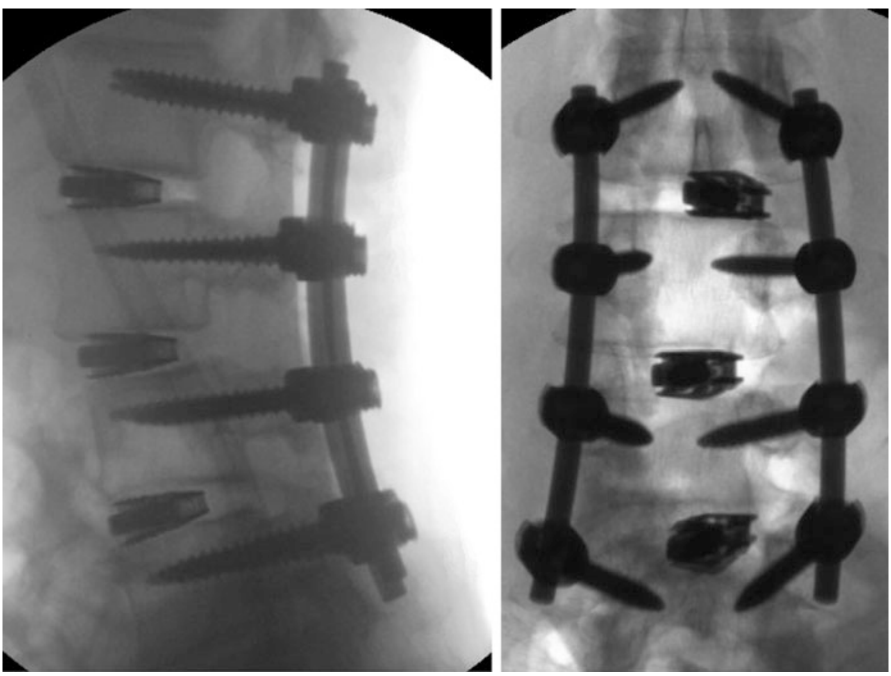

Fig. 2 Intraoperative lateral and AP x-rays demonstrating open L2–5 pedicle screw fixation and interbody fusion with expandable cages to restore foraminal height as well as segmental lordosis

preoperative imaging. Aiming perpendicularly toward the floor in the craniocaudal plane at L4 and adding approximately 5° of medialization per level to a baseline of 10° at L1 serve as useful additional guides.

The entry point is at the junction between the SAP and the bisected transverse process, where the mammillary process may be visualized (Fig. 3). To identify the entry point, it is often necessary to remove the lateral overhang of hypertrophic facets. This also serves to create sufficient room to house the head of the screw. Entry points can be customized to facilitate easier rod passage, particularly if multiple levels are instrumented. Furthermore, the trajectory of open pedicle screws is usually less medialized than their percutaneous counterparts due to the significantly increased amount of tissue dissection necessary in order to achieve a sufficiently lateral starting point, and the hindrance of both paraspinal musculature and retractors to medialization.

In probing the pedicle, tactile feedback is provided by the crunchiness of cancellous bone (in contrast to the hardness of cortical bone), and visual feedback by the marrow blush of the cancellous bone. It is critical that the screw goes down the same tapped hole, and can be aided by marking the trajectory on the skin edge, and to avoid forcefully tightening the screw against the facet, losing its poly-axiality and potentially stripping the screw. Screw symmetry can be achieved by leaving the handle on the contralateral screw as a guide or using fluoroscopic control. Pull-out strength is improved by using the longest screw possible with the widest diameter and augmenting with cement in osteoporotic patients. Given the largely cancellous nature of S1, it may be desirable to achieve bicortical purchase through the sacral promontory (the most corticated part of the vertebra) at this level. Compression and reduction are achieved against a final tightened screw if necessary, aided by extension tabs on the screw head, lordotically contoured rods, and cantilever maneuvers, although a significant degree of reduction is often already accomplished through the interbody work.

One must also be adept at managing breaches of the pedicular wall. While medial and inferior breaches have classically been associated with injury to the traversing and exiting nerve roots, respectively, lateral breaches can be equally undesirable, with potential injury to the adjacent intrapsoas lumbar plexus, as well as lumbosacral trunk at the caudalmost levels. While existing pilot holes can sometimes be rescued by redirecting the pedicle probe, including using ones with curved tips, it is often easier to fashion

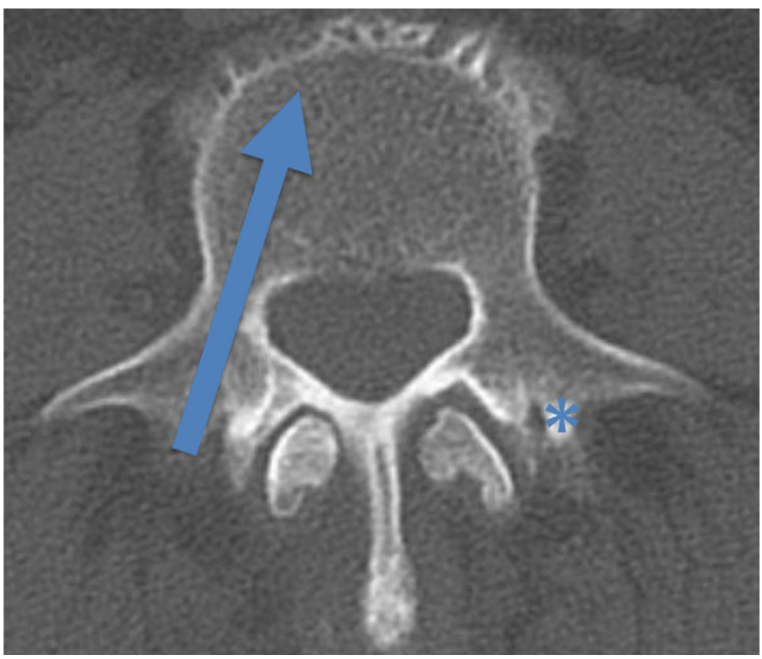

Fig. 3 Axial CT demonstrating the typical latero-medial trajectory of a lumbar pedicle screw (asterisk represents the mammillary process, an ideal entry point)

new entry points in order to avoid existing tracts. Careful examination of preoperative imaging can aide in preventing pedicular breach, including accounting for rotational deformities, as well as accounting for narrow, dysmorphic, or sclerotic pedicles, particularly on the concavity of a scoliotic curve in the latter.

Selected Variations in Open Lumbar Fusion

Posterolateral Fusion

We place interbody grafts routinely due to the aforementioned benefits. However, there may be clinical scenarios such as significant disc space collapse, weakened osteoporotic endplates, or minimal neuro-foraminal stenosis, in which interbody fusion may be difficult, inappropriate, or unnecessary. In these cases, posterolateral fusion serves as a reasonable alternative. Equally, posterolateral fusion may serve as a useful adjunct to interbody fusion in patients at risk for nonunion and in revision cases for pseudoarthrosis. It is critical that meticulous decortication of the transverse processes down to bleeding cancellous bone is performed to create an ideal fusion environment, a process that is often neglected. The remaining facet joint may also be decorticated. A cottonoid may be temporarily placed over the thecal sac as a barrier against bone graft inadvertently placed epidurally, preventing iatrogenic stenosis.

Pedicle Screws Via a Wiltse Approach

One of the criticisms of open pedicle screws is the difficulty in achieving the desired medialization due to hindrance by paraspinal muscles and retractors. Idealized exposures often require extensive lateral dissection and lengthy incisions. To mitigate this, bilateral incisions can be made in the lumbodorsal fascia through a single midline skin incision. Dissection is then carried down between the multifidus and longissimus muscles, often through a natural avascular cleavage plane, landing directly onto the junction between the facet joint and transverse process (Wiltse et al. 1968). This plane between the two muscles is measurable from the midline on preoperative imaging (Fig. 4), and often palpable and visible

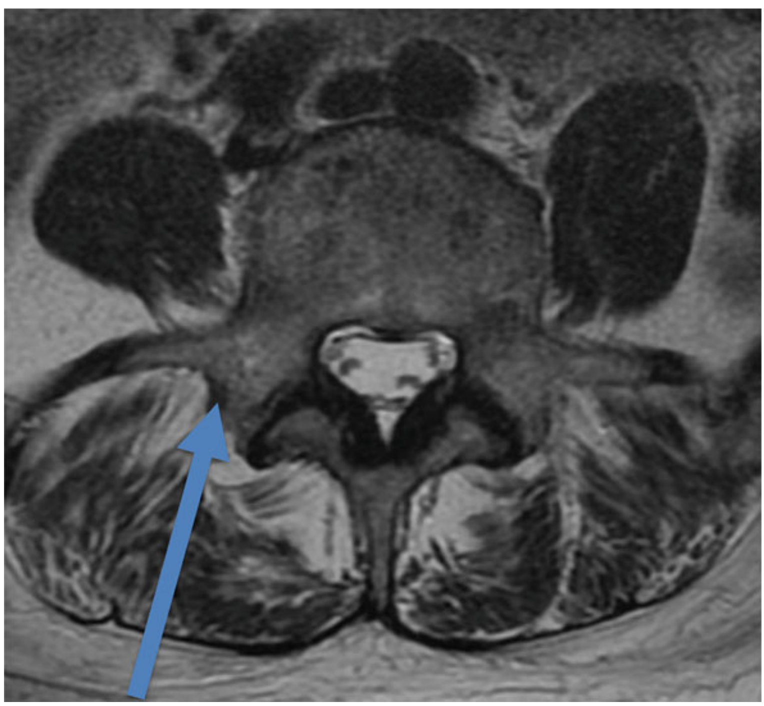

Fig. 4 Axial T2-weighted magnetic resonance imaging (MRI) illustrating the Wiltse paraspinal plane between medial multifidus and lateral longissimus, with a muscle-sparing approach (arrow) landing directly onto the facet-transverse process junction

intraoperatively. Pedicle screw insertion then proceeds in the aforementioned fashion. However, the extensive suprafascial undermining required creates significant dead space, which must be obliterated to prevent postoperative seroma and potential infection.

Cortical Bone Trajectory Screws

Some of the other criticisms of the open approach to pedicle screw placement are the amount of lateral muscular dissection required and the propensity to violate the facet capsule at the upper-instrumented level, thus potentially accelerating adjacent segment degeneration (Sakaura et al. 2019). Furthermore, pedicle screws reside mostly in cancellous bone, which is significantly weaker than cortical bone, an issue accentuated in osteoporotic patients. Within the last decade, a medial to lateral and inferior to superior screw trajectory has been proposed to address these issues, including maximizing purchase into cortical bone (Santoni et al. 2009). The entry point is in the pars, and the upward and outward trajectory is analogous to lateral mass screws in the cervical spine (Fig. 5). The poorer definition on fluoroscopy of the pars on fluoroscopy and the lack of tactile feedback due to the cortical nature of the traversed bone can be mitigated by use of intraoperative navigation. The spinous process navigation clamp, if used, should be placed at the cranial end of the exposure (rather than caudal end in navigated pedicle screws) to ensure that it remains between the surgeon and navigation camera, as well as maximizing the amount of

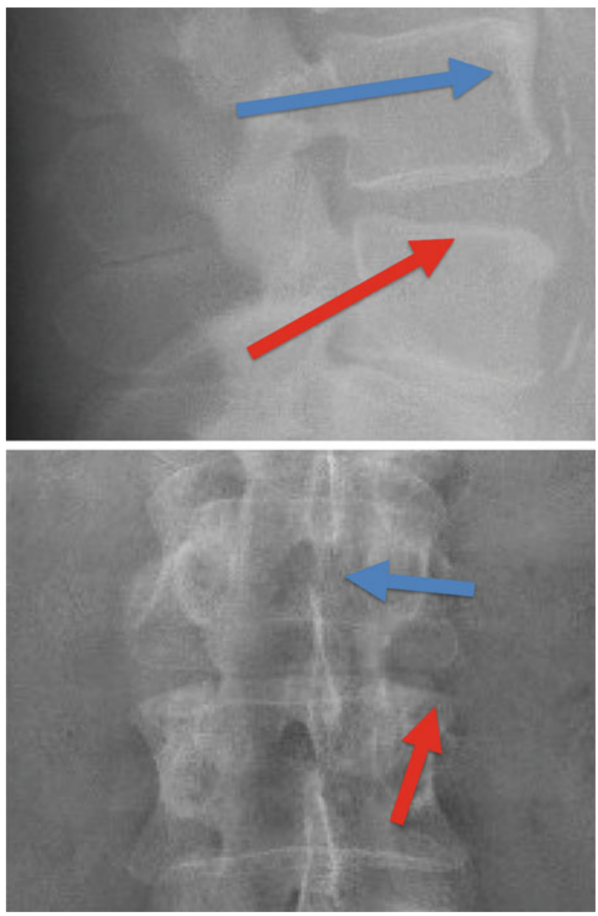

Fig. 5 Lateral and AP radiographs contrasting the latero-medial trajectory of traditional pedicle screws (blue arrows) versus the infero-superior and medio-lateral trajectories of CBT screws (red arrows)

working space given the caudo-cranial trajectory of these screws. The diameter and length of cortical bone trajectory (CBT) screws are typically narrower and shorter. While laboratory studies have demonstrated comparable biomechanical strength and some evidence exists to support similar short-term clinical and radiographic outcomes compared to traditional pedicle screws, long-term follow-up data remains pending (Phan et al. 2015b). The CBT screw certainly represents a less invasive open alternative to traditional pedicle screws, with a potential specific role in osteoporotic patients, although its efficacy in multilevel constructs, high-grade spondylolistheses, and deformity remains unknown.

Hybrid Percutaneous Screws with Miniopen Interbody

A minimally invasive variation on the traditional open PLIF combines percutaneous pedicle screw fixation, described later, with a miniopen midline incision for laminectomy and interbody work (Mobbs et al. 2012). This reduces the amount of lateral muscular dissection required and shortens the midline incision. In these hybrid cases, we prefer transversely oriented stab incisions for pedicle screw placement to longitudinal ones to minimize devascularization of overlying skin and soft tissues. A further variation involves paramedian stab incisions in the fascia through a single midline incision to avoid multiple unsightly skin incisions. The same percutaneous instrumentation can then be used through the fascial incisions. However, this often necessitates a longer incision, such as a traditional open approach, as well as extensive undermining of the skin alluded to previously.

Minimally Invasive Lumbar Fusion

An MISS TLIF is the archetypal MISS fusion procedure. It is often synonymous with tubular retractors and percutaneous pedicle screws, (Foley et al. 2003) although several variations exist. We prefer the miniopen paramedian Wiltse approach on the side of interbody, dissecting between the multifidus and longissimus muscles as this represents a natural cleavage plane, landing the surgeon directly onto the junction between the SAP and transverse process. Critics of the unilateral transforaminal approach cite poor disc clearance and endplate preparation for fusion, comparative biomechanical weakness in lateral bending compared to bilateral PLIF constructs (Sim et al. 2010), and inability to induce significant segmental lordosis (Carlson et al. 2019) as justification against minimally invasive TLIF. However, in cases of immobile facets, or where significant segmental lordosis induction (Jagannathan et al. 2009) or spondylolisthesis reduction is desirable, we often perform bilateral facetectomies for complete segmental mobilization through short bilateral paramedian incisions and muscle splitting Wiltse approaches. Expandable cages can further facilitate induction of segmental lordosis without compromising disc and foraminal height. Percutaneous pedicle screws are inserted through the Wiltse incision on the side of the interbody and small contralateral stab incisions. The MISS transforaminal approach also naturally lends itself to revision cases where florid epidural scar makes reapproaching through the midline technically challenging and potentially hazardous, with heightened risks of durotomy and cerebrospinal fluid leak.

Fluoroscopy Nuances

Once the patient is positioned, prepped, and draped, the C-arm is positioned in the anteroposterior (AP) plane. Kirschner wires are used to identify the desired level, as well as mark out the lateral border of the pedicle in the vertical plane and the bisected pedicle in the transverse plane. It is imperative that a true AP image of the desired vertebra is obtained, with a clearly defined superior endplate without any elliptical shadow, and midline spinous processes (Fig. 6). The C-arm should be locked in this position and any adjustments from the orthogonal plane recorded to ensure ease of return to the same desired position.

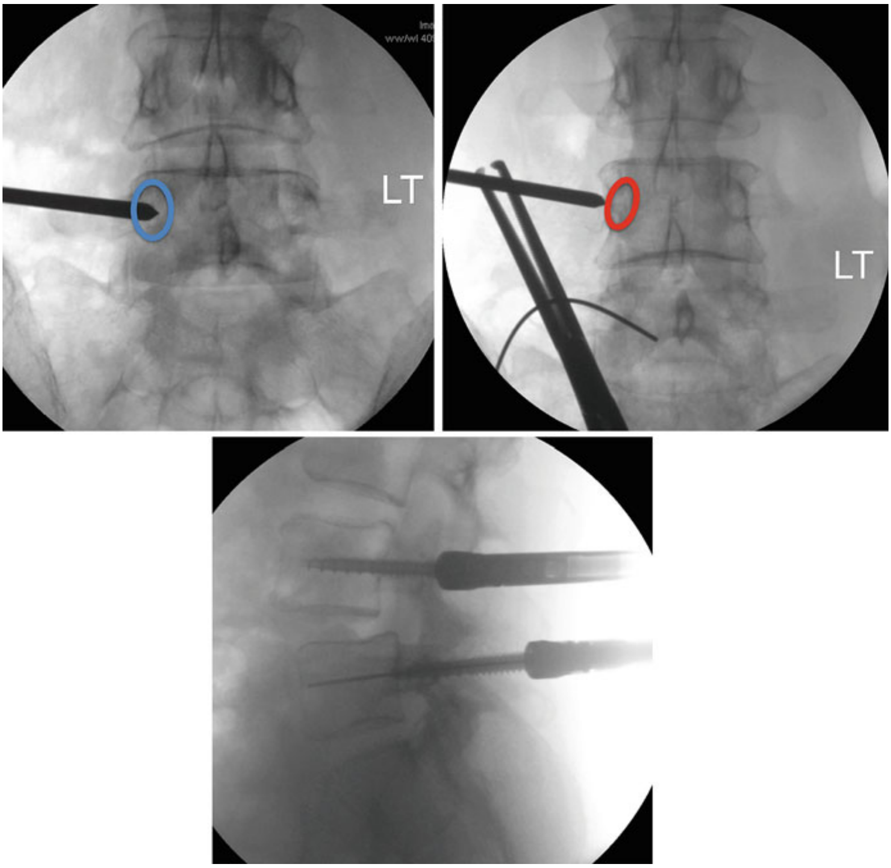

Fig. 6 True AP fluoroscopy with crisp L5 superior endplate (top image) and midline spinous process, demonstrating passage of Jamshidi needle and K-wire through the right L5 pedicle (blue circle, top image), followed by L4 (red circle, middle image), starting at 9 o'clock. At an approximate depth of 2 cm (usually heralding the junction between pedicle and vertebral body), the tip of the needle should not transgress the medial border of the pedicle. Screws are subsequently placed under lateral fluoroscopy (bottom images)

The importance of having a skilled radiographer experienced in the percutaneous workflow cannot be overemphasized. Draping of the C-arm and absolute attention to sterility are also of paramount importance, as any adjustments to the C-arm, particularly switching between AP and lateral views, can desterilize the drape and endanger the operative field.

Jamshidi Needle Advancement

Stab incisions are made approximately 1–2 cm lateral to the outer border of the pedicle, depending on the body habitus of the patient and the depth of intervening soft tissue. The bull's eye technique is used for pedicle cannulation (Fig. 6). The Jamshidi needle is docked at the junction of the SAP and the transverse process. It is often useful to walk the tip of the needle along the superior and inferior borders of the transverse process and the lateral wall of the facet joint for secondary anatomical confirmation. Close examination of preoperative imaging is crucial, as a severely hypertrophied facet joint can significantly alter the desired entry point as well as increase the depth the Jamshidi needle needs to be advanced in order to traverse the pedicle, traditionally considered to be 2 cm in patients without distorted anatomy. Failure to account for this can lead to complications, including medial pedicular breach, and injury to the traversing nerve root and common thecal sac. The craniocaudal trajectory of the Jamshidi needle should match the degree of tilt or Ferguson on the C-arm.

While fluoroscopic control is critical, a degree of both tactile and aural feedback, similar to traditional open pedicle screw probing, remains possible and serves as secondary confirmation. Tactilely, advancement through crunchy cancellous bone should be relatively unhindered. Resistance often heralds proximity to cortical bone and forewarns against imminent pedicular breach. Similarly, the sound the Jamshidi needle makes against cortical bone when using the mallet is usually lower in frequency and duller in quality. There is often a small amount of toggle within the cancellous part of the pedicle to allow subtle redirections of the Jamshidi needle. Excessive force should, however, be avoided as the needle may bend, making passage of the Kirschner wire and subsequent needle removal from the vertebra difficult. It is critical to be constantly cognizant and wary of the length of the needle that has been advanced. Sclerotic pedicles pose a specific challenge to Jamshidi needle advancement and may necessitate gentle coring out of the pedicle with a high-speed drill to facilitate Kirschner wire passage, both carefully performed under fluoroscopic control but nonetheless often still achievable percutaneously.

Kirshner Wire Management and Screw Placement

The Kirschner wire can often be manually advanced up to 1 cm further into the cancellous bone through the Jamshidi needle without need for the mallet. Tip position within the vertebral body is confirmed if a bottom is palpable, analogous to using the ball tip feeler in open cases. At all stages, including Jamshidi needle removal, tissue dilation, tapping, and screw insertion, care must be taken to avoid inadvertent loss of wire position, including pullout or advancement, and undue twisting and bending. This is achieved both manually with judicious control with the noninstrumenting hand as well as constant attention to fluoroscopy.

Pedicle screws are inserted down the Kirschner wire through the tapped hole under lateral fluoroscopy (Fig. 6). When advancing the pedicle screw, resistance is met once the screw head meets the facet capsule. Further forceful advancement may cause stripping of the screw and loss of poly-axiality of its head. Systems incorporating a sharp-tipped stylet into a self-tapping screw now exist and further streamline the percutaneous workflow (Huang et al. 2020), although possibly at the cost of reduced tactile feedback. Navigation and robotic technologies that marry percutaneous pedicle screw systems also exist, reducing radiation exposure for the surgeon and other operating room staff, while maintaining high rates of placement accuracy (Kochanski et al. 2019).

Interbody

Once the contralateral pedicle screws and ipsilateral Kirschner wires have been placed, the ipsilateral skin and fascial incision are connected, and the facet landed upon by dissecting down through the natural cleavage plane between multifidus and longissimus. This is often accomplishable by spreading the tips of the bipolar forceps, coagulation and division of any small bridging fibers, and gradual retractor advancement. Blunt finger dissection is also often effective. Upon landing on the facet joint, we use a bladed retractor system such as the McCullough, with the short blade medial and long lateral, to maintain exposure. Kirschner wires can often be engaged into the teeth of the retractor blades and kept out of instruments' way. Further medial dissection with electrocautery is carried out, partially exposing the lamina. The steps that follow are like the interbody portion of the open approach detailed earlier, performed either under loupe magnification and headlight illumination, or microscopic visualization. A laminotomy is performed, followed by facetectomy, discectomy, and endplate preparation. Disc removal and fusion bed preparation can be optimized by gradual medialization of interbody instruments and deployment of forward angled rongeurs. Distraction on the contralateral screws can be performed if necessary, to facilitate entrance into the disc space and maintenance of working corridor. Several interbody options exist, including banana-shaped devices, initially inserted vertically then gradually horizontalized to optimize ventral and medial positioning, maximizing cortical apophyseal ring contact, and potentially inducing lordosis, as well as bulleted and the expandable technologies previously described.

Rod Passage

After interbody and once the pedicle screws have been inserted bilaterally, attention is turned to rod placement. The incision through which the rod is placed may need to be extended to facilitate passage to avoid excessive skin tension. The tip of the rod is inserted initially vertically to engage the screw head and then advanced through each successive tower. This not only ensures subfascial placement, but also minimizes the amount of paraspinal muscle captured, preventing possible compartment syndrome. The rod is maneuvered with subtle movements to engage each tower, including medially or laterally rotating the rod holder. Screw engagement is confirmed if the overlying tower no longer rotates, by dropping a specialized measuring tool down the tower, by direct visualization, or by fluoroscopy. Placing the set screw into the tulip closest to the rod holder first brings the rod beyond the screw head, ensuring sufficient rod proximally. Reduction can be achieved through a variety of means, including rod contouring, extension, and cantilever maneuvers, as well as specialized reduction tools.

Selected Variations in Minimally Invasive Lumbar Fusion

Tubular Retractors

Traditionally, MIS lumbar fusions have been associated with the tubular retractor (Foley and Smith 1997). This requires gradual dilation through the paraspinal musculature and docking of the final tube on the facet joint prior to securement onto a table-mounted arm. Despite gradual dilation, a small amount of muscle is invariably encountered at the depth of the retractor, which then requires excision for exposure. If the tubular system is used, we advise against the use of the initial Kirschner wire due to the risk of inadvertent dural puncture and neural injury. The retractor should be docked onto the facet joint with sufficient exposure of the adjacent lamina, and ideally orthogonal to both the desired disc space as well as the floor to optimize disc access and surgical ergonomics. Given the narrow working corridor, specialized angled and bayonetted instruments are necessary. Similarly, the protected portion of the conventionally straight monopolar tip can be manually bent to facilitate use. Various other retractor systems, including bladed and screw-based assemblies, are also available.

Cross over the Top Decompression for Bilateral Stenosis

If decompression of the contralateral subarticular zone is desired, the retractor can be wanded medially (Fig. 7) or the bed rotated to facilitate over-the-top decompression. In this method, also known as unilateral laminotomy for bilateral decompression (ULBD) or ipsilateral-contralateral approach, the ligamentum is left intact while the base of the spinous process and under surface of the contralateral lamina are drilled to protect the underlying dura. Flavum and contralateral medial facet can subsequently be removed till the hump of the thecal sac drops away and the contralateral traversing nerve root visualized. The dura is at greatest risk of injury when rongeuring medially due to the upward slope of the thecal sac, though the risk of overt cerebrospinal fluid leak is low as the paraspinal muscles remain largely intact and reapproximate following retractor removal, obliterating any dead space. Use of upward angled Kerrison punches can also be useful in this approach to achieve contralateral decompression. The results of this approach are comparable to the traditional midline laminectomy, while largely

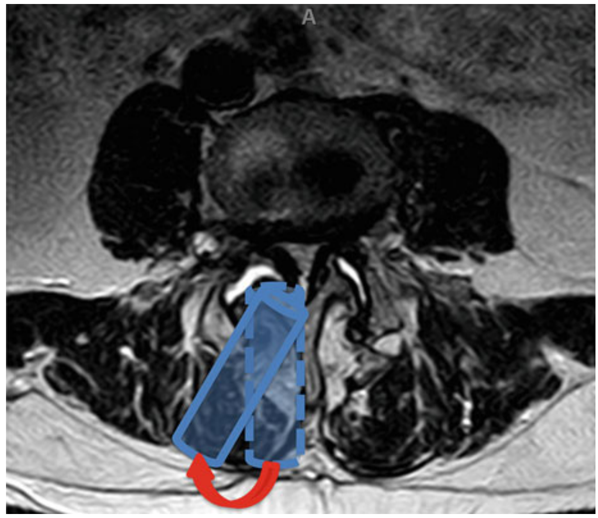

Fig. 7 Axial MRI simulating wanding (red arrow) of the tubular retractor (blue cylinders) to facilitate decompression of the contralateral lateral recess from a unilateral approach

preserving the posterior tension band (Mobbs et al. 2014).

Endoscopy

More recently, endoscopic techniques have been applied to minimally invasive TLIFs, permitting even smaller incisions and less tissue destruction. This has been combined with awake anesthetic techniques, application of long-acting liposomal local anesthetic agents, expandable technologies, biologic materials, and ERAS protocols to treat a range of lumbar spondylotic conditions (Kolcun et al. 2019). The intervertebral disc is accessed via percutaneous transforaminal route through Kambin's triangle using a spinal needle, followed by nitinol wire insertion and sequential dilation and docking of an endoscopic channel, all under constant fluoroscopic control (Fig. 8). Discectomy and endplate preparation are accomplished using specialized endoscopic rongeurs and curettes, and percutaneous reamers, shavers, and stainless-steel brushes, followed by sizing and insertion of an expandable interbody device. The procedure is completed by standard insertion of percutaneous pedicle screws. While long-term and comparative data are eagerly awaited, this technique, representing the least anatomically and physiologically disruptive of all MIS fusion methods, holds promise for elderly and infirm patients who may not otherwise tolerate lengthy prone general anaesthetics (Kolcun et al. 2019).

Thoracic Instrumentation and Selected Variations

A comprehensive description of the multitude of approaches to the thoracic spine is beyond the scope of this chapter. We will, however, endeavor to describe the various options for posterior thoracic instrumentation, both open and minimally invasive. MIS thoracic instrumentation naturally lends itself to scenarios in which direct decompression or fusion is unnecessary, such as burst fractures in patients without neurological compromise, while traditional open methods remain valid, particularly if concomitant direct decompression, fusion, or anterior column reconstruction is required, such as in oncologic pathologies.

The traditional entry point for thoracic pedicle screws is immediately inferior to the intersection between the superior border of the transverse process and the lateral border of the SAP, classically

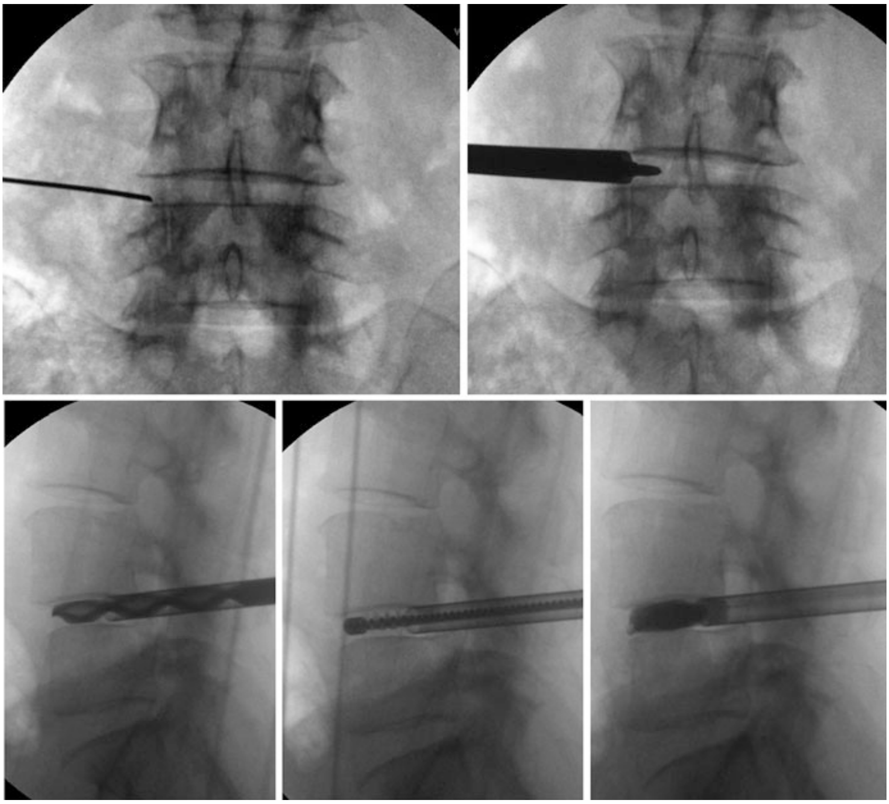

Fig. 8 Intraoperative fluoroscopy demonstrating transforaminal entrance into the L4–5 intervertebral space via Kambin's triangle using a spinal needle (**a**), followed by sequential dilation (**b**), introduction of percutaneous reamer and stainless steel brush (**c** and **d**), and measurement of extent of discectomy and sizing of interbody graft size by inflation of a balloon with radio-opaque contrast (**e**)

described as the junction between the medial two-thirds and lateral one-third of the base of the SAP (Fig. 9) (Chung et al. 2008). The ideal entry point moves slightly laterally and inferiorly as one progresses toward the cranial and caudal ends of the thoracic spine (Kim et al. 2004). Adjustments to the entry point in the axial plane can also be made based on the patient's unique anatomy on preoperative CT. Furthermore, bleeding cancellous pedicular bone can often be exposed by removing the tip of the transverse process, particularly at T12 (Fig. 10). Medialization increases at the superior-most segments of the thoracic spine, while both straight forward and the more caudally directed anatomical trajectories (Fig. 9) in the sagittal plane are acceptable (Puvanesarajah et al. 2014). The in-out-in technique (Fig. 9) with a more lateral entry point along the superior edge of the transverse process to minimize risk of medial breach has also been advocated and may be especially useful in patients with narrow pedicles, particularly in the mid-thoracic spine, enabling the insertion of wider and longer screws with tri-cortical purchase (Jeswani et al. 2014).

Percutaneous thoracic pedicle screw insertion follows the same principles described previously for the lumbar spine. We adopt a strategy of erring on the side of less medialization of the Jamshidi until the pedicle-vertebral body junction is reached to minimize risk of medial breach, followed by subtle toggling of the needle to

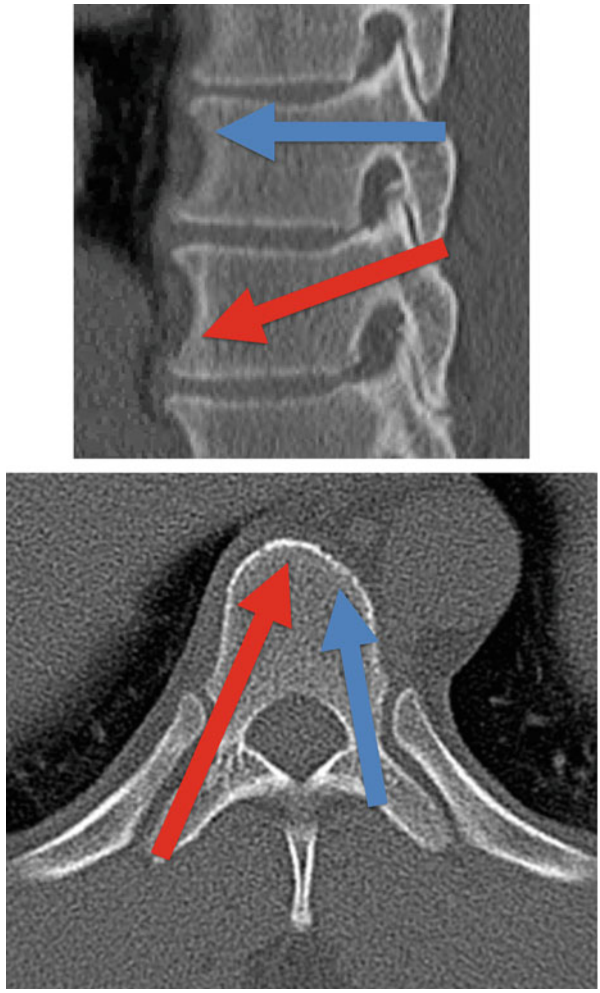

Fig. 9 CT comparing the straight forward (blue arrow) trajectory, parallel to the endplates, with anatomical (red arrow), parallel with the superior and inferior pedicular borders, in the sagittal plane (top image), and traditional intrapedicular (blue arrow) and in-out-in (red arrow) techniques in the axial plane (bottom image)

achieve more medialization to ensure that it remains within the vertebral body. Navigation and robotics may also improve accuracy of thoracic pedicle screw insertion, both open and percutaneous, especially in cases with narrow pedicles or significant deformity (Kochanski et al. 2019).

Conclusion

In summary, the posterior approach to the thoracolumbar spine is a versatile workhorse for the spine surgeon, affording access to all three columns of the spine and enabling the trinity of decompression, instrumentation, and interbody through a single approach. Both open and minimally invasive approaches present valid options, and the modern spine surgeon should be adept at both in order to cater to the needs of different patient populations with contrasting pathologies. Advances in navigation and robotics, biologics, access, instrumentation, and expandable technologies have improved the safety and efficacy of minimally invasive thoracolumbar fusions. These advances, coupled with progress in perioperative protocols and multidisciplinary care, will continue to deliver improvements in posterior thoracolumbar surgery.

Fig. 10 Removing the tip of the T12 transverse process (asterisk) can aide in the exposure of the underlying cancellous pedicular bone

Cross-References

- ▶ Lumbar Interbody Fusion Devices and Approaches: When to Use What
- ▶ Minimally Invasive Spine Surgery
- ▶ Pedicle Screw Fixation

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