World Journal of Orthopedics

Online Submissions: http://www.wjgnet.com/esps/
bpgoffice@wjgnet.com
doi:10.5312/wjo.v5.i2.112

World J Orthop 2014 April 18; 5(2): 112-123
ISSN 2218-5836 (online)

REVIEW

Techniques and accuracy of thoracolumbar pedicle screw placement

Varun Puvanesarajah, Jason A Liauw, Sheng-fu Lo, Ioan A Lina, Timothy F Witham

Varun Puvanesarajah, Jason A Liauw, Sheng-fu Lo, Ioan A Lina, Timothy F Witham, Department of Neurosurgery, Johns Hopkins University School of Medicine, Baltimore, MD 21287, United States

Author contributions: Puvanesarajah V, Liauw JA, Lo SF, Lina IA and Witham TF contributed to research and writing of this manuscript.

Supported by Gordon and Marilyn Macklin Foundation

Correspondence to: Timothy F Witham, MD, Department of Neurosurgery, Johns Hopkins Hospital, 600 North Wolfe Street, Meyer 7-109, Baltimore, MD 21287, United States. twitham2@jhmi.edu
Telephone: +1-410-5022383 Fax: + 1-410-5023399

Received: November 30, 2013 Revised: February 11, 2014
Accepted: March 13, 2014
Published online: April 18, 2014

Abstract

Pedicle screw instrumentation has been used to stabilize the thoracolumbar spine for several decades. Although pedicle screws were originally placed *via* a free-hand technique, there has been a movement in favor of pedicle screw placement with the aid of imaging. Such assistive techniques include fluoroscopy guidance and stereotactic navigation. Imaging has the benefit of increased visualization of a pedicle's trajectory, but can result in increased morbidity associated with radiation exposure, increased time expenditure, and possible workflow interruption. Many institutions have reported high accuracies with each of these three core techniques. However, due to differing definitions of accuracy and varying radiographic analyses, it is extremely difficult to compare studies side-by-side to determine which techniques are superior. From the literature, it can be concluded that pedicles of vertebrae within the mid-thoracic spine and vertebrae that have altered morphology due to scoliosis or other deformities are the most difficult to cannulate. Thus, spine surgeons would benefit the most from using assistive technologies in these circumstances. All other pedicles in the thoracolumbar spine should theoretically be cannulated with ease via a free-hand technique, given appropriate training and experience. Despite these global recommendations, appropriate techniques must be chosen at the surgeon's discretion. Such determinations should be based on the surgeon's experience and the specific pathology that will be treated.

Key words: Thoracic vertebrae; Lumbar vertebrae; Pedicle screw; Fluoroscopy; Computed tomography

Core tip: Pedicle screws are currently placed in the thoracolumbar spine via three main techniques: free-hand, fluoroscopy guidance, and stereotactic navigation. Various studies have reported success with each of these techniques. However, it is clear that there is some difficulty in comparing such studies due to differing definitions of accuracy and methods of evaluation. Regardless, it is evident that image-assisted techniques provide some benefit when cannulating mid-thoracic vertebral levels and vertebrae that have altered morphology due to deformation from complex pathologies. However, a surgeon's ultimate decision must be based on individual experience and comfort with a given technique.

Puvanesarajah V, Liauw JA, Lo SF, Lina IA, Witham TF. Techniques and accuracy of thoracolumbar pedicle screw placement. *World J Orthop* 2014; 5(2): 112-123 Available from: URL: http://www.wjgnet.com/2218-5836/full/v5/i2/112.htm DOI: http://dx.doi.org/10.5312/wjo.v5.i2.112

INTRODUCTION

Since it was first described by Boucher[1] in the 1950s,

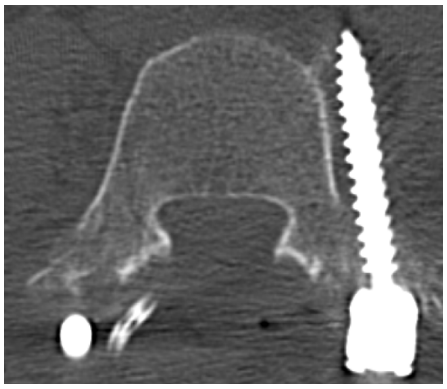

Figure 1 Axial computed tomography image depicting lateral breach of a pedicle screw intended for the L4 vertebrae.

used more extensively by Roy-Camille *et al*[2] later in the 1960s and 1970s, and then downclassified from an FDA Class Ⅲ to Class Ⅱ device in 1998, pedicle screw instrumentation has been steadily gaining popularity. This technology is now almost exclusively used when securing fusion constructs in the thoracolumbar spine, due to the purported improved fusion rates and rigidity afforded by these constructs[3-9]. Furthermore, studies have found that pedicle screws are biomechanically advantageous when compared to predecessors, including previous rod and hook systems[10-12]. Furthermore, pedicle screws are generally considered to be safer than other constructs, including sublaminar wiring, which often necessitate placement of instrumentation within the spinal canal with resultant neurological risk[13].

Initially, pedicle screws were used more frequently in the lumbar spine, where pedicles are thicker and thus easier to cannulate and generally have trajectories that do not skirt important neural or vascular structures. In particular, these lower spinal levels are less susceptible to serious neural damage from medially directed screws, as components of the cauda equina are much less prone to damage[14]. However, the inherent biomechanical advantages of pedicle screws led to their adoption in the thoracic spine. In the thoracic spine, there is admittedly a much lower margin of error, as errant screws are capable of injuring the spinal cord and other structures intimately related to the vertebrae, including the thoracic pleura, esophagus and intercostal and segmental vessels. Other structures within the thoracic cavity at risk include the thoracic duct, azygous vein, inferior vena cava, and aorta[15].

Placement of thoracic pedicle screws can be even more challenging as the thoracic vertebrae tend to be more anatomically varied than lumbar vertebrae when considering pedicle angles and attachment to the vertebral body[16]. This is particularly observed at the middle thoracic levels (T3-T9), which have the narrowest pedicles and have decreased space between the medial border of the pedicle and spinal cord[17-19]. Studies have estimated that screws placed in this region have a 1 mm translational margin of error and a maximal permissible rotational error of 5° off the pedicular axis, due to anatomically small pedicle diameters[17]. Apart from complexity associated with normal anatomy, pedicles can be difficult to instrument due to presenting pathologies. In patients with significant scoliosis, rotation and asymmetric compression of vertebrae can significantly alter pedicle anatomy and complicate pedicle screw placement[20]. Surgeons must be cognizant of such asymmetries intraoperatively as there is little margin for error in optimal screw placement in the thoracic spine. In reality, there are three general technique classes currently used by surgeons for placement of pedicle screws. Techniques can be classified as either free-hand (*i.e.*, without the aid of any imaging) or assisted with either fluoroscopy or stereotactic navigation technology. Free-hand technique relies on appreciation of normal and abnormal spinal anatomy, as the surgeon is entirely reliant on pre-operative imaging and intra-operative anatomical landmarks. Assistive fluoroscopy and navigation are helpful in that they guide pedicle screw placement more or less in real time, but are limited by time costs and in the case of fluoroscopy, significant radiation exposure.

Assistive techniques were designed to decrease the breach rate and improve pedicle screw placement accuracy. However, it is unclear whether assistive technologies actually decrease cortical breach and improve outcomes when compared to free-hand techniques. There have been many studies both illustrating institutional practices and pedicle screw placement accuracy, but due to differing definitions of breach and the lack of explicit control groups, many of these studies are difficult to interpret. In this review, we first define different methods of assessing cortical breach of pedicle screws and summarize the literature to date concerning pedicle screw placement accuracy by these various techniques. From this analysis, we hope to make conclusions regarding the necessity of assistive technology when placing pedicle screws in the thoracolumbar spine.

BREACH CLASSIFICATION

As mentioned previously, incorrect placement of pedicle screws (Figure 1) is a potential source of great patient morbidity. As such, there has been a large volume of data concerning how best to interpret pedicle screw cortical breaches. Several metrics have been applied to characterize cortical breach. These metrics vary slightly when applied in studies from different institutions, which adds an extra level of difficulty when comparing study results. However, they often all require the use of postoperative CT scans, which are generally accepted as being the most beneficial imaging study when judging pedicle screw accuracy[21-25].

In essence, variations of two grading scales are currently used to describe pedicle screw placement. In the first, which is often referred to as the Gertzbein scale, cortical breaches are described by the extent of extracortical screw violation. In this system, Grade 0 screws are

Table 1 Gertzbein classification[5]

Grade	Breach distance
0	0 mm (no breach)
1	< 2 mm
2	2-4 mm
3	> 4 mm

Table 2 Heary classification[22]

Grade	Breach
1	None
2	Lateral, but screw tip is within VB
3	Anterior or lateral breach of screw tip
4	Medial or inferior breach
5	Breach that requires immediate revision (due to proximity to sensitive structures)

those that are fully contained within a pedicle with no evidence of cortical breach, while higher grades are assigned in breach distances of multiples of 2 mm, where distance is measured from the medial border of the pedicle (Table 1)[5]. This scale was first applied when assessing screws placed from T8 to S1. During this initial application, the scale was intended to only assess the degree of spinal canal encroachment, as lateral screws were excluded from graded classification. A later study by Youkilis *et al*[14] slightly altered this classification to specify three different grades: Grade 1 screws did not show evidence of pedicle breach, Grade 2 screws breached 2 mm or less, and Grade 3 screws were those that breached more than 2 mm. However, recent studies have expanded on the original Gertzbein scale by applying it in every direction of possible cortical breach. One more recent study pioneered the use of this graded classification in each of six possible directions of cortical breach: anterior, lateral, medial, inferomedial, inferolateral, and superior. As such, each screw was given six different grades ranging from 0-3[25].

In practice, multiple studies have used variations of the Gertzbein classification and initial assertions from his pioneering study have been used to define pedicle screw accuracy. Gertzbein and Robbins noted that at the levels investigated by the authors, cortical breaches of greater than 4 mm were associated with neurologic deficits, leading them to conclude that this 4 mm range may constitute a "safe zone" for screws placed from T10 to L4[5]. Other studies have similarly termed breaches ranging from 2 mm medially and 4 mm laterally as a "safe zone"[26]. However, these safe zone definitions reflect opinions that have not necessarily been substantiated by specific data or facts.

A study conducted by Heary *et al*[22] noted that such grading of inaccurate screw placement may not be representative of clinical repercussions of cortical breaches. In particular, the thoracic spine is characterized by pedicle-rib complexes, where laterally penetrating pedicle screws can often be contained within the posterior rib. In fact, the study's authors considered lateral breach at mid-thoracic and lower thoracic regions to be sometimes optimal, as additional bony rib purchase could theoretically increase pullout strength. As such, at these levels, they advocated for the use of larger screws at these levels with the intention of lateral pedicle breach. At T1 or T2, where nerve root injury was a greater concern due to their role in upper extremity function, smaller screws were purposefully used to more easily keep screws within the pedicles. The Heary classification is summarized in Table 2. In essence, this classification scheme serves to stress that some screws require immediate removal due to proximity to critical structures (Grade 5), while other screws that breach laterally but are still contained within the rib may be acceptable (Grade 2). Additionally, this scheme was novel in that it was the first classification that graded anterior breaches, *i.e.*, those through the vertebral body (Grade 3). This scale is limited in that it doesn't consider the metric extent of breach in any direction, although this is somewhat rectified by the Grade 5 classification, which is ultimately most clinically relevant[22].

Other classification schemes include methods that grade screws as either "in" or "out" by using a cortical breach threshold defined by the amount of the screw's diameter that exists outside of the pedicle. The most notable example of this technique was illustrated in a study that defined breached screws as those where 25% of the screw diameter was located outside of the pedicle. In this study, it was theorized that CT-related metal artifact, which was estimated to distort perceived screw location by 25% of the diameter of the screw, could skew perception of cortical breach[27]. Importantly, this particular breach classification appropriately adjusts for screws that increase in size at lower vertebral levels. However, this classification is not often used due to the frequent usage of the Gertzbein classification scheme.

PEDICLE SCREW PLACEMENT TECHNIQUES

In the following section, we briefly review each of the three major classes of techniques: free-hand, fluoroscopy-guided, and stereotactic navigation. In these sections, we describe each technique and discuss some of the salient pros and cons associated with each technique. Furthermore, studies reporting isolated use of each technique are provided in a tabular format to demonstrate institutional success with a given technique and associated concerns. Comparison studies are also provided when available. For each study, accuracies and revision rates are listed. Some studies reported multiple accuracy measurements. For these studies, accuracies that were defined by the lowest margin of error were tabulated.

FREE-HAND TECHNIQUE

Free-hand pedicle screw placement relies on an intricate

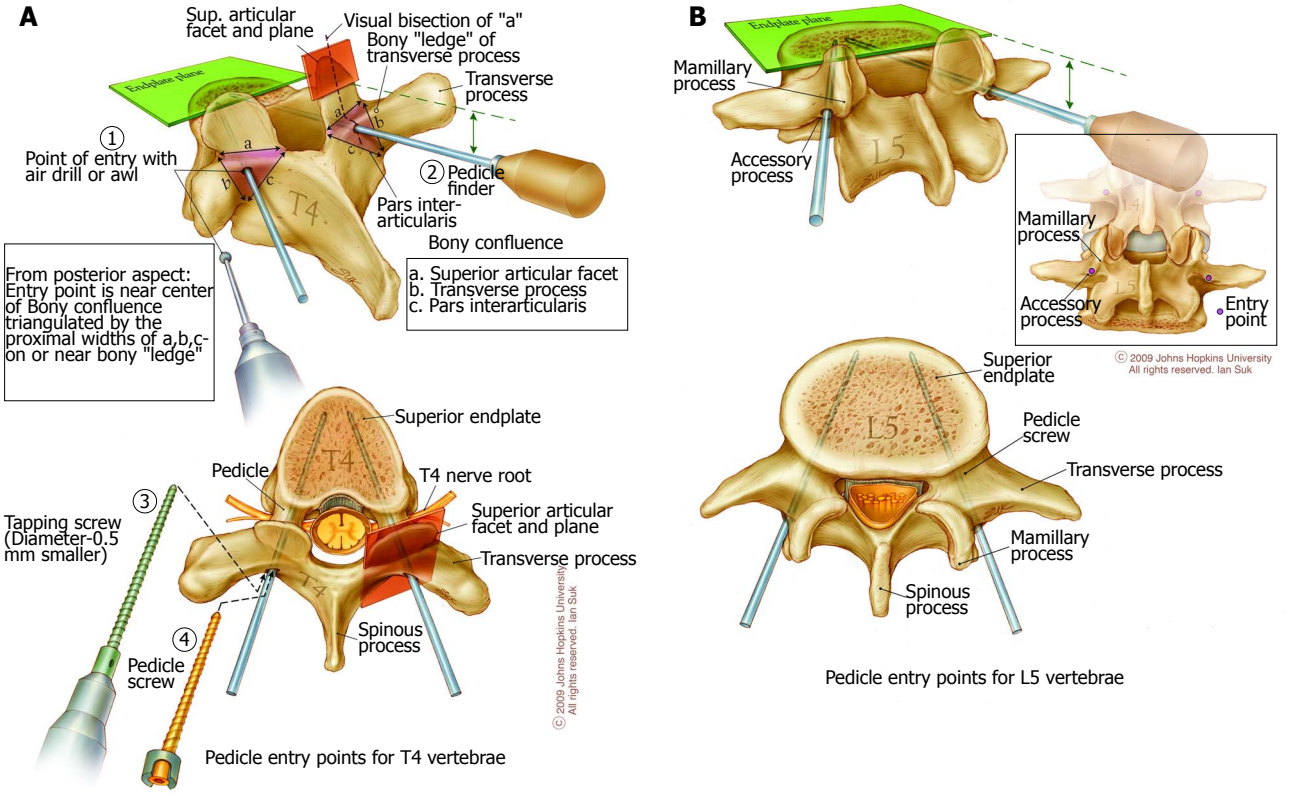

Figure 2 Artist depiction of the entry site used in the T4 (A) and L5 (B) vertebrae. Image has been reproduced (WITH PERMISSION) from manuscript published by Parker *et al*[27].

appreciation of the relationship of various anatomical landmarks at each level of the thoracolumbar spine. Analogous entry sites guided by differential anatomy are utilized for both the thoracic and lumbar spine. These anatomical sites are specified in such a way that allows direct trajectory along the pedicle axis, providing maximal screw stability. Before targeting an initial entry site, an intraoperative localizing radiograph is often performed to assess spinal alignment.

In the thoracic spine, the lower border of the superior articular facet, the medial border of the transverse process, and the pars interarticularis form a triangle, the center of which should be targeted for initial entry (Figure 2A)[27]. This has been variably reported as "the base of the superior articular process at the junction of the lateral one-third and medial two-thirds[28]." Within the thoracic spine, entry sites tend to be more medial and cephalad when progressing from T12 to T7. Above T7, entry sites tend to be more lateral and caudad[29]. In the thoracic spine, the "in-out-in" technique, where screws are intentionally placed more laterally to decrease the risk of medial breach and potentially increase bony rib purchase, is often also utilized. The "in-out-in" technique can also be used in situations where patients have congenitally small thoracic pedicles.

In the lumbar spine, the entry site is located at the intersection of the bony confluences of the pars interarticularis, the transverse process, and the mammillary process of the vertebrae that will be instrumented (Figure 2B)[27]. In patients with degenerative joint disease that precludes adequate pedicle screw stability at this location, an appropriate entry site would be one that is further medial, at the inferior border of the superior articular process[27].

After using a drill or awl to create a hole at the thoracic pedicle entry site, a trajectory that parallels the superior endplate is often used due to biomechanical superiority over more anatomical trajectories[30]. A curved gear shaft pedicle probe should first be directed laterally to avoid medial breach for approximately 15-20 mm. This distance represents a distance just past the widest portion of the spinal canal. At this point, the risk of medial breach is decreased significantly and the probe or drill can be directed more medially to prevent lateral breach. After assessing the integrity of the tract with a feeler, it is optional to first use a "tap" to determine if the screw tract is correct and appropriately directed, before using the final, larger screw.

There have been several studies that have investigated the accuracy of free-hand techniques for pedicle screw placement. Selected studies from the last ten years that reported case series where screw placement was only performed *via* the free-hand method are reported in Table 3. In these studies, accuracy rates ranged from 71.9% to 98.3%[5,9,23,26,27,31-33]. Of note, the lowest accuracies were associated with the mid-thoracic spine. In particular, Parker *et al*[27] found that screws inserted into T4 and T6 were most likely to breach, while Modi *et al*[26] found that screws inserted into the pedicles of T5-T8 had a greater incidence of breaches, particularly those that breached beyond a 6-mm wide safe zone. Furthermore, as expected, free-hand techniques have been noted to have a

Table 3 Summary of studies that have evaluated free-hand pedicle screw placement

	Most common pathology	Screw location	Number of patients	Number of screws	Accuracy (%)	Revision rate (%)
Gertzbein *et al*[5], 1990	Trauma	T8-S1	40	167	71.9	N/A
Liljenqvist *et al*[9], 1997	Scoliosis	T4-T12	32	120	75.0	N/A
Kim *et al*[23], 2004	Scoliosis	T1-T12	Unclear	577	93.8	0
Karapinar *et al*[31], 2007	Trauma	T10-L3	98	640	94.2	0
Schizas *et al*[32], 2007	Trauma	T1-T6	13	60	88.3	0
Kotil *et al*[33], 200	Trauma	T1-L5	Unclear	368	93.5	1.5
Modi *et al*[26], 2009	Scoliosis	T1-T12	43	854	93.0	N/A
Parker *et al*[27], 2011	Degenerative/Deformity	T1-S1	964	6816	98.3	0.8

N/A: Not applicable.

significant learning curve. In one particular study, accuracy rates were observed to increase when comparing the accuracy rate of the entire study (71.9%) to that of only the last 25% of placed screws (84.0%)[5].

The greatest benefit from usage of a free-hand technique lies in decreased radiation exposure and decreased procedure time. Both increased radiation exposure and operative time will be discussed at length in later sections that review both fluoroscopy and navigation techniques.

FLUOROSCOPY-GUIDED

Free-hand pedicle screw placement is essentially a blind technique that relies on correct identification of anatomical landmarks, surgeon experience, and reproducible technique to ensure adequate screw placement. As such, early on, the learning curve associated with usage of this technique became apparent, leading to increased surgeon-usage of image-assisted techniques. One such assistive technology is intraoperative fluoroscopy. Intraoperative fluoroscopy relies on serial X-rays to allow surgeons to view a screw's trajectory in real time. Fluoroscopy is used so often during pedicle screw placement that it has been referred to as the "conventional" method, perhaps reflecting its almost expected usage when attempting to employ free-hand techniques[34,35].

Fluoroscopy often utilizes a C-arm to take AP and lateral images parallel to the superior endplate. After an entry site hole is created using anatomic landmarks as described above, it is subsequently marked and the C-arm is utilized in either a lateral plane, anterior-posterior plane, or a combination of both at the level to be instrumented. Subsequent serial images guide surgeon screw placement.

Fluoroscopy has a much lower associated learning curve when compared to free-hand pedicle screw placement. In theory, the breach rate should be lower as fluoroscopy can give surgeons a chance to correct errors while the surgical field is still open. However, this added safety mechanism comes at a cost. The use of intraoperative fluoroscopy is associated with increased operating times and increased radiation exposure. Increased operating times are mostly due to the time it takes to request a technician and subsequently set-up a C-arm, including sterile draping and positioning of the device at the correct location. Additionally, each use of the C-arm requires movement of the equipment into the surgeon's working field, disrupting the workflow and thus increasing operating time. Apart from trivial decreases in efficiency, increased operating times are associated with very real clinical consequences for patients. Increased operating times have been associated with increased incidences of surgical site infection[36].

The radiation risk associated with fluoroscopy during pedicle screw placement has been well-studied in the literature. This risk exists for both the patient and the surgeon, the latter of whom arguably has a greater chance for later development of adverse side effects. Three studies have used anthropomorphic phantoms to approximate radiation exposure in patients treated with pedicle screws guided via intraoperative fluoroscopy[37-39]. In the most recent study, the study's authors first acquired radiation exposure data (including total duration of radiation exposure, parameters associated both AP and lateral images, and the cumulative dose-area product) from 20 patients undergoing procedures requiring pedicle screw instrumentation. Using this data, the authors subsequently treated anthropomorphic phantoms with embedded dosimeters with radiation beams to represent clinical operative exposure. From this experimentation, they were able to approximate the radiation dosage experienced by various organ systems. The study found that on average 4.8 pedicle screws were placed, with the average pedicle screw placement requiring 1.2 and 2.1 min of AP and lateral radiation exposure. When the applicable dose was applied to the anthropomorphic phantom, radiation doses were centered over L4, which the study found to be the most common location of screw placement. This resulted in a mean dose of 1.5 mSv[37], which is comparable to radiation doses postulated by other studies that have noted mean effective doses of 6.8 mSv[38] and 1.0 mSv[39], which as expected are somewhat dependent on the number of pedicle screws used and the time it takes to seat a pedicle screw, the latter of which can be directly attributable to surgeon experience. Perisinakis *et al*[37] estimated that the adjusted risk of fatal cancer in patients receiving an average of 4.8 pedicle screws at the L4 level was about 110 per million, which when compared to a spontaneous cancer risk of 200000 per million is fairly insignificant.

This data suggests that radiation exposure during fluoroscopy is not a relevant consideration when evaluating

Table 4 Summary of studies evaluating fluoroscopy-aided pedicle screw placement

	Most common pathology	Screw location	Number of patients	Number of screws	Accuracy (%)	Revision rate (%)
Halm *et al*[44], 2000	Scoliosis	T10-L4	12	104	81.7	8.3
Belmont *et al*[7], 2001	Scoliosis	T1-T12	40	279	57.0	5.0
Carbone *et al*[45], 2003	Trauma	T1-T12	22	126	86.5	N/A
Kuntz *et al*[46], 2004	Trauma	T1-T12	28	199	27.6	N/A
Vougioukas *et al*[47], 2005	Degenerative	T1-T12	41	328	78.0	0.0
Amato *et al*[48], 2010	Degenerative	L1-S1	102	424	92.2	8.8

N/A: Not applicable.

the merits of this assistive modality during pedicle screw placement. However, it must be noted that these cancer risks are heightened in pediatric populations and patients who have much larger numbers of pedicle screws placed. As such, patients with adolescent idiopathic scoliosis and other significant deformities should be considered at increased risk, although likely still significantly less risk than that incurred from daily living[37].

Although patient radiation exposure is a significant consideration, it is arguable that cumulative surgeon radiation exposure from years of instrumentation procedures is a much more pressing concern. In one study that placed a dosimeter both inside and outside of the thyroid shield to approximate whole-body and thyroid radiation doses, respectively, it was determined that within ten years, a thirty-year old surgeon would supersede the maximum allowable whole body radiation dosage[40]. However, this study did not take into account the dose reduction that occurs through wearing a lead apron, which is estimated to be around 94%[41]. The study further found that thyroid doses were significantly lower than the threshold suggested by the same organization. Hands, on the other hand, are subjected to radiation doses without any real lead protection and undoubtedly receive a significant radiation dose[42].

In recognition of this potential safety issue, studies have postulated that minimizing fluoroscopic time and moving away from beam sources may be indicated to decrease surgeon radiation exposure[43]. Hand doses can be reduced with lead impregnated gloves, which reduce radiation exposure by 33%[42]. Though most studies have focused on surgeon radiation exposure, it is also important to note that other individuals on a surgical team are at similar risk for heightened radiation doses[43].

Studies have generally shown that accuracy rates of screws placed with this technique have ranged from as low as 27.6% to above 90%. These results are summarized in Table 4, which lists a series of publications that reported institutional experience with only fluoroscopic guided pedicle screw technique[7,44-48]. The accuracy range observed here is extended by a study by Kuntz *et al*[46], which reported absence of cortical breach in only 27.6% of studied screws. This rate is substantially lower than that reported in other studies that used intraoperative fluoroscopy to guide thoracic screws, owing to the fact that a majority of the screws included in this study were placed in the mid-thoracic region (T3-T9), a region with proven screw placement difficulty, and that many of the screws were purposefully chosen such that their diameters were larger than corresponding pedicle widths (for purported increased pullout strength).

Interestingly enough, the combination of narrow pedicles and difficult pedicle trajectories in the mid-thoracic spine again resulted in the greatest number of misplaced pedicle screws. The same Kuntz study noted that "high-risk medial wall perforation" was observed much more frequently when trying to place screws into the pedicles of T3-T9[46].

In addition to its use with open techniques, fluoroscopy is often also used with percutaneous pedicle screw placement. Percutaneous screws placed under fluoroscopic guidance have been shown to be as least as accurate as screws placed with open techniques, if not more accurate[49-52].

IMAGE-GUIDED OR STEREOTACTIC PEDICLE SCREW PLACEMENT

Stereotactic neurosurgical techniques were first applied during cranial procedures before being applied in the spinal axis, an inherently complex structure due to numerous degrees of freedom. Stereotactic guidance requires initial image registration for eventual computer model generation. This computer-generated structure must then be matched to the actual operating room volume space by way of fiducial markers placed on prominent bony landmarks, a spinal reference marker, and subsequent matching of these points to analogous points on the generated image. This process was originally accomplished with a pre-operative CT and then surgeon matching of points on the computer-generated image to anatomical points on the patient[53]. From the reference marker, "virtual" fiducial markers, and strategically placed cameras in the operating room, a surgeon's instruments can be triangulated and displayed relative to a 3D reconstruction displayed on a screen within the operating room. This allows the surgeon to plan screw entry site and adjust the trajectory of screws in real-time.

However, with increased use of fluoroscopy and more recently intraoperative CT scans, both the reference marker and fiducials are now often placed on bony landmarks prior to image acquisition within the operating room. This prevents any inaccuracy that might result

from re-positioning of the patient that undoubtedly occurs between pre-operative CT scans and transition to the operating table[54]. Fluoroscopy, as it was first pioneered, only captures images in the lateral and AP planes. As such, appreciation of pedicular structure is typically limited to only two planes. The development of intraoperative 3D imaging techniques has given surgeons the ability to navigate in a truly three-dimensional fashion, without the inaccuracy of images generated by preoperative scans. Recently, intraoperative CT scanners and O-arms have been used more frequently for pedicle screw navigation purposes.

In its infancy, navigated pedicle screw placement was limited by poor image registration due to re-positioning after pre-operative CTs and computing power. However, currently, these limitations are relatively non-existent with the development of sophisticated intraoperative CT and O-arm technology. Regardless, there are still some clear limitations associated with the technique. For example, image-guided techniques have been associated with decreasing accuracy with increasing distance from the spinal reference marker[54-55]. Furthermore, it is reasonable to believe that the process of tapping vertebrae and placing screws can cause motion of vertebral segments relative to one another and can also result in advertant movement of the reference arc. To circumvent any errors caused by such motion, more frequent auto registration verification steps must be taken, which can add time to procedures. Scheufler *et al*[55] further noted that certain inaccuracies pertaining to CT image registration exist with respiration, which moves the entire vertebral column. This was most notable at the mid-thoracic levels. Theoretically, ventilation could be halted during image acquisition, although this carries its own risks.

One of the more prominent criticisms of image-guided techniques centers on associated workflow interruption and additional time costs when compared to free-hand techniques. Much time is spent on vertebral registration and assessing image quality, which can vary from patient to patient. However, some studies have noted that surgical navigation systems used by well-trained operating room staff can decrease surgical time when compared to usage of intraoperative fluoroscopy[56]. Another possible criticism is the exorbitant cost associated with purchase and installation of an image-guided surgical suite.

As mentioned earlier, fluoroscopy-guided pedicle screw placement has been associated with increased radiation exposure to both the operating room staff and the patient. Since image registration occurs fairly infrequently, as compared to fluoroscopy shots, there is very little radiation exposure to operating room staff and the surgeon. In particular, there is theoretically much less radiation exposure to the surgeon's hands, which are probably the most exposed area during fluoroscopic-guided techniques. During image registration via intraoperative imaging, both the surgeon and operating staff can move safely away from the radiation source. However, these techniques, which often rely on CT-based image registration, still result in increased radiation exposure to the patient. Recent technological developments, such as helical CT, can potentially limit this radiation risk to the patient[57].

Studies evaluating the individual use of image-guided techniques have reported accuracy rates ranging from 91.5%-97.7% (Table 5)[14,53-55,58-62]. These rates are subjectively much higher on average than the rates observed for both free-hand and fluoroscopy-guided screw placement. Again, perforation rates were higher in the mid-thoracic spine[14].

Navigation techniques have also benefited from direct comparisons with other techniques in both retrospective and prospective institutional studies with multiple treatment groups (Table 6)[34,35,56,63-66]. These studies have almost unilaterally shown that image-guided techniques have improved accuracy when compared to fluoroscopy-based[34,35,56,64-66] and free-hand techniques[63]. Of interest, one study by Waschke *et al*[66] directly calculated the improvements in accuracy that were observed with CT-navigated pedicle screw placement in both the thoracic and lumbar spine. In the lumbar spine, accuracy improvements were marginal, with a reported accuracy of 96.4% with CT-navigation, as compared to 93.9% with fluoroscopy. However, in the thoracic spine, CT-navigation was associated with a breach rate of 4.5%, while fluoroscopy resulted in breached screws 21.0% of the time, suggesting that image-guided techniques have much higher benefit when applied in the thoracic spine. CT-navigation may similarly be advantageous over fluoroscopy in the context of minimally invasive screws[67].

DISCUSSION

Regardless of technique, pedicle screw-based instrumentation remains one of the strongest posterior fixation techniques for the thoracolumbar spine. In essence, it is only limited by the risk of patient morbidity due to errant screw placement. As such, techniques such as fluoroscopy and stereotactic screw placement have come in vogue to improve on free-hand technique. In combination, all three techniques have resulted in impressive pedicle screw accuracies. A recent meta-analysis investigating studies published between 1990 and 2009 demonstrated that 89.2% of 7533 pedicle screws were placed accurately[68].

For the most part, pedicle screw placement technique as it is practiced today anecdotally appears to be based more or less on institutional practices and surgeon preference. Understandably, there has been a recent push across the field for usage of more guided techniques, to instill confidence and assure the best patient outcome. In keeping with this message, published data has generally reported improved pedicle screw accuracy with such techniques. However, it must be noted that accuracy data from studies must be interpreted. As mentioned before, studies invariably have different metrics for assessing screw accuracy and thus may present improved institu-

Table 5 Summary of studies evaluating navigation-aided pedicle screw placement

	Most common pathology	Screw location	Number of patients	Number of screws	Accuracy (%)	Revision rate (%)
Idler *et al*[53], 1996	Postlaminectomy instability and spinal stenosis	L1-S1	30	139	95.7	N/A
Youkilis *et al*[14], 2000	Assorted	T1-T12	52	224	91.5	N/A
Bledsoe *et al*[58], 2009	Cervical deformity	T1-T3	34	150	93.3	0
Nottmeier *et al*[59], 2009	Unclear	T1-S1	184	951	92.5	N/A
Oertel *et al*[60], 2011	Degenerative Disease	T8-S1	50	278	96.8	0
Scheufler *et al*[55], 2011	Idiopathic and Degenerative Deformity	T2-S1	46	Ta-243 LSb-542	T-96.5 LS-94.4	4.3
Dinesh *et al*[54], 2012	Metastasis	T1-T12	43	261	97.3	1.5 (intraop) 1.2 (postop)
Lee *et al*[61], 2013	Degenerative Spondylolisthesis	T1-S1	178	932	96.8	1.4
Ling *et al*[62], 2013	Degenerative Disease	T5-S1	92	467	95.3	1.3 (intraop)

T: Thoracic spine; LS: Lumbosacral spine; N/A: Not applicable.

Table 6 Studies comparing navigation methods to either free-hand or fluoroscopic methods

	Most common pathology	Screw location	Method	Patients (*n*)	Screws (*n*)	Revision rate (%)	Accuracy (%)	Method	Patients (*n*)	Screws (*n*)	Revision rate (%)	Accuracy (%)	Study design
Amiot *et al*[34], 2000	Degenerative disease	T2-S1	CT-navigation	50	294	0	95	Fluoroscopy	100	544	2	85.0	R, P
Laine *et al*[63], 2000	Spinal stenosis	T8-S1	CT-navigation	41	219	4 (intraop)	95.4	Free-hand	50	277	0 (intraop)	86.8	P
Rajasekaran *et al*[56], 2006	Deformity	T1-T12	Fluoroscopy-navigation	17	242	N/A	98	Fluoroscopy	16	236	N/A	77.0	P
Merloz *et al*[35], 2007	Trauma and degenerative disease	T8-L5	Fluoroscopy-navigation	26	140	N/A	95	Fluoroscopy	26	138	N/A	87.0	R
Tormenti *et al*[64], 2010	Deformity	T1-S1	CT-navigation	12	164	0	98.8	Fluoroscopy	14	211	7.1	94.8	R
Shin *et al*[65], 2013	Degenerative disease	T9-S1	O-arm navigation	20	124	5 (intraop)	91.9	Fluoroscopy	20	138	5 (postop)	87.7	P
Waschke *et al*[66], 2013	Trauma and degenerative disease	T1-S1	CT-navigation	505	2422	1.2	L-96.4 T-95.5	Fluoroscopy	501	2002	4.4	L-93.9 T-79.0	R

R: Retrospective; P: Prospective; N/A: Not applicable.

tional accuracies with certain techniques solely due to differing interpretations of misplacement or breach. A clear example of this is the usage of accuracy to variably represent everything from placement of the entire screw within the pedicle to placement of the screw within a six millimeter wide "safe zone" (four mm laterally and two mm medially)[26]. The concept of a "safe zone" has been based on previous assertions by Gertzbein *et al*[5] that there is a total of 4 mm of allowable medial pedicle screw encroachment within the lower thoracic spine and lumbar spine consisting of 2 mm of epidural space and 2 mm of subarachnoid space. In the thoracic spine, this "safe zone" has been generally decreased to 2 mm to reflect both reduced margin of error[17] and to adjust for cortical expansion and benign pedicle fracture[7]. Regardless of previous literature examinations of this notion of a "safe zone", it is important to point out that the "safe zone" is fairly arbitrary and warrants discussion of the true necessity of its existence as a conceptual entity. A more realistic measure would be revision rates or patient morbidity, which are direct clinical entities that are not reflected in reported accuracy rates. Both morbidity and revision rates are much lower than reported accuracy rates, suggesting that perhaps ever increasing accuracy rates might be associated with diminishing returns in terms of patient outcomes. One last consideration that provides added difficulty in comparing and interpreting reported accuracies is that accuracy rates have a large dependence on the relative proportions of various instrumented levels. A preponderance of lumbar screws, for example, invariably inflates accuracy as these vertebrae tend to have much larger pedicles that are easier to instrument when compared to those in thoracic vertebrae. Due to these reasons, systematic reviews are not completely effective at painting a complete picture when comparing pedicle screw placement, although several have been published[69,70].

As alluded to earlier, the study of pedicle screw placement techniques and their relative accuracies is important in terms of revision of faulty screws. In the literature, screw revision rates are low and generally occur less than once out of every forty pedicle screws placed[55,64,71-73].

However, screw revision can be difficult and time-consuming, as the faulty screw track often hinders effective screw repositioning[61]. When considering screw revision time and possible decreases in biomechanical stability, it is reasonable to use image-guided techniques when there is a high chance of failure.

Considering this information, we have fairly specific recommendations concerning pedicle screw placement and choice of technique. It is the authors' opinion that free-hand pedicle screw placement still has a definite role in modern day posterior instrumentation. It is difficult to argue against this technique when used in either the lumbar spine and/or in patients with no significant deformity. Anecdotally, these patients would derive less benefit from image-based techniques that require more radiation exposure and operating room time. Placement of lumbar screws have a much larger margin of error when compared to thoracic screws, due to pedicle size and the transition of the spinal cord into the cauda equina[17]. However the free-hand technique has demonstrated reasonable results with regards to accuracy in thoracic pedicle screw placement in the hands of surgeons well versed with the free-hand technique. It is particularly important to mention that accuracy with the free-hand technique increases with experience[5], as noted earlier, although a recent study demonstrated a 15% breach rate of thoracic pedicle screws when placed by neurosurgery residents, a rate that is comparable to reported accuracies and suggests that less experienced surgeons may be able to place pedicle screws with high accuracy[74]. Regardless, the free-hand technique may be limited in patients with complicated pathology that can make it difficult to accurately place screws.

In patients with significant deformity or a requirement of mid-thoracic instrumentation, image-guided techniques are recommended. In the literature, high accuracies have in fact been demonstrated in patients with severe scoliosis when using the free-hand technique. However, this can be extremely challenging as even with the aid of pre-operative imaging as curve correction can alter the expected trajectory of non-anatomic pedicles. Thoracic screws similarly pose challenges due to inherent anatomical characteristics. This is particularly evident in the mid-thoracic spine, which is characterized by narrow pedicles[17-19]. As expected, this region is characterized by the lowest accuracy rates[14,26,27,46]. This has real clinical consequences, as the mid-thoracic region is also associated with a smaller "safe zone" in terms of injury to sensitive structures. Usage of pedicle screws at the T4-T9 vertebral levels has an increased risk of injury to both the cord and the aorta[75].

Regardless of technique, there are a number of methods by which pedicle screw placement accuracy can be improved. Such methods include saline irrigation of drilled pedicles to detect breaches[76], endoscopic visualization[77], and electromyographic monitoring[78]. Additionally, with the advent of O-arm and intraoperative CT technology, surgeons can now radiographically assess pedicle screw placement before full closure of the patient, albeit at increased radiation risk to the patient.

Usage of image-guided techniques has clear benefits due to improved pedicle visualization. However, it may not be needed and might ultimately result in an added hindrance that can be avoided with free-hand pedicle screw placement without endangering the patient. The benefits and disadvantages of each technique must be appropriately weighed on a patient-by-patient basis in order to establish the best possible treatment strategy that both limits morbidity and ensures positive patient outcomes. Ultimately, it is the surgeon's experience with a particular screw technique that determines his or her ability to accurately place pedicle screws.

CONCLUSION

There are many published studies evaluating the use of free-hand technique, fluoroscopy-guidance, and stereotactic navigation in placing thoracolumbar pedicle screws. Between studies, assessment of screw accuracy varies significantly, which adds difficulty when interpreting and comparing them. When considering time expense and radiation exposure, it is our recommendation to utilize free-hand techniques when instrumenting regions outside of the mid-thoracic spine in pathologies without significant deformity. Screws placed in the mid-thoracic spine and/or in spines with significant deformity should be guided stereotactically to ensure accuracy. However, these are general recommendations and ultimately appropriate screw placement techniques should be determined on a case-by-case basis, taking into account a surgeon's experience.

REFERENCES

1 **Boucher HH**. A method of spinal fusion. *J Bone Joint Surg Br* 1959; **41-B**: 248-259 [PMID: 13641310]

2 **Roy-Camille R**, Saillant G, Berteaux D, Salgado V. Osteosynthesis of thoraco-lumbar spine fractures with metal plates screwed through the vertebral pedicles. *Reconstr Surg Traumatol* 1976; **15**: 2-16 [PMID: 968155]

3 **Gaines RW**. The use of pedicle-screw internal fixation for the operative treatment of spinal disorders. *J Bone Joint Surg Am* 2000; **82-A**: 1458-1476 [PMID: 11057475]

4 **Hartl R**, Theodore N, Dickman CA, Sonntag VKH. Technique of thoracic pedicle screw fixation for trauma. *Operative Techniques Neurosurg* 2004; **7**: 22–30 [DOI: 10.1053/j.otns.2004.04.005]

5 **Gertzbein SD**, Robbins SE. Accuracy of pedicular screw placement in vivo. *Spine* (Phila Pa 1976) 1990; **15**: 11-14 [PMID: 2326693 DOI: 10.1097/00007632-199001000-00004]

6 **O'Brien MF**, Lenke LG, Mardjetko S, Lowe TG, Kong Y, Eck K, Smith D. Pedicle morphology in thoracic adolescent idiopathic scoliosis: is pedicle fixation an anatomically viable technique? *Spine* (Phila Pa 1976) 2000; **25**: 2285-2293 [PMID: 10984779 DOI: 10.1097/00007632-200009150-00005]

7 **Belmont PJ**, Klemme WR, Dhawan A, Polly DW. In vivo accuracy of thoracic pedicle screws. *Spine* (Phila Pa 1976) 2001; **26**: 2340-2346 [PMID: 11679819 DOI: 10.1097/00007632-200111010-00010]

8 **Suk SI**, Kim WJ, Lee SM, Kim JH, Chung ER. Thoracic pedicle screw fixation in spinal deformities: are they really safe?

Spine (Phila Pa 1976) 2001; **26**: 2049-2057 [PMID: 11547207 DOI: 10.1097/00007632-200109150-00022]
9 **Liljenqvist UR**, Halm HF, Link TM. Pedicle screw instrumentation of the thoracic spine in idiopathic scoliosis. *Spine* (Phila Pa 1976) 1997; **22**: 2239-2245 [PMID: 9346144 DOI: 10.1097/00007632-199710010-00008]
10 **Krag MH**, Beynnon BD, Pope MH, DeCoster TA. Depth of insertion of transpedicular vertebral screws into human vertebrae: effect upon screw-vertebra interface strength. *J Spinal Disord* 1988; **1**: 287-294 [PMID: 2980257 DOI: 10.1097/00002517-198800140-00003]
11 **Krag MH**, Weaver DL, Beynnon BD, Haugh LD. Morphometry of the thoracic and lumbar spine related to transpedicular screw placement for surgical spinal fixation. *Spine* (Phila Pa 1976) 1988; **13**: 27-32 [PMID: 3381134 DOI: 10.1097/00007632-198801000-00007]
12 **Roy-Camille R**, Saillant G, Mazel C. Internal fixation of the lumbar spine with pedicle screw plating. *Clin Orthop Relat Res* 1986; **(203):** 7-17 [PMID: 3955999]
13 **Broom MJ**, Banta JV, Renshaw TS. Spinal fusion augmented by luque-rod segmental instrumentation for neuromuscular scoliosis. *J Bone Joint Surg Am* 1989; **71**: 32-44 [PMID: 2913001]
14 **Youkilis AS**, Quint DJ, McGillicuddy JE, Papadopoulos SM. Stereotactic navigation for placement of pedicle screws in the thoracic spine. *Neurosurgery* 2001; **48**: 771-778; discussion 771-778 [PMID: 11322437 DOI: 10.1097/00006123-200104000-00015]
15 **Vaccaro AR**, Rizzolo SJ, Balderston RA, Allardyce TJ, Garfin SR, Dolinskas C, An HS. Placement of pedicle screws in the thoracic spine. Part II: An anatomical and radiographic assessment. *J Bone Joint Surg Am* 1995; **77**: 1200-1206 [PMID: 7642665]
16 **McCormack BM**, Benzel EC, Adams MS, Baldwin NG, Rupp FW, Maher DJ. Anatomy of the thoracic pedicle. *Neurosurgery* 1995; **37**: 303-308 [PMID: 7477783 DOI: 10.1097/00006123-199508000-00016]
17 **Rampersaud YR**, Simon DA, Foley KT. Accuracy requirements for image-guided spinal pedicle screw placement. *Spine* (Phila Pa 1976) 2001; **26**: 352-359 [PMID: 11224881 DOI: 10.1097/00007632-200102150-00010]
18 **Ebraheim NA**, Jabaly G, Xu R, Yeasting RA. Anatomic relations of the thoracic pedicle to the adjacent neural structures. *Spine* (Phila Pa 1976) 1997; **22**: 1553-1556; discussion 1557 [PMID: 9253087 DOI: 10.1097/00007632-199707150-00002]
19 **Liljenqvist UR**, Link TM, Halm HF. Morphometric analysis of thoracic and lumbar vertebrae in idiopathic scoliosis. *Spine* (Phila Pa 1976) 2000; **25**: 1247-1253 [PMID: 10806501 DOI: 10.1097/00007632-200005150-00008]
20 **Modi HN**, Suh SW, Hong JY, Yang JH. Accuracy of thoracic pedicle screw using ideal pedicle entry point in severe scoliosis. *Clin Orthop Relat Res* 2010; **468**: 1830-1837 [PMID: 20182830 DOI: 10.1007/s11999-010-1280-1]
21 **Fayyazi AH**, Hugate RR, Pennypacker J, Gelb DE, Ludwig SC. Accuracy of computed tomography in assessing thoracic pedicle screw malposition. *J Spinal Disord Tech* 2004; **17**: 367-371 [PMID: 15385875 DOI: 10.1097/01.bsd.0000112049.36255.bc]
22 **Heary RF**, Bono CM, Black M. Thoracic pedicle screws: postoperative computerized tomography scanning assessment. *J Neurosurg* 2004; **100**: 325-331 [PMID: 15070139]
23 **Kim YJ**, Lenke LG, Bridwell KH, Cho YS, Riew KD. Free hand pedicle screw placement in the thoracic spine: is it safe? *Spine* (Phila Pa 1976) 2004; **29**: 333-342; discussion 342 [PMID: 14752359 DOI: 10.1097/01.BRS.0000109983.12113.9B]
24 **Schwarzenbach O**, Berlemann U, Jost B, Visarius H, Arm E, Langlotz F, Nolte LP, Ozdoba C. Accuracy of computer-assisted pedicle screw placement. An in vivo computed tomography analysis. *Spine* (Phila Pa 1976) 1997; **22**: 452-458 [PMID: 9055375 DOI: 10.1097/00007632-199702150-00020]
25 **Mirza SK**, Wiggins GC, Kuntz C, York JE, Bellabarba C, Knonodi MA, Chapman JR, Shaffrey CI. Accuracy of thoracic vertebral body screw placement using standard fluoroscopy, fluoroscopic image guidance, and computed tomographic image guidance: a cadaver study. *Spine* (Phila Pa 1976) 2003; **28**: 402-413 [PMID: 12590219 DOI: 10.1097/01.BRS.0000048461.51308.CD]
26 **Modi H**, Suh SW, Song HR, Yang JH. Accuracy of thoracic pedicle screw placement in scoliosis using the ideal pedicle entry point during the freehand technique. *Int Orthop* 2009; **33**: 469-475 [PMID: 18357448 DOI: 10.1007/s00264-008-0535-x]
27 **Parker SL**, McGirt MJ, Farber SH, Amin AG, Rick AM, Suk I, Bydon A, Sciubba DM, Wolinsky JP, Gokaslan ZL, Witham TF. Accuracy of free-hand pedicle screws in the thoracic and lumbar spine: analysis of 6816 consecutive screws. *Neurosurgery* 2011; **68**: 170-178; discussion 178 [PMID: 21150762 DOI: 10.1227/NEU.0b013e3181fdfaf4]
28 **Chung KJ**, Suh SW, Desai S, Song HR. Ideal entry point for the thoracic pedicle screw during the free hand technique. *Int Orthop* 2008; **32**: 657-662 [PMID: 17437109 DOI: 10.1007/s00264-007-0363-4]
29 **Xu R**, Ebraheim NA, Ou Y, Yeasting RA. Anatomic considerations of pedicle screw placement in the thoracic spine. Roy-Camille technique versus open-lamina technique. *Spine* (Phila Pa 1976) 1998; **23**: 1065-1068 [PMID: 9589548 DOI: 10.1097/00007632-199805010-00021]
30 **Lehman RA**, Polly DW, Kuklo TR, Cunningham B, Kirk KL, Belmont PJ. Straight-forward versus anatomic trajectory technique of thoracic pedicle screw fixation: a biomechanical analysis. *Spine* (Phila Pa 1976) 2003; **28**: 2058-2065 [PMID: 14501914 DOI: 10.1097/01.BRS.0000084628.37133.BA]
31 **Karapinar L**, Erel N, Ozturk H, Altay T, Kaya A. Pedicle screw placement with a free hand technique in thoracolumbar spine: is it safe? *J Spinal Disord Tech* 2008; **21**: 63-67 [PMID: 18418139 DOI: 10.1097/BSD.0b013e3181453dc6]
32 **Schizas C**, Theumann N, Kosmopoulos V. Inserting pedicle screws in the upper thoracic spine without the use of fluoroscopy or image guidance. Is it safe? *Eur Spine J* 2007; **16**: 625-629 [PMID: 17106663 DOI: 10.1007/s00586-006-0262-1]
33 **Kotil K**, Bilge T. Accuracy of pedicle and mass screw placement in the spine without using fluoroscopy: a prospective clinical study. *Spine J* 2008; **8**: 591-596 [PMID: 17602885 DOI: 10.1016/j.spinee.2007.04.002]
34 **Amiot LP**, Lang K, Putzier M, Zippel H, Labelle H. Comparative results between conventional and computer-assisted pedicle screw installation in the thoracic, lumbar, and sacral spine. *Spine* (Phila Pa 1976) 2000; **25**: 606-614 [PMID: 10749638 DOI: 10.1097/00007632-200003010-00012]
35 **Merloz P**, Troccaz J, Vouaillat H, Vasile C, Tonetti J, Eid A, Plaweski S. Fluoroscopy-based navigation system in spine surgery. *Proc Inst Mech Eng H* 2007; **221**: 813-820 [PMID: 18019467 DOI: 10.1243/09544119JEIM268]
36 **Fang A**, Hu SS, Endres N, Bradford DS. Risk factors for infection after spinal surgery. *Spine* (Phila Pa 1976) 2005; **30**: 1460-1465 [PMID: 15959380 DOI: 10.1097/01.brs.0000166532.58227.4f]
37 **Perisinakis K**, Theocharopoulos N, Damilakis J, Katonis P, Papadokostakis G, Hadjipavlou A, Gourtsoyiannis N. Estimation of patient dose and associated radiogenic risks from fluoroscopically guided pedicle screw insertion. *Spine* (Phila Pa 1976) 2004; **29**: 1555-1560 [PMID: 15247578 DOI: 10.1097/01.BRS.0000131214.57597.21]
38 **Jones DP**, Robertson PA, Lunt B, Jackson SA. Radiation exposure during fluoroscopically assisted pedicle screw insertion in the lumbar spine. *Spine* (Phila Pa 1976) 2000; **25**: 1538-1541 [PMID: 10851103 DOI: 10.1097/00007632-200006150-00013]
39 **Slomczykowski M**, Roberto M, Schneeberger P, Ozdoba C, Vock P. Radiation dose for pedicle screw insertion. Fluoro-

scopic method versus computer-assisted surgery. *Spine* (Phila Pa 1976) 1999; **24**: 975-982; discussion 983 [PMID: 10332788 DOI: 10.1097/00007632-199905150-00009]
40 **Ul Haque M**, Shufflebarger HL, O'Brien M, Macagno A. Radiation exposure during pedicle screw placement in adolescent idiopathic scoliosis: is fluoroscopy safe? *Spine* (Phila Pa 1976) 2006; **31**: 2516-2520 [PMID: 17023864 DOI: 10.1097/01.brs.0000238675.91612.2f]
41 **Ahn Y**, Kim CH, Lee JH, Lee SH, Kim JS. Radiation exposure to the surgeon during percutaneous endoscopic lumbar discectomy: a prospective study. *Spine* (Phila Pa 1976) 2013; **38**: 617-625 [PMID: 23026867 DOI: 10.1097/BRS.0b013e318275ca58]
42 **Rampersaud YR**, Foley KT, Shen AC, Williams S, Solomito M. Radiation exposure to the spine surgeon during fluoroscopically assisted pedicle screw insertion. *Spine* (Phila Pa 1976) 2000; **25**: 2637-2645 [PMID: 11034650 DOI: 10.1097/00007632-200010150-00016]
43 **Mulconrey DS.** Fluoroscopic Radiation Exposure in Spinal Surgery: In Vivo Evaluation for Operating Room Personnel. *J Spinal Disord Tech* 2013; Epub ahead of print [PMID: 23381176]
44 **Halm H**, Niemeyer T, Link T, Liljenqvist U. Segmental pedicle screw instrumentation in idiopathic thoracolumbar and lumbar scoliosis. *Eur Spine J* 2000; **9**: 191-197 [PMID: 10905435 DOI: 10.1007/s005860000139]
45 **Carbone JJ**, Tortolani PJ, Quartararo LG. Fluoroscopically assisted pedicle screw fixation for thoracic and thoracolumbar injuries: technique and short-term complications. *Spine* (Phila Pa 1976) 2003; **28**: 91-97 [PMID: 12544964 DOI: 10.1097/00007632-200301010-00021]
46 **Kuntz C**, Maher PC, Levine NB, Kurokawa R. Prospective evaluation of thoracic pedicle screw placement using fluoroscopic imaging. *J Spinal Disord Tech* 2004; **17**: 206-214 [PMID: 15167336 DOI: 10.1097/00024720-200406000-00007]
47 **Vougioukas VI**, Weber J, Scheufler KM. Clinical and radiological results after parapedicular screw fixation of the thoracic spine. *J Neurosurg Spine* 2005; **3**: 283-287 [PMID: 16266069 DOI: 10.3171/spi.2005.3.4.0283]
48 **Amato V**, Giannachi L, Irace C, Corona C. Accuracy of pedicle screw placement in the lumbosacral spine using conventional technique: computed tomography postoperative assessment in 102 consecutive patients. *J Neurosurg Spine* 2010; **12**: 306-313 [PMID: 20192632 DOI: 10.3171/2009.9.SPINE09261]
49 **Laine T**, Schlenzka D, Mäkitalo K, Tallroth K, Nolte LP, Visarius H. Improved accuracy of pedicle screw insertion with computer-assisted surgery. A prospective clinical trial of 30 patients. *Spine* (Phila Pa 1976) 1997; **22**: 1254-1258 [PMID: 9201865 DOI: 10.1097/00007632-199706010-00018]
50 **Oh HS**, Kim JS, Lee SH, Liu WC, Hong SW. Comparison between the accuracy of percutaneous and open pedicle screw fixations in lumbosacral fusion. *Spine J* 2013; **13**: 1751-1757 [PMID: 23647827]
51 **Smith ZA**, Sugimoto K, Lawton CD, Fessler RG. Incidence of Lumbar Spine Pedicle Breach Following Percutaneous Screw Fixation: A Radiographic Evaluation of 601 Screws in 151 Patients. *J Spinal Disord Tech* 2012; Epub ahead of print [PMID: 22688617]
52 **Yang BP**, Wahl MM, Idler CS. Percutaneous lumbar pedicle screw placement aided by computer-assisted fluoroscopy-based navigation: perioperative results of a prospective, comparative, multicenter study. *Spine* (Phila Pa 1976) 2012; **37**: 2055-2060 [PMID: 23149423 DOI: 10.1097/BRS.0b013e31825c05cd]
53 **Idler C**, Rolfe KW, Gorek JE. Accuracy of percutaneous lumbar pedicle screw placement using the oblique or "owl's-eye" view and novel guidance technology. *J Neurosurg Spine* 2010; **13**: 509-515 [PMID: 20887149 DOI: 10.3171/2010.4.SPINE09580]
54 **Dinesh SK**, Tiruchelvarayan R, Ng I. A prospective study on the use of intraoperative computed tomography (iCT) for image-guided placement of thoracic pedicle screws. *Br J Neurosurg* 2012; **26**: 838-844 [PMID: 22698392 DOI: 10.3109/02688697.2012.690917]
55 **Scheufler KM**, Franke J, Eckardt A, Dohmen H. Accuracy of image-guided pedicle screw placement using intraoperative computed tomography-based navigation with automated referencing. Part II: thoracolumbar spine. *Neurosurgery* 2011; **69**: 1307-1316 [PMID: 21734616 DOI: 10.1227/NEU.0b013e31822ba190]
56 **Rajasekaran S**, Vidyadhara S, Ramesh P, Shetty AP. Randomized clinical study to compare the accuracy of navigated and non-navigated thoracic pedicle screws in deformity correction surgeries. *Spine* (Phila Pa 1976) 2007; **32**: E56-E64 [PMID: 17224800]
57 **Abul-Kasim K**, Overgaard A, Maly P, Ohlin A, Gunnarsson M, Sundgren PC. Low-dose helical computed tomography (CT) in the perioperative workup of adolescent idiopathic scoliosis. *Eur Radiol* 2009; **19**: 610-618 [PMID: 18810453]
58 **Bledsoe JM**, Fenton D, Fogelson JL, Nottmeier EW. Accuracy of upper thoracic pedicle screw placement using three-dimensional image guidance. *Spine J* 2009; **9**: 817-821 [PMID: 19664966 DOI: 10.1016/j.spinee.2009.06.014]
59 **Nottmeier EW**, Seemer W, Young PM. Placement of thoracolumbar pedicle screws using three-dimensional image guidance: experience in a large patient cohort. *J Neurosurg Spine* 2009; **10**: 33-39 [PMID: 19119930 DOI: 10.3171/2008.10.SPI08383]
60 **Oertel MF**, Hobart J, Stein M, Schreiber V, Scharbrodt W. Clinical and methodological precision of spinal navigation assisted by 3D intraoperative O-arm radiographic imaging. *J Neurosurg Spine* 2011; **14**: 532-536 [PMID: 21275555 DOI: 10.3171/2010.10.SPINE091032]
61 **Lee MH,** Lin MH, Weng HH, Cheng WC, Tsai YH, Wang TC, Yang JT. Feasibility of Intra-operative Computed Tomography Navigation System for Pedicle Screw Insertion of the Thoraco-lumbar Spine. *J Spinal Disord Tech* 2012; Epub ahead of print [PMID: 23222100]
62 **Ling JM**, Dinesh SK, Pang BC, Chen MW, Lim HL, Louange DT, Yu CS, Wang CM. Routine spinal navigation for thoraco-lumbar pedicle screw insertion using the O-arm three-dimensional imaging system improves placement accuracy. *J Clin Neurosci* 2014; **21**: 493-498 [PMID: 24090516 DOI: 10.1016/j.jocn.2013.02.034]
63 **Laine T**, Lund T, Ylikoski M, Lohikoski J, Schlenzka D. Accuracy of pedicle screw insertion with and without computer assistance: a randomised controlled clinical study in 100 consecutive patients. *Eur Spine J* 2000; **9**: 235-240 [PMID: 10905443]
64 **Tormenti MJ**, Kostov DB, Gardner PA, Kanter AS, Spiro RM, Okonkwo DO. Intraoperative computed tomography image-guided navigation for posterior thoracolumbar spinal instrumentation in spinal deformity surgery. *Neurosurg Focus* 2010; **28**: E11 [PMID: 20192656 DOI: 10.3171/2010.1.FOCUS09275]
65 **Shin MH,** Hur JW, Ryu KS, Park CK. Prospective Comparison Study Between the Fluoroscopy Guided and Navigation Coupled with O-arm® Guided Pedicle Screw Placement in the Thoracic and Lumbosacral Spines. *J Spinal Disord Tech* 2013; Epub ahead of print [PMID: 23563342]
66 **Waschke A**, Walter J, Duenisch P, Reichart R, Kalff R, Ewald C. CT-navigation versus fluoroscopy-guided placement of pedicle screws at the thoracolumbar spine: single center experience of 4500 screws. *Eur Spine J* 2013; **22**: 654-660 [PMID: 23001415 DOI: 10.1007/s00586-012-2509-3]
67 **Fraser J**, Gebhard H, Irie D, Parikh K, Härtl R. Iso-C/3-dimensional neuronavigation versus conventional fluoroscopy for minimally invasive pedicle screw placement in lumbar fusion. *Minim Invasive Neurosurg* 2010; **53**: 184-190 [PMID: 21140333 DOI: 10.1055/s-0030-1267926]
68 **Tian NF**, Xu HZ. Image-guided pedicle screw insertion accuracy: a meta-analysis. *Int Orthop* 2009; **33**: 895-903 [PMID:

19421752 DOI: 10.1007/s00264-009-0792-3]
69 **Gelalis ID**, Paschos NK, Pakos EE, Politis AN, Arnaoutoglou CM, Karageorgos AC, Ploumis A, Xenakis TA. Accuracy of pedicle screw placement: a systematic review of prospective in vivo studies comparing free hand, fluoroscopy guidance and navigation techniques. *Eur Spine J* 2012; **21**: 247-255 [PMID: 21901328 DOI: 10.1007/s00586-011-2011-3]
70 **Shin BJ**, James AR, Njoku IU, Härtl R. Pedicle screw navigation: a systematic review and meta-analysis of perforation risk for computer-navigated versus freehand insertion. *J Neurosurg Spine* 2012; **17**: 113-122 [PMID: 22724594 DOI: 10.3171/2012.5.SPINE11399]
71 **Costa F**, Cardia A, Ortolina A, Fabio G, Zerbi A, Fornari M. Spinal navigation: standard preoperative versus intraoperative computed tomography data set acquisition for computer-guidance system: radiological and clinical study in 100 consecutive patients. *Spine* (Phila Pa 1976) 2011; **36**: 2094-2098 [PMID: 21304425 DOI: 10.1097/BRS.0b013e318201129d]
72 **Cui G**, Wang Y, Kao TH, Zhang Y, Liu Z, Liu B, Li J, Zhang X, Zhu S, Lu N, Mao K, Wang Z, Zhang X, Yuan X, Dong T, Xiao S. Application of intraoperative computed tomography with or without navigation system in surgical correction of spinal deformity: a preliminary result of 59 consecutive human cases. *Spine* (Phila Pa 1976) 2012; **37**: 891-900 [PMID: 22024897 DOI: 10.1097/BRS.0b013e31823aff81]
73 **Zausinger S**, Scheder B, Uhl E, Heigl T, Morhard D, Tonn JC. Intraoperative computed tomography with integrated navigation system in spinal stabilizations. *Spine* (Phila Pa 1976) 2009; **34**: 2919-2926 [PMID: 20010400 DOI: 10.1097/BRS.0b013e3181b77b19]
74 **Wang VY**, Chin CT, Lu DC, Smith JS, Chou D. Free-hand thoracic pedicle screws placed by neurosurgery residents: a CT analysis. *Eur Spine J* 2010; **19**: 821-827 [PMID: 20135332 DOI: 10.1007/s00586-010-1293-1]
75 **Sarlak AY**, Tosun B, Atmaca H, Sarisoy HT, Buluç L. Evaluation of thoracic pedicle screw placement in adolescent idiopathic scoliosis. *Eur Spine J* 2009; **18**: 1892-1897 [PMID: 19526376 DOI: 10.1007/s00586-009-1065-y]
76 **An HS**, Benoit PR. Saline injection technique to confirm pedicle screw path: a cadaveric study. *Am J Orthop* (Belle Mead NJ) 1998; **27**: 362-365 [PMID: 9604108]
77 **Frank EH**. The use of small malleable endoscopes to assess pedicle screw placement: technical note. *Minim Invasive Neurosurg* 1998; **41**: 10-12 [PMID: 9565958]
78 **Reidy DP**, Houlden D, Nolan PC, Kim M, Finkelstein JA. Evaluation of electromyographic monitoring during insertion of thoracic pedicle screws. *J Bone Joint Surg Br* 2001; **83**: 1009-1014 [PMID: 11603513]

P- Reviewers: Chen YK, Grote S, Melanie F **S- Editor**: Qi Y
L- Editor: A **E- Editor**: Lu YJ

百世登

Baishideng®

Published by **Baishideng Publishing Group Co., Limited**
Flat C, 23/F., Lucky Plaza, 315-321 Lockhart Road,
Wan Chai, Hong Kong, China
Fax: +852-65557188
Telephone: +852-31779906
E-mail: bpgoffice@wjgnet.com
http://www.wjgnet.com