Pedice Screw Fixation

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Nickul S. Jain and Raymond J. Hah

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Abstract

Pedicle screws and rods are a modern posterior spinal instrumentation system that has gained widespread adoption throughout the world as the gold standard for instrumentation of the spine over the last two decades. They provide significant advantages in that they provide rigid 3-column fixation of the spine from an entirely posterior approach without reliance on intact dorsal elements. However, there is a steep learning curve for their placement, and adequate training is required prior to their routine use. They are not without their own set of unique complications. Many modifications to pedicle screws exist to improve clinical

N. S. Jain · R. J. Hah (✉)
Department of Orthopaedic Surgery, University of Southern California, Los Angeles, CA, USA
e-mail: njain@scoi.com; Ray.Hah@med.usc.edu

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outcomes including augmentation with cement, and a variety of novel technologies can be used to help improve accuracy in their placement including fluoroscopy, computer navigation, and robotics.

Keywords

Pedicle screw · Pedicle instrumentation · Transpedicular fixation · Navigation · Screw · Dorsal instrumentation

Introduction and History

Posterior spinal instrumentation has been used for decades to allow surgeons to correct spinal deformity, stabilize fractures and instability, and promote arthrodesis. They have provided surgeons many advantages including a more stable, low-strain environment for fusion procedures and more immediate stability in unstable conditions requiring fixation (Vanichkachorn et al. 1999). This allows for early patient mobility, often times eliminating the need of external orthoses. Many indications for posterior spinal instrumentation have been described including unstable thoracolumbar fractures, metastatic tumor resulting in spine instability, spondylolisthesis, scoliosis, and pseudarthrosis (Vaccaro and Garfin 1995a).

Scoliosis was previously often treated with posterior spine fusion without instrumentation. Complications included a reported 30–40% pseudarthrosis rate with progressive loss of scoliotic correction. Harrington first described a hook-rod posterior spinal instrumentation system in 1962 which allowed for distraction and compression of the spine and marked reduction in pseudarthrosis rates (1–15%) (Harrington 1962). The system provided excellent coronal plane correction but had no rotational stability or sagittal alignment control. This predisposed patients to develop a hypolordotic "flat back" but was protective against progressive kyphosis and neurological decline. Disadvantages included loss of fixation with hook disengagement in up to 20% of cases and an inability to perform short-segment fixation (Harrington 1988).

Luque in 1980 then described the first dorsal instrumentation that allowed for segmental fixation and short constructs using sublaminar wires attached to rods. The authors demonstrated decreased pseudarthrosis rates and stable fixation; however, the system did not have the ability to resist axial load. Other complications included durotomies, neurologic injury, and wire failure (Luque 1980). Cotrel and Dubousset modified this technique to use laminae or pedicle hooks to achieve segmental fixation; however, this required intact dorsal elements including the lamina and facet joints (Cotrel et al. 1988).

Pedicle fixation allows for segmental fixation of the spine while providing the ability to control axial displacement and functions independent of the presence or absence of the dorsal elements of the spine. Additionally, they are the only posterior spinal instrumentation that allows for entire 3-column fixation of the spine which provides significant biomechanical advantage. The first posterior-based screws were described in the 1940s by King as short transfacet screws with high pseudarthrosis rates (King 1944, 1948). Boucher then described a longer screw that crossed the facet joint in 1958 (Boucher 1959).

Roy-Camille first applied screws through the entirety of the pedicle attached to plates for thoracolumbar fractures, instability after tumor resection, and lumbosacral fusion (Roy-Camille 1970). Multiple newer and improved iterations were then developed in the following decades including the AO internal fixator, the variable spinal plating (VSP) system, the Cotrel-Dubousset Universal Spinal Instrumentation (USI), the Texas Scottish Rite (TSRH), and Isola systems all providing various advantages including variable angles to ease screw-rod connection. Newer, modern designs have increased adaptability with polyaxial heads, variable diameter rods, side-to-side connectors, and modern materials including titanium and cobalt-chrome alloys.

Pedicle screws are a versatile and powerful tool for posterior spinal instrumentation. They can resist load in all planes given their 3-column fixation nature and provide a powerful fulcrum for correction of rotational, sagittal, and coronal plane deformities. Pedicle screws also allow for the surgeon to apply significant forces to the spine (including distraction, compression, and translation). They have a proven benefit in enhancing fusion rates and avoid the complications of entering the spinal canal of some of the predecessor posterior spine instrumentation systems (Lorenz et al. 1991). Additionally, they allow for earlier rehabilitation and obviate the need for postoperative external orthoses.

However, they are not without disadvantages. Pedicle screw insertion has a steep learning curve, and malpositioned screws can result in durotomies or neural injury if there is pedicle wall penetration. Their use increases operative time and cost. Additionally, they often require increased radiation exposure for both patient and surgeon, and they often obscure postoperative imaging. Additionally, the rigidity of fixation and placement of screws that violate adjacent segment facet joints may result in accelerated rates of adjacent segment degeneration. Despite these shortcomings, pedicle screws are still widely considered the gold standard for posterior spinal instrumentation today.

Anatomy of the Pedicle

The pedicle is the strongest part of the vertebra and has often been described as the "force nucleus" of the spine. The posterior elements of the vertebra converge and are linked to the anterior vertebral body and the anterior two columns of the spine by the cylindrical pedicle (Steffee et al. 1986). The pedicle is comprised of a strong shell of cortical bone with a cancellous bone core. Typically, the transverse width of the pedicle is less than the sagittal pedicle height with the exception of the low lumbar spine (Figs. 1 and 2).

Clinically, it is critical to understand the pedicle anatomy for accurate placement of screws within the pedicle. The coronal and sagittal angulation and the transverse diameter vary from level to level within the entire spinal axis. In the sagittal plane, cephalad and caudal angulation of the pedicle starts at neutral in the thoracic spine at T1 and increases to approximately 10° of cephalad angulation at T8 before decreasing back to 0° by T12 (McCormack et al. 1995). In the axial plane, beginning at T1, medial angulation decreases as one travels through the thoracic spine. In the lumbar spine, medial angulation in the axial plane increases from neutral at L1 to approximately 25–30° of medial angulation at L5. The width of the pedicle increases from L1 to S1 (Krag 1991), while the midthoracic pedicles (T4–T8) are typically considered the most narrow.

The inner diameter of the pedicle has been shown to account for 60% of the screw pullout strength and 80% of the longitudinal stiffness (Hirano et al. 1997). It has been correlated to the height of the patient. Typical screw sizes have been proposed as 4.5 mm diameter and 25–30 mm in length for T1–T3 and 4.5–5.5 mm in diameter and 30–35 mm in length from T4 to T10 (Louis 1996). Pedicles do have some plasticity and ability to undergo expansion however.

Many structures exist in close contact and surround the pedicle. Intrathecal nerve roots course along the medial aspect of the pedicle as the traversing root and have been shown to be 0.2–0.3 mm from the pedicle at T12 and touching the dura below L1. Exiting nerve roots then course beneath the pedicle and enter the neural foramen, occupying the ventral and rostral one third of the foramen (Benzel 1995a). Clinically, this is relevant as violation of the pedicle medially or caudally can injure the nerve root.

Design and Anatomy of the Pedicle Screw

The pedicle screw consists of a head, neck, body, and threads, each serving a distinct purpose (Fig. 3). The head of the pedicle screw facilitates attachment of the screw to longitudinal rods to provide fixation to adjacent segments or levels. Modern screws can have either monoaxial or polyaxial translating heads. Monoaxial screws have significant biomechanical advantages and reduce head-neck junction failure commonly seen in polyaxial screws; however some cadaveric testing has shown no differences between the two

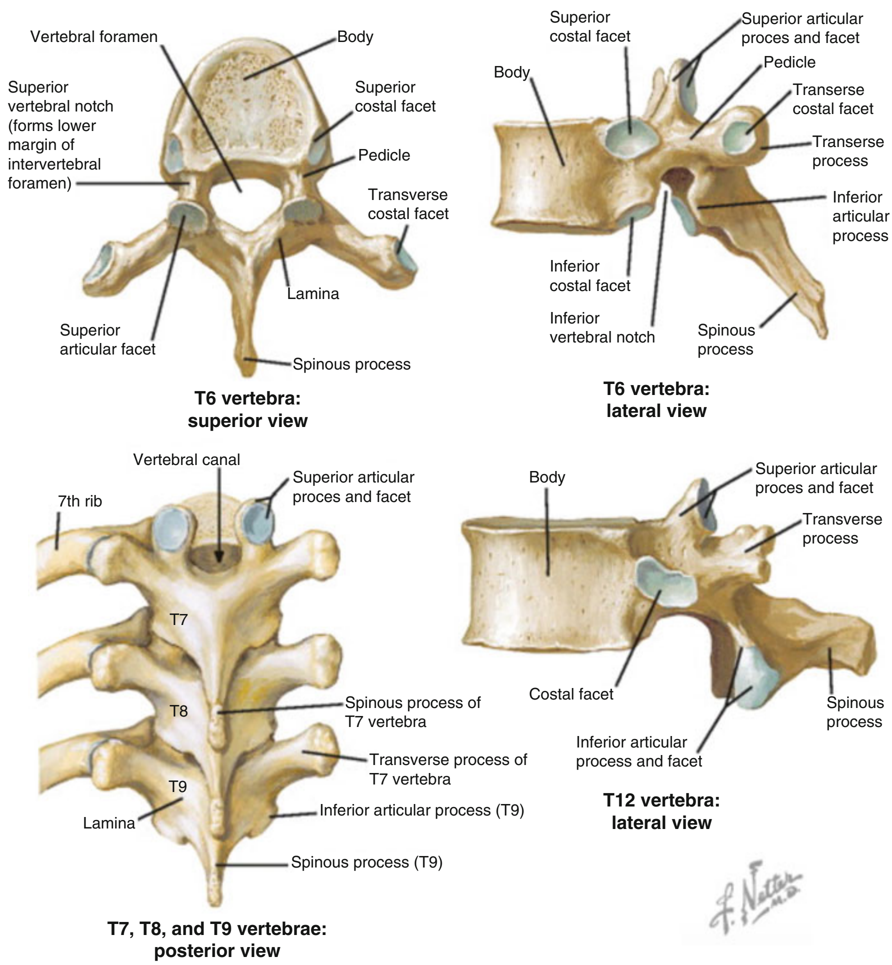

Fig. 1 Anatomy of the thoracic pedicle. (Reproduced from *Netter's Concise Orthopaedic Anatomy*, 2010 with permission from Elsevier)

in regard to construct stiffness (Fogel et al. 2003; Shepard et al. 2002). However, in exchange for this vulnerability to fatigue failure, polyaxial screws provide surgeons significant increased versatility and facilitate ease of rod to screw fixation and rod contouring across multiple levels. This helps limit implant-bone contact stress which can be increased when there is screw-plate or screw-rod mismatch. Additionally, the head-neck junction in polyaxial screws may be protective against pedicle screw breakage within a pedicle (Fogel et al. 2003).

The neck of the screw bridges the head to the body and is typically considered the weakest part of the screw. The body of a screw contains threads to obtain bony purchase. The bending or fatigue strength of a screw is proportional to the core (or inner) diameter of the screw body (Benzel et al. 1995). Liu and coauthors found fatigue strength of a screw increased 104% following a 27% increase in diameter (Liu et al. 1990).

The body of a screw can be conical or cylindrical (Fig. 4). Conical screws have been shown by some authors to have superior insertional torque with no difference in pullout strength (Kwok et al. 1996). However, other authors have advocated that conical screws, when backed out half to one full turn, lose significant purchase (Lill

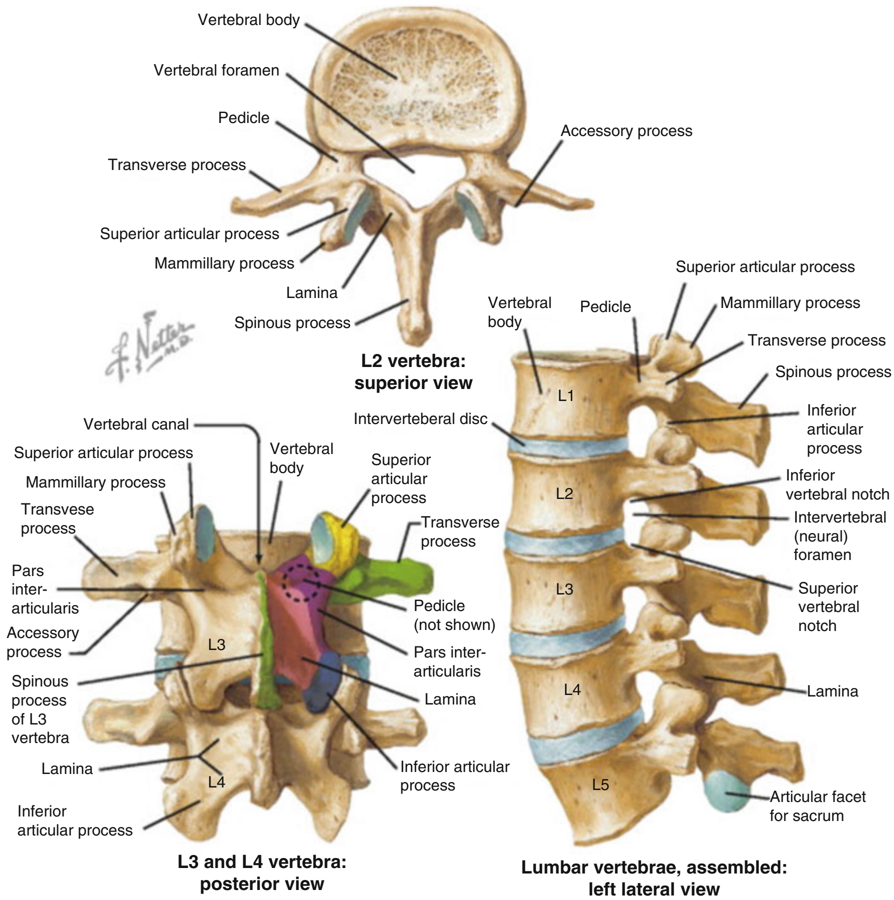

Fig. 2 Anatomy of the lumbar pedicle. (Reproduced from *Netter's Concise Orthopaedic Anatomy*, 2010 with permission from Elsevier)

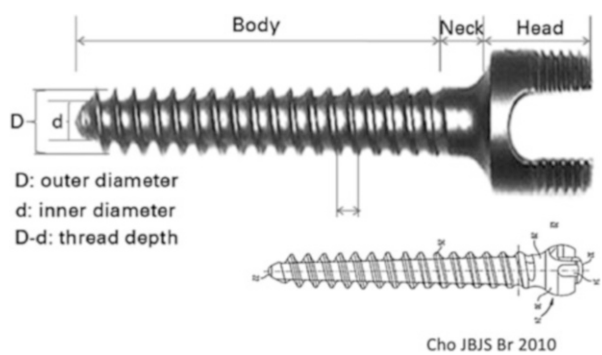

Fig. 3 Anatomy of the pedicle screw. (Reproduced from Cho et al. 2010 with permission from *J Bone Joint Surgery British*)

et al. 2006). The conical geometry of a screw may also be beneficial as 60% of the screw pullout strength is obtained from the cortical bone of the pedicle as opposed to the trabecular bone of the vertebral body (Shea et al. 2014). There has been significant debate between the two screw designs and their effectiveness with conflicting studies showing either no difference or biomechanical advantages of conical screws over cylindrical screws.

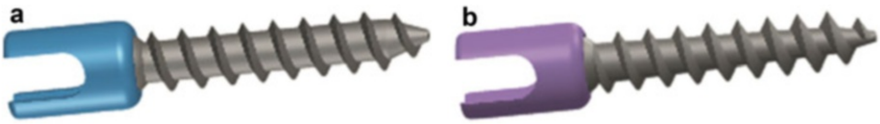

Fig. 4 Cylindrical versus conical screw design. (Reproduced from Shea et al. 2014 with permission from *Biomed Rest Int*)

The body of a screw can also be hollow to allow for screw passage over a wire in a cannulated fashion. This has been shown to be safe and effective but does decrease the bending strength of screws significantly when compared to solid bore-bodied screws. Threads are the portion of the body of the screw that allows for bony purchase. The difference in the inner and outer diameter of a screw is equal to the thread depth. The pitch is the distance between threads longitudinally across the body. Threads can be fully threaded along the entirety of the body of the screw or partially threaded across only a part and are typically cancellous type thread pattern given their fixation within the cancellous bone of the pedicle. However, some newer screw designs incorporate a dual-thread design with cortical threads dorsally along the screw to obtain cortical fixation within the pedicle and cancellous threads within the anterior column (vertebral body).

The pullout strength of screws is determined by the amount and quality of bone between the threads of a screw. Smaller thread pitches confer slightly stronger pullout strength as do deeper thread depths and more total threads (fully threaded). A general rule of thumb is that large outer diameters, small inner diameters, short pitch, and strong bone maximize pullout strength of the screw. These factors in combination with bone mineral density (BMD) help determine insertional torque of a screw which has been demonstrated to have a linear correlation with cycles to screw loosening (Zdeblick et al. 1993).

Modern pedicle screw systems typically have polyaxial heads, and diameters range from 4.5 to 8.5 mm for the thoracic and lumbar spines and lengths between 25 and 60 mm increments. They are typically made up of either stainless steel, titanium alloys, or cobalt-chrome-molybdenum alloys. Stainless steel (a nickel-chromium-iron alloy) was originally used due to its biocompatibility, low cost, and high stiffness in bending strength. However, modern screws have moved away from stainless steel as a material given their MRI incompatibility for postoperative imaging, higher corrosion rates, and the prevalence of nickel allergies. Titanium-aluminum-vanadium alloys (TiAlVa or Ti6-4) have been commonly used in bone implants given their lower modulus of elasticity than stainless steel that more closely approximates the modulus of bone. This has been hypothesized to decrease stress shielding of bone. Additionally, Ti alloys have high yield strength, are biocompatible, promote osteointegration, and are MRI safe. Cobalt-chromium alloys (CoCr) have also been more recently popularized given their superior stiffness and fatigue strength when compared to Ti alloys; however, they are often times significantly more expensive. Both titanium alloys and cobalt-chrome implants have low risk of corrosion when compared to stainless steel.

Various coatings have been added to screws in attempts to improve fixation. Hydroxyapatite coatings allow for bone ingrowth and provide thicker threads with increased initial friction and stability and have been shown to be useful in osteoporotic animal models (Sandén et al. 2001).

Biomechanics of Pedicle Screw Fixation

Spinal instrumentation functions to stabilize the spine, and its construct strength is determined by the mechanical load at which implants fail. Stiffness of a given spine construct is defined as the ability of fixation to resist axial compression as well as linear and circular moment forces.

These biomechanical characteristics of implants help define clinical success as implant failure typically leads to poor clinical outcomes.

Pedicle screws have been compared biomechanically to other dorsal spinal instrumentations. When compared to Harrington rods and Luque sublaminar wiring constructs, pedicle screw constructs have been shown to have greater torsional rigidity, overall construct stiffness and strength, and a significant reduction in the strain of flexion loading (Chang et al. 1989; Puno et al. 1987). They also have been shown to be superior in flexion-extension and lateral bending strength when compared to facet screw fixation (Panjabi et al. 1991a).

Dorsal pedicle screw systems allow for the surgeon to impart cantilever bending forces to the spine around a fixed moment arm which can provide distraction, compression, as well as tension band fixation of the spine. Since they extend past the instantaneous axis of rotation of the spine, they do allow for three-dimensional control of the spine. These constructs do become load bearing as well with adequate anterior column support for load sharing. Without additional anterior column support (i.e., corpectomy model), they can be vulnerable to construct failure (Yoganandan et al. 1990) (Fig. 5). Ensuring that maximal pedicle screw biomechanical advantage is achieved is critical to help avoid catastrophic implant failure or pullout.

Pilot holes in the dorsal pedicular cortex are used to begin cannulation of a pedicle and allow safe screw passage. Pilot hole size has been described to contribute to the insertional torque of a screw, critical for establishing both maximum pullout strength and preventing pedicle fracture. Battula et al. established the critical pilot hole size as 71.5% of the outer diameter of the pedicle screw was ideal in osteoporotic bone to optimize the balance between low insertional torque and high pullout strength (Battula et al. 2008).

Pedicle screws should be placed in a convergent fashion with medial angulation (Cho et al. 2010). This allows for a more lateral starting point resulting in longer screw lengths and reduced contact with the superior facet joint of the vertebra. Additionally, the convergence allows for an interlocking effect that increases resistance to torsional and lateral bending and up to 28.6% increase in pullout strength when compared to a straight-ahead technique (Barber et al. 1997).

They should also be placed parallel to the superior end plate to minimize screw breakage as the "straight-forward" technique paralleling the superior end plate has been shown to be biomechanically superior to the anatomic screw trajectory in the thoracic spine (Lehman et al. 2003; Youssef et al. 1999). An anatomic screw trajectory can be used as a salvage technique especially within the thoracic spine, when multiple screw attempts have been attempted and failed,

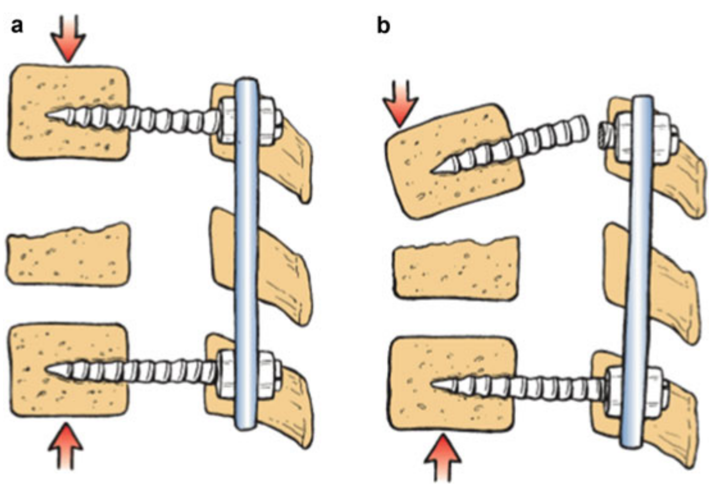

Fig. 5 Screw failure without anterior column support. (Reproduced from *Benzel's Spine Surgery*, 2017 with permission from Elsevier)

given its more cephalad starting point (Lehman et al. 2003).

Ideal screw length has been determined to be at least 60–70% across the body and total length of the pedicle. Screws placed to only 50% of anterior-posterior length of the pedicle had 30% less pullout strength than screws that spanned 80% of the width (Krag et al. 1988). Minimum engagement of at least the neurocentral junction is critical as it has been demonstrated to provide 75% of the maximum insertional torque of a screw (Lehman et al. 2003). Lateral fluoroscopy and a measured ball-tip probe can be used intraoperatively to aid in determining screw length, and care should be taken not to place screws longer than 80% of the length of the pedicle on imaging as this can penetrate the anterior cortex 10–30% of the time (Whitecloud et al. 1989a). While bicortical fixation spanning the entirety of the pedicle has been shown to improve pullout strength up to 25%, the dangers of anterior perforation to critical vascular structures are too great to advocate routine bicortical screw fixation. One exception is at the S1 level where anterior midline penetration and bicortical purchase are safe due to the capacious pedicle and absence of midline vascular structures at this level (Lonstein et al. 1999).

Ideal screw diameter should be such that the screw threads obtain purchase at the inner cortical portion of the pedicle which serves to decrease hoop stresses and cortical deformation. A screw diameter that is too large can result in risk of perforation or pedicle fracture, especially in weak or osteoporotic bone.

Indications for Use

Pedicle screws as dorsal spine instrumentation have many uses including fracture stabilization to allow early mobilization, even in the setting of posterior element injury, tumor instability, infection, spondylolisthesis, fusion assistance in degenerative conditions, and scoliotic deformity correction of the spine. Overall, they serve to provide rigid internal immobilization that allows mechanical support, early mobilization, and rehabilitation.

Contraindications to pedicle screw fixation include small pedicles, severe osteoporosis, and absence of adequate anterior column support (Orndorff and Zdeblick 2017).

Insertion Techniques

General

Placement of pedicle screws requires a thorough understanding of the anatomy of the pedicle for safe passage of a screw. In general, screws should not penetrate the pedicle and be placed away from critical neural and vascular structures as well as facet joints. An exception to this rule is the case of the "in-out-in" screw, typically reserved for severe deformity or congenital small pedicles. This method utilizes a far lateral entry point and is an extrapedicular tract through the transverse process into the pedicle (Perna et al. 2016). The dorsal cortex of the pedicle should be kept intact as much as possible to allow for maximal insertional torque and pullout strength (Daftari et al. 1994).

Freehand Technique

The pedicle screw entry point is identified by the surgeon using anatomic landmarks (described below) and careful review of preoperative imaging studies. Once a pilot hole in the dorsal cortex of the pedicle is made at the ideal starting point, typically a blunt-tipped gearshift probe can be used to cannulate the cancellous bone of the pedicle and allow for creation of a safe screw track within the cortical pedicle walls. Tactile feedback and experience are used in the freehand technique to establish this safe corridor. Typically, the pedicle probe is directed laterally for the first 15–20 mm of the pedicle before being removed and flipped 180° and then directed medially into the vertebral body once past the neurocentral junction. A sudden loss of resistance is often indicative of a cortical breach. The passing of the probe allows compaction of the cancellous bone during cannulation of the pedicle. Alternatively, a drill can be used to cannulate the pedicle without significant difference in biomechanical properties of final screw placement (George et al. 1991). A ball-tip feeler or another pedicle sounder can be used to palpate the anterior, superior, inferior, medial, and lateral margins of the pedicle to verify pedicle cortical integrity and provide a depth measurement. This however has variable accuracy even among expert surgeons.

A tap can be used to create screw threads within the pedicle prior to screw placement; however it is not required as most modern screw systems are self-tapping. Self-tapping screws do have the disadvantage of increased insertional torque and pedicle fracture risk. Tapping has demonstrated improved screw trajectory but variable effects on screw pullout strength (Erkan et al. 2010; Pfeiffer et al. 2006). Line-to-line tapping (using a tap the same size as the screw) is not recommended as it reduces screw purchase and pullout strength. However, using a tap 1 mm smaller in diameter has been shown to have the same pullout strength as untapped pilot holes (Carmouche et al. 2005; Chatzistergos et al. 2010). Tapping is typically performed just within the cortical bone of the pedicle cylinder and not extended into the cancellous bone of vertebral body as tapping cancellous bone reduces screw-bone contact and pullout strength (Chapman et al. 1996). The pedicle is then gently probed after tapping again to confirm no cortical perforations. A screw is then placed.

Freehand pedicle screw placement has a steep learning curve and requires detailed understanding of an individual patient's anatomy as it is essentially a blind technique. Accuracy rates for freehand pedicle screw placement have been reported between 59% and 91% in the lumbar spine and 45% and 97% in the thoracic spine (Perna et al. 2016).

Cervical

Traditionally, posterior instrumentation of the subaxial cervical spine has been limited to lateral mass fixation, sublaminar or interspinous wiring, and translaminar fixation. While pedicle screw fixation has been commonly described at C2 and C7 with good safety and efficacy, pedicles at C3–C6 have often been considered too dangerous to attempt screw fixation due to the proximity of the vertebral artery and the cervical nerve roots as well as the significant variability in the cervical pedicle morphology between patients.

Panjabi et al. demonstrated anatomically the ability for the cervical spine to accommodate pedicle screws (Panjabi et al. 1991b). They quantified the C2 pedicle to be the largest, the C3 to be the smallest, and the increasing pedicle size up to C7. At C4, an approximate 45° medial angulation in the coronal plane is required for insertion, and it decreases sequentially to about 30° at C7. The sagittal angle (superior-inferior) is determined by review of the preoperative imaging of the individual patient.

Cervical pedicle screw fixation has been shown to have superior biomechanical properties in regard to loosening and fatigue testing compared to other dorsal cervical spine instrumentation. Indications for cervical pedicle screw fixation have been described as trauma-induced cervical fractures and/or dislocations, multilevel instability, tumor resection, osteoporosis, or absence of dorsal spine elements (Pelton et al. 2012).

Typical cervical pedicle screw size is 3.5–4.5 mm in diameter and requires careful study of preoperative imaging for length determination and to ensure a safe passageway. For C2, the pedicle starting point has been well established as 2 mm lateral to the bisection of a horizontal line through the mid-pars of C2 and a line vertically between the midpoints of the facets. The trajectory is typically 30–45° medial angulation and 35° superior angulation. Typically at C2 cannulation of the pedicle is done with a drill as opposed to a larger gearshift probe. Laminoforaminotomy can be added to allow for palpation of the medial border of the C2 pedicle to confirm the trajectory.

For C3–C7, there is more heterogeneity in the starting point, but many authors describe it as slightly lateral to the midpoint of the lateral mass and superior (closer to the cephalad inferior articular process) (Fig. 6). Laminoforaminotomy can be added to allow for palpation of the medial border of the pedicle to confirm the trajectory.

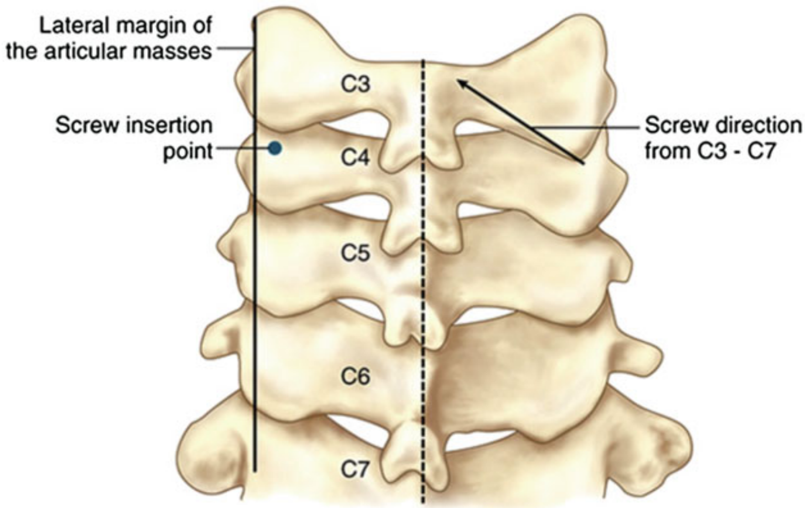

Fig. 6 Entry point for cervical pedicle screw placement. (Reproduced from Spine surgery. Operative techniques, 2008 with permission from Elsevier)

Cannulation of the pedicle can then be performed with a drill with set depth stops as the cervical pedicles are typically hard and hand-controlled instruments can slip or create too much downward pressure (Ludwig et al. 1999). At C7, some authors have described the pedicle entry point to be 1 mm inferior to the midportion of the facet joint above, with a 25–30° medial angulation and neutral sagittal plane (Ludwig et al. 1999).

Freehand technique is not usually recommended in the cervical spine, and image-guided assistance with fluoroscopy or computer-assisted stereotactic navigation is recommended as there is evidence to support improved safety (Ludwig et al. 2000).

Complications of cervical pedicle screw placement include misplacement, pedicle fracture, CSF leak, infection, nerve root injury, spinal cord injury, and vascular injury. Despite the serious consequences that can occur with cervical pedicle screw placement and previous anatomic studies suggesting vascular injury being the most likely complication of cervical pedicle screws, Kast et al. reported in their series of 26 patients with 94 total screws a 30% malposition rate with 9% being critical and 1 patient requiring revision surgery for nerve root symptoms. There were no vascular injuries. The authors described a significant learning curve for this technique that has also been reported by other authors (Kast et al. 2006; Yoshihara et al. 2013).

Thoracic

Much like the cervical spine, thoracic pedicle screws have a low margin of error due to the proximity of the spinal cord, lungs, esophagus, great vessels, and large intercostal and segmental vessels that are closely associated with the thoracic vertebrae (Vaccaro et al. 1995). Scoliosis increases the difficulty of accurate cannulation with altered trajectory from axial rotation and hypoplastic pedicles at the concavity of the curvature.

Progressing cephalad from T12, the starting points tend to be progressively more medial and cephalad up to T7, at which point they then shift to be more lateral and caudal (Parker et al. 2011; Xu et al. 1998; Chung et al. 2008). Typical medial angulation is 30° at T1–T2 and approximately 20° from T3 to T12. Sagittal angulation varies based on the level and patient, but a general rule is to cannulate the pedicle orthogonal to the dorsal spine.

Anatomic landmarks can also be used to identify the starting point and have been described as the midpoint of a triangle formed by the lower border of the superior articular facet, the medial border of the transverse process, and the pars interarticularis medially. Some authors have proposed a consistent starting point, as opposed to varying starting points, for the thoracic screws that are 3 mm caudal to the junction of the lateral aspect of the superior articular process and

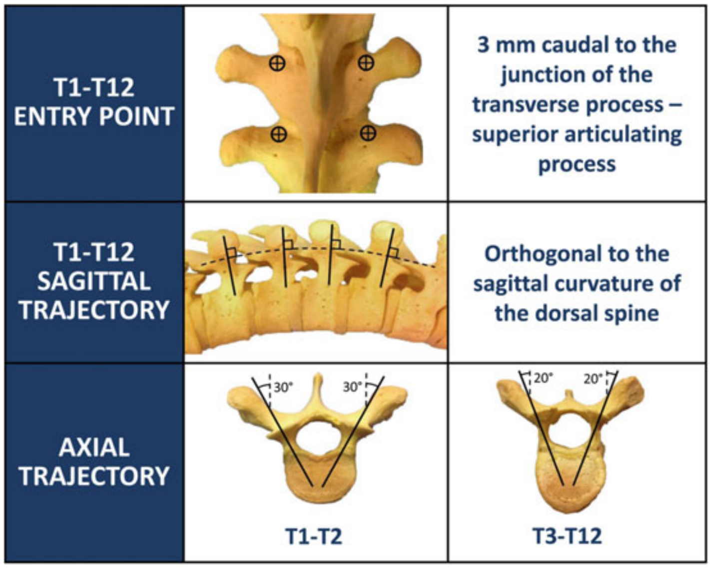

Fig. 7 One method of thoracic pedicle screw entry point localization. (Reproduced from Avila and Baaj 2016 with permission from *Cureus*)

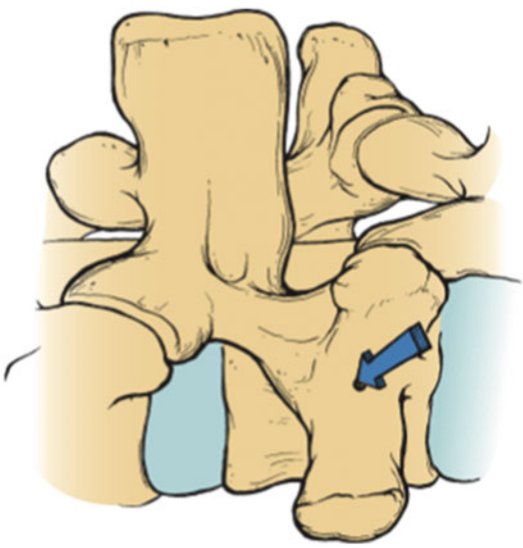

Fig. 8 Lumbar pedicle screw entry point. (Reproduced from *Benzel's Spine Surgery*, 2017 with permission from Elsevier)

transverse process (Avila and Baaj 2016) (Fig. 7). During decortication of the dorsal cortex, the surgeon can look for the pedicle blush of cancellous bleeding bone to ensure an accurate starting point.

The thoracic pedicles are most narrow between T4 and T9. Typical screw sizes are between 4.5 and 5.5 mm. Overall accuracy of freehand thoracic screws has been reported in the literature between 85% and 98% (Avila and Baaj 2016).

Lumbar

In the lumbar spine, the ideal pedicle screw starting point is the bony junction of the pars interarticularis, the transverse process, and the mammillary process or lateral facet joint. Alternatively, it can be described as the intersection of a vertical line bisecting the facet joint and a horizontal line through the midportion of the transverse process (Fig. 8). A laminoforaminotomy may also be used to palpate the medial wall of the pedicle from within the epidural space to allow guidance of the cannulation. Cannulation is performed as described above. Typical lumbar pedicle violations are lateral more commonly than medial or inferior.

In the lumbar spine, a novel pedicle screw tract known as the cortical screw has been described. It utilizes a more medial and caudal starting point and has a medial-lateral and caudal-to-cranial direction in order to increase screw-cortical bone contact to improve fixation in osteoporotic patients (Santoni et al. 2009). It does require some resection of the inferior spinous process and has been theorized to be weaker in axial rotation but does have advantages including potential increased fixation strength and less required muscle dissection (Rodriguez et al. 2014; Calvert et al. 2015). Screws are typically shorter in length and smaller in diameter but placed in a similar fashion as described above (Fig. 9).

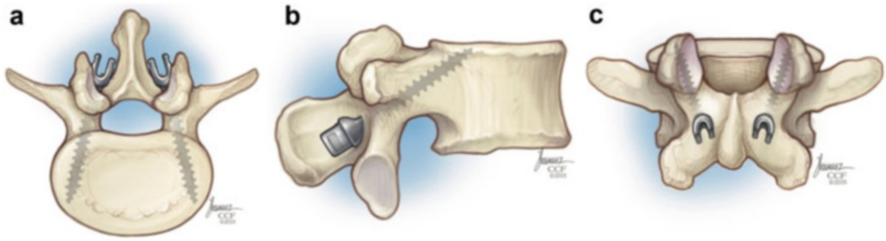

Fig. 9 Cortical screw trajectory for the lumbar spine. (Reproduced from *Benzel's Spine Surgery*, 2017 with permission from Elsevier)

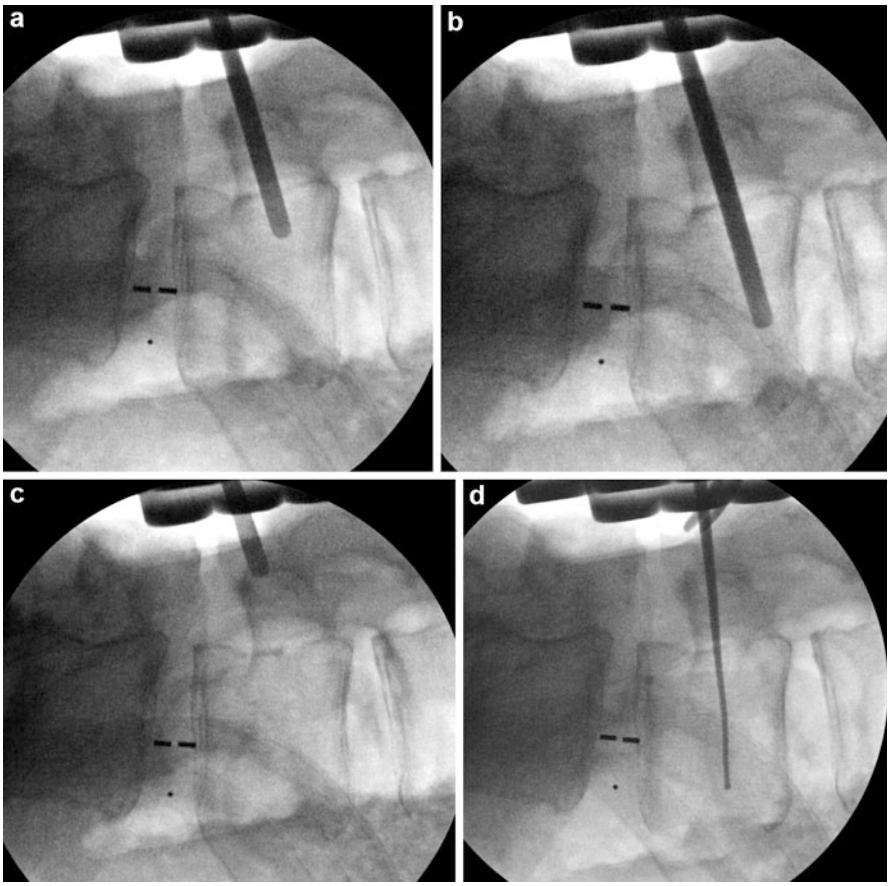

Fig. 10 Fluoroscopic-assisted screw placement. Cannulation was performed under lateral XR guidance followed by pedicle probing. Start points can be confirmed using AP and lateral fluoroscopic imaging

Fluoroscopic-Guided Technique

Intraoperative fluoroscopy can be used to aid pedicle screw placement as it provides 2D imaging of the entry point to the pedicle using radiographic markers as well as the trajectory of a pedicle to aid in cannulation. Using a combination of serial AP and lateral images with a parallel superior end plate, the pedicle cannula is started in the midpoint of the lateral most edge of the pedicle on the AP image and directed in the cranial-caudal direction of the pedicle on the lateral image (Fig. 10). While this can verify and increase accuracy rates of placement, it does not guarantee accurate trajectory.

Fluoroscopic-assisted pedicle screw placement accuracy rates have been reported to be similar to the freehand technique with one study reporting a 68.1% accuracy rate (Mason et al. 2014). 3D fluoroscopy software has more recently been implemented to allow consecutive images from different angles to create a 3D visualization to improve accuracy rates in fluoroscopic screw placement with the caveat of increased radiation exposure to the patient (Perna et al. 2016).

Percutaneous Screw Placement

Pedicle screws can also be placed via a Wiltse paraspinal approach percutaneously with the assistance of one or multiple of any of the abovementioned imaging modalities (fluoroscopy, intraoperative CT, computer-assisted navigation, or robotic-assisted systems). Purported advantages include reduced length of stay, earlier mobilization, decreased postoperative pain and blood loss, and earlier return to work. Principles for placement of pedicle screws percutaneously are no different than that of fluoroscopic or navigated screw placement and utilize imaging to guide the surgeon through the pedicle. Typically for fluoroscopic percutaneous screw placement, K-wires can be used after cannulation of the pedicle to maintain the pedicular track, and cannulated screws can be placed over these wires into the pedicle (Fig. 11).

Computer-Assisted Surgery and Navigation Technique

Computer stereotactic navigation techniques have recently been utilized to assist in pedicle screw

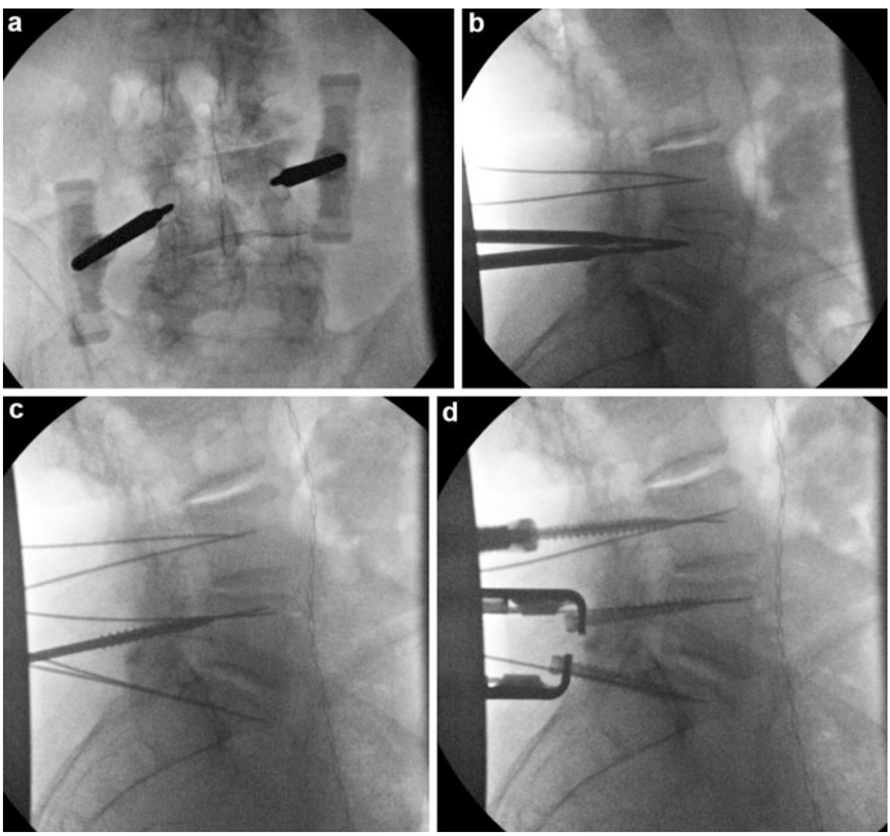

Fig. 11 Percutaneous screw placement: (**a**) Pedicle cannulation using a Jamshidi needle, (**b**) guide wire placement into cannulated pedicle, (**c**) cannulated tap using guidewire, and (**d**) cannulated screw placement over guidewires

placement by correlating a patient's preoperative or intraoperative acquired images to the patient's real-time surgical anatomy using fixed-point optical or electromagnetic markers. A computer model generation is then used to guide the surgeon in real time relative to the patient's anatomy (Fig. 12). Many authors have advocated for the safe and effective use of computer-assisted technology to make pedicle screw placement more reproducible by guiding the surgeon to the appropriate trajectory; however, effects on patient outcomes and benefit in reducing neurologic complications are unclear (Ughwanogho et al. 2012; Verma et al. 2010). The use of intraoperative cross-sectional imaging and referencing has gained popularity as it limits the inaccuracies that may develop due to patient repositioning when using computer-assisted navigation based on preoperative imaging. However, inaccuracy can still develop, and the further away one works from a reference frame, the less accurate the navigation system becomes (Scheufler et al. 2011). Disadvantages include increased radiation exposure to the patient, cost, and operative time. Overall accuracy of pedicle screw placement using navigated technology has been reported between 91.5% and 97.7%, which appear to be significantly higher than freehand or fluoroscopic placement rates, with the most benefits seen in the accuracy of thoracic pedicle screw placement (Puvanesarajah et al. 2014; Waschke et al. 2013). Additionally, repeat imaging using intraoperative CT scan can detect misplaced screws and allow the surgeon to correct them intraoperatively (reported at a rate of 1.8% in one series) (Van de Kelft et al. 2012).

Navigated optical technology has been expanded into robotic-assisted pedicle screw placement as well. Using preoperative or intraoperative imaging and appropriate patient fiducial markers, a robotic guidance arm can be used to guide pedicle cannulation trajectory and screw placement with increased reliability, reproducibility, and accuracy with potentially reduced radiation exposure. Disadvantages include significant cost, operative time, and learning curve.

Intraoperative Neuromonitoring (IONM)

Electrophysiological intraoperative testing can be useful to assess or confirm pedicle screw placement within a pedicle. Stimulation of pedicle screws or cannulation tools allows for electric currents to be transmitted into the pedicle. Cortical bone has a high resistance to electrical current resulting in minimal stimulation of nearby nerve roots if intact. Cortical breaches of the pedicle can allow for electric current to flow into soft tissues and allow for depolarization of nearby nerve roots which can be picked up on EMG recordings of specific myotomes in monitored extremities. Typically acceptable minimum thresholds of depolarization for safe screws are reported between 10 and 12 mA.

This technique of triggered EMG is useful in detecting misplaced pedicle screws as it has been shown to be highly specific; however, there is a high false-negative rate with only fair sensitivity with up to 22% of misplaced screws being

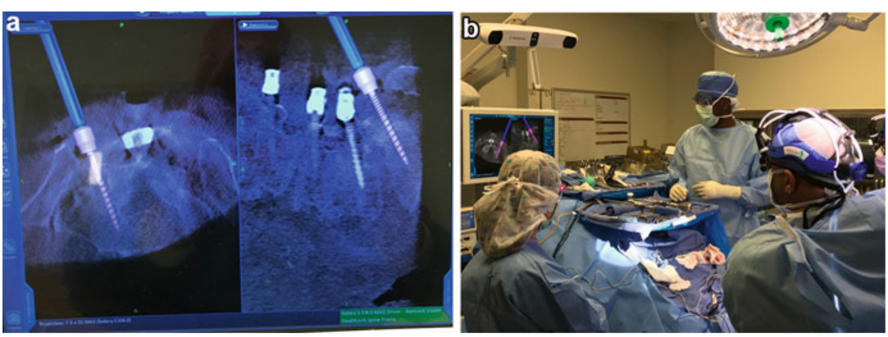

Fig. 12 Navigated screw placement and workflow

missed (Mikula et al. 2016). This technique, while primarily used for the lumbar spine given the lower extremity myotomes, has been described for monitoring thoracic nerve roots as well by selective myotome monitoring of the rectus abdominis for T6–T12 and the intercostal muscles from T3 to T6. This technique has been described for cervical screws as well as iliosacral screws.

While widely advocated for general use for safe placement of pedicle screws, there is a paucity of clinical data supporting improved clinical outcomes with routine IONM and EMG testing of screws (Reidy et al. 2001).

Pedicle Screw Outcomes

Pedicle screws first received US FDA approval as a class III device in 1995 but were frequently used prior to that throughout the world. Early transpedicular fixation screws were found by McAfee to have an approximate 80% survival rate at 10-year follow-up with 90% incidence of successful fusion in a mixed cohort of patients undergoing fusion with the early VSP device or the Cotrel-Dubousset transpedicular screw systems (McAfee et al. 1991). Yuan et al. established the safety of pedicle screw fixation in 1994 with a cohort of 303 surgeons with nearly 3,500 patients revealing very low rates (<1%) of implant failure, neurovascular injury, and dural tears in their cohort (Yuan et al. 1994). In 1998, the FDA downgraded pedicle screws to a class II device with increasing evidence of their safety.

Arthrodesis or fusion involves a surgeon-created artificial process of bone formation across a motion segment. It has a useful tool for spine surgeons to eliminate pathologic motion within the spine and provide stability to unstable segments. Fusion success is often directly proportional to construct stiffness and is dependent on a low-strain environment for primary or secondary bone healing and formation. Typically, a goal of <10% strain is desired in a construct. Wolff's law describes increased loads that result in increasing competitive strain. As bone adapts to load, bone formation occurs to add rigidity.

Pedicle screw constructs are ideal to provide a construct with adequate stiffness and provide a low-strain environment within the spine to allow for bone formation and fusion. Multiple studies have shown that pedicle fixation increases spinal arthrodesis rates. Louis in 1986 studied 266 patients in the lumbosacral spine who underwent instrumentation with pedicle screws and plates and found a 97% rate of successful fusion (Louis 1986). West et al. studied 62 patients undergoing spinal arthrodesis and found a 90% fusion rate and 2/3 of patients returned to full-time work (West et al. 1991). Zdeblick compared degenerative lumbar spine surgical patients with and without rigid pedicle screw instrumentation and found in short-term follow-up a significant difference in fusion rates (64% in uninstrumented patients and 95% in patients with pedicle screw and rigid rod instrumented fusions). However, clinical outcomes were not significantly different (87% good to excellent in uninstrumented, 95% instrumented) (Zdeblick et al. 1993; Zdeblick 1995). He also noted a significantly increased fusion rate in rigid screw-rod constructs when compared to semirigid plate and screw constructs. These findings were confirmed by Fischgrund et al. in 1997 in regard to improved fusion rates but no difference in overall clinical outcomes between instrumented and uninstrumented patients in the degenerative lumbar spine.

Complications

Pedicle screws, while consistently shown to be a safe method of posterior spinal instrumentation, are not without complications. Overall complication rates have been reported up to 25%; however, many are without significant clinical consequence, while others can be catastrophic.

Misplaced pedicle screws occur in various rates reported from 5% to 41% in the lumbar spine and from 3% to 55% in the thoracic spine and have been reported in up to 21% of posthumous cadaveric studies (Perna et al. 2016; Vaccaro and Garfin 1995b). The majority of misplaced screws are asymptomatic; however, medial-breached pedicle screws can cause nerve root injury or irritation that can be symptomatic and require screw revision (approximate incidence of 0.5%). Misplaced screws are typically classified as screws greater than 4 mm of breach (Gertzbein and Robbins 1990) or by the thoracic safe zone criteria of up to 6 mm lateral breach and 2 mm medial breach as described by Belmont et al. (2002). Most case series have shown that less than 2 mm of breach is not associated with complications (Gelalis et al. 2012; Belmont et al. 2002). Superior or rostral breach can lead to superior adjacent-level disc penetration resulting in poor screw purchase. Inferior breach can lead to nerve root or dural injury. Lateral screw placement can lead to segmental vessel injury and poor screw purchase. Nerve root injury can occur in 2.5–7.5% of cases, and removal of malpositioned screws can lead to resolution (Ohlin et al. 1994). Dural tears have been reported to be about 2–4% (Robert 2000).

Screw pullout or cutout from the pedicle is very common and dependent on not only technical surgeon-controlled factors of insertion but also implant design and host bone mineral density (Chapman et al. 1996; Zindrick and Lorenz 1997; Coe et al. 1990). Pedicle fracture can also occur resulting in loss of fixation or injury to surrounding neurovascular structures.

Implant failure or fatigue has also been reported, and early pedicle screw systems such as the VSP system reported rates as high as 17.5% screw failure (Whitecloud et al. 1989b). As technology has improved including material science and surgeon understanding of pedicle screw fixation techniques, this rate has dramatically decreased.

Posterior spinal instrumentation (and pedicle screws in particular) does increase rates of surgical site infections (SSIs) when compared to uninstrumented fusions approximately twofold from 3% to 6%.

Pedicle screw systems can also cause direct irritation symptoms to dorsal soft tissues as they are relatively raised compared to the dorsal elements of the spine. This can lead to wound breakdown or painful bursitis, especially in thin patients.

Augmentation

With a rapidly aging population, an increasing number of spine fusion procedures being performed each year with pedicle screw instrumentation, the issue of bone mineral density has become increasingly important for surgeons to be cognizant of when planning pedicle screw fixation. Many strategies have been developed to help improve pedicle screw fixation in the setting of osteoporosis or osteopenia via pedicle augmentation.

Polymethyl methacrylate (PMMA) bone cement has been described to augment pedicle screw fixation and can increase screw pullout strength in osteoporosis from 50% to 250% (Becker et al. 2008). Typically 1–1.5 mL of PMMA is placed into the vertebral body after pedicle cannulation followed by immediate screw placement to allow for hardening of the cement around the screw. Alternatively, some cannulated and fenestrated screw designs allow for cement delivery through the screw itself (Fig. 13). This technique, while effective, does pose a safety risk as cement extravasation resulting in emboli or neurovascular damage has been reported. Alternatively, biodegradable bone substitutes such as calcium sulfate or phosphate have been used in a similar fashion as a potentially safer alternative without the exothermic reaction of PMMA (Rohmiller et al. 2002; Bai et al. 2001).

Novel screw designs to aid in screw fixation in osteoporotic spines have also been described in

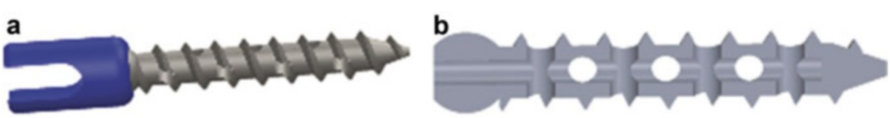

Fig. 13 Fenestrated screw design. (Reproduced from Shea et al. 2014 with permission from *Biomed Rest Int*)

an attempt to avoid PMMA use. Expandable screws that allow for finned expansion in the distal portion of a screw have been described with varying reports on the biomechanical properties of the expandable screw in different osteoporotic spine models (Cook et al. 2004; Koller et al. 2013; Gao et al. 2011; Liu et al. 2016; Lei and Wu 2006). A definitive advantage has not been shown over PMMA augmentation of traditional pedicle screws; however future research may demonstrate a clinical advantage.

Conclusions

Transpedicular fixation has been rapidly adopted among the spine surgery community in the last two to three decades due to its many advantages and ability to provide immediate three column stability to the spine and impart corrective forces all from a posterior-only approach. It is critical for surgeons to have a thorough understanding of the pedicle screw design options and flaws in order to achieve maximum fixation for a given scenario and avoid common complications of screw pull-out, pedicle fracture, or misplacement. Given the potential for catastrophic neurovascular injury during pedicle screw placement, adequate training must be obtained before attempting placement of these fixation devices. New technologies such as computer-assisted and robotic navigation can aid in the safe placement of pedicle screws, but their clinical advantage and value have yet to be definitively proven. As pedicle screw technology and design continue to evolve, their widespread adoption, safety, and efficacy are likely to continue to improve.

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