Instrumenting the small thoracic pedicle: the role of intraoperative computed tomography image-guided surgery

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Object. Traditionally, instrumentation of thoracic pedicles has been more difficult because of their relatively smaller size. Thoracic pedicles are at risk for violation during surgical instrumentation, as is commonly seen in patients with scoliosis and in women. The laterally based “in-out-in” approach, which technically results in a lateral breach, is sometimes used in small pedicles to decrease the comparative risk of a medial breach with neurological involvement. In this study the authors evaluated the role of CT image-guided surgery in navigating screws in small thoracic pedicles.

Methods. Thoracic (T1–12) pedicle screw placements using the O-arm imaging system (Medtronic Inc.) were evaluated for accuracy with preoperative and postoperative CT. “Small” pedicles were defined as those ≤ 3 mm in the narrowest diameter orthogonal to the long axis of the pedicle on a trajectory entering the vertebral body on preinstrumentation CT. A subset of “very small” pedicles (≤ 2 mm in the narrowest diameter, 13 pedicles) was also analyzed. Screw accuracy was categorized as good (< 1 mm of pedicle breach in any direction or in-out-in screws), fair (1–3 mm of breach), or poor (> 3 mm of breach).

Results. Twenty-one consecutive patients (age range 32–71 years) had large (45 screws) and small (52 screws) thoracic pedicles. The median pedicle diameter was 2.5 mm (range 0.9–3 mm) for small and 3.9 mm (3.1–6.7 mm) for large pedicles. Computed tomography-guided surgical navigation led to accurate screw placement in both small (good 100%, fair 0%, poor 0%) and large (good 96.6%, fair 0%, poor 3.4%) pedicles. Good screw placement in very small or small pedicles occurred with an in-out-in trajectory more often than in large pedicles (large 6.8% vs small 36.5%, $p < 0.0005$; vs very small 69.2%, $p < 0.0001$). There were no medial breaches even though 75 of the 97 screws were placed in postmenopausal women, traditionally at higher risk for osteoporosis.

Conclusions. Computed tomography-guided surgical navigation allows for safe, effective, and accurate instrumentation of small (≤ 3 mm) to very small (≤ 2 mm) thoracic pedicles.

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KEY WORDS • spine instrumentation • thoracic spine • O-arm imaging •
intraoperative CT • pedicle screw

PLACEMENT of thoracic pedicle screws has become a widely used treatment during spine surgery for deformity, tumor, trauma, and degenerative conditions. The resulting 3-column fixation offers instrumentation constructs with high biomechanical strength. However, placing pedicle screws in the thoracic spine can be more technically challenging than in the lumbar spine. The proximity of nearby neurovascular structures, including the great vessels and the spinal cord, increases the risk for serious complications. Additionally, the smaller diameter of the thoracic pedicles (compared with lumbar pedicles) increases the chance of improperly positioned screws and a medial breach of the pedicle. This

issue seems to be most pronounced in the midthoracic spine between T-4 and T-6, a place where cadaveric studies have found the pedicle width to be the narrowest, creating special concern for women and children as their pedicle diameters tend to be significantly smaller than in their male counterparts.¹³

Intraoperative CT-based navigation systems have been increasingly used with high accuracy in the thoracolumbar spine.^{8,16} Given the greater probability of error in placing pedicle screws in small thoracic pedicles, we retrospectively examined the accuracy of previous screw placements in patients with small thoracic pedicles that had been performed using intraoperative CT-guided navigation. In the present study, we analyze our experience with pedicle screw placements in thoracic pedicles with diameters ≤ 3 mm. To our knowledge, this is the first study in which the efficacy of CT image-guided surgery

Abbreviations used in this paper: CT-IGS = CT image-guided surgery; DRF = dynamic reference frame.

(CT-IGS) for placing pedicle screws in such small thoracic pedicles has been exclusively examined.

Methods

Using postoperative CT scans, we retrospectively evaluated the safety and accuracy of thoracic pedicle screw placements that had been performed at Cedars-Sinai Medical Center between 2009 and 2012 using both intraoperative navigation software (StealthStation, Medtronic Inc.) on a computer system (S7 Treon, Medtronic Inc.) and an intraoperative CT imaging system (O-arm, Medtronic Inc.). Included in our analysis were all patients with 1) both preoperative and postoperative CT studies, 2) uninstrumented thoracic pedicles preoperatively, and 3) O-arm navigation-guided placement of thoracic screws in a new and/or revision thoracic spine surgery. Excluded from the study were all patients with prior instrumentation in any thoracic vertebral level, because of the difficulty in accurately classifying preoperative pedicle diameter.

Screws were divided into two groups: 1) those placed into “small” pedicles with ≤ 3 mm in the narrowest diameter orthogonal to the long axis of the pedicle on a trajectory entering the vertebral body on preinstrumentation CT, and 2) screws placed into “large” pedicles with > 3 mm in the narrowest diameter orthogonal to the long axis of the pedicle on a trajectory entering the vertebral body on preinstrumentation CT. A subgroup analysis of “very small” pedicles with ≤ 2 mm in the narrowest diameter was also completed.

Surgical Technique

All patients were prone on a Jackson table with appropriate padding, and sterile preparation and draping were performed. A longitudinal midline incision exposed the thoracic levels to be instrumented. The Stealth Optical dynamic reference frame (DRF) was then rigidly affixed in one of two ways: 1) to an exposed spinous process, or 2) if a spinous process was not available, to an existing pedicle screw via a custom-bent rod with a DRF. The DRF was rigidly affixed between the camera and the working surgical level to provide line of site and out of contact with soft tissue to reduce DRF drift.

The O-arm was then brought into the surgical field. Anteroposterior and lateral fluoroscopic scout images were obtained for localization of the region of interest. During intraoperative CT image acquisition, the anesthesiologist was asked to temporarily suspend respiration until the scan was complete. Next, we obtained an intraoperative scan that allowed automated registration of images spanning approximately 4–6 vertebral levels. These images were automatically transferred to the S7 Treon system. The O-arm was then removed from the surgical field. StealthStation neuronavigation software was used for intraoperative planning of screw placement, including selection of the screw diameter, length, and trajectory based on specific pedicle diameter and relevant anatomy.

In all cases, screws were planned for a purely intrapedicular approach when possible. When pedicle morphology made an intrapedicular approach impossible, an

extrapedicular, laterally based “in-out-in” trajectory was used. This trajectory is “in” through the cortex of the transverse process, “out” with a deliberate screw thread breach out of the lateral thoracic pedicle wall into the costovertebral joint, and back “in” through the vertebral body. This in-out-in approach is biomechanically sound, as it allows for larger and longer screws (up to 60 mm in the thoracic spine) with tricortical or quadricortical purchase, although it does result in deliberate pedicle violation. It is also safe since no vital structures are within the pedicle-rib complex.

We navigated all instruments including the probe, pneumatic drill, awl, pedicle finder probes, screw tap, and pedicle screw itself. Specifically, under image guidance, the pedicle entry hole was predrilled with or without an awl. Screws were then inserted with the navigated pedicle finder probe and tap. Each tapped hole was manually probed with a ball-tipped probe for sidewall or deep breach. The screw was inserted with a navigated screwdriver. System accuracy was checked following each screw insertion by placing the navigated probe onto a known anatomical landmark and visually confirming accuracy with the image guidance system. If accuracy deviated more than 1 mm, the O-arm was brought into the surgical field, and a scan of the same region was obtained. Once all screws were placed for the scanned vertebral levels, the DRF was repositioned as necessary and the O-arm was brought in for a scan of the next levels to be addressed. Surgeons standing on either side of the patient inserted the instrumentation on that side; for example, the surgeon standing on the patient’s left inserted the left screws. All surgeons were right-handed.

To reduce radiation to the patient, an intraoperative CT scan was not routinely obtained using the O-arm after screw insertion unless there was concern for malpositioning. Motor evoked potentials, somatosensory evoked potentials, and electromyographic activity were routinely monitored in patients with thoracic exposure. Patients were evaluated postoperatively for any signs of deficit or morbidity associated with a malpositioned screw. Postoperative CT scans were routinely obtained within 3 months of surgery.

Assessment of Pedicle and Pelvis Screws

A single reviewer blinded to the surgical group and individual patient evaluated all screws to reduce interobserver error. Of note, the reviewer was not informed whether a screw was planned for an intrapedicular or an extrapedicular approach. Postoperative axial and sagittal CT images obtained at our institution only were used to review screw placements to reduce variance in scan quality.

All screws lay completely within the thoracic pedicle in the rostral-caudal plane. Each instrumented pedicle was evaluated for any medial or lateral breach on axial views. Screw depth was also evaluated on axial images. Pedicle violations were defined as medial, lateral, or bicortical, and the degree of violation for each screw was categorized as good, fair, or poor (Figs. 1–4).

“Good” screws were defined as those that were anatomically acceptable and safe. Neither the tip nor the screw violated the cortex of the corresponding pedicle

FIG. 1. Pedicle diameter measurement (blue rectangle). Red rectangle (inset) shows that other trajectories with wider diameters would miss the vertebral body.

by more than 1 mm. In those instances in which pedicle morphology or diameter precluded a screw's ability to be contained purely within the pedicle, extrapedicular screws inserted in an in-out-in trajectory through the pedicle-rib complex were allowed and classified as good.

"Fair" screws were defined as screws that were considered safe but biomechanically suboptimal. They violated the cortex of the corresponding pedicle or pelvis by

FIG. 2. Screws placed in the trajectory of maximal diameter.

FIG. 3. Example of very small pedicles (≤ 2 mm in diameter).

more than 1 mm but less than or equal to 3 mm. Screws that were prominent by 1–3 mm were biomechanically suboptimal because the tip extended longer than necessary, but not to a degree that irritated ventral neural or vascular elements. In these cases of 1–3 mm of sidewall breach, the shaft was invariably contained within 50% of the central axis of bone, did not cross the midline of the vertebral body, and did not significantly endanger the spinal cord in the central canal or the thoracic contents.

"Poor" screws were defined as screws in which the tip or thread violated the cortex of the corresponding pedicle or pelvis by more than 3 mm. These violations had

FIG. 4. In-out-in trajectory through a very small left pedicle.

the potential to injure the spinal cord or other vital tissue or had biomechanically unsound purchase.

Levels were evaluated based on the overall region, divided by differences in anatomy. Regions were categorized as high thoracic (T1–3), midthoracic (T4–9), and low thoracic (T10–12).

Patient charts were reviewed for intraoperative complications, including neurological signal changes, as well as postoperative follow-up. All relevant associated morbidity was documented, as was any screw repositioning.

Results

In total, 97 screws (45 in small pedicles and 52 in large pedicles) were placed in 21 consecutive patients. The median patient age was 56 years (range 32–71 years), and 75 of the 97 screws had been placed in women over the age of 40 years. Eleven (48 screws) of the 21 patients underwent thoracic revision spine surgery with no prior instrumentation at these levels. There were no reoperations for screw malpositions and no postoperative morbidity due to screw placement even though most of the screws had been placed in women who were more likely to have reached the age of menopause and thus more likely to have osteoporotic bone. No other major morbidity or mortality was associated with surgery.

There were region-specific differences in pedicle diameter. Instrumented midthoracic (T4–9) pedicles were consistently smaller, with a median pedicle diameter of 2.5 mm (range 0.9–3.3 mm), followed by high thoracic (T1–3; median 2.6 mm, range 1.2–5.2 mm) and low thoracic (T10–12; median 3.4 mm, range 1.9–6.7 mm) pedicles. When analyzing small versus large pedicle diameters, the median diameters were 2.5 mm (range 0.9–3 mm) for small and 3.9 mm (3.1–6.7 mm) for large pedicles. The greatest percentage of small pedicles occurred in the midthoracic spine (T1–3: 24 pedicles total, 54% small; T4–9: 25 pedicles, 80% small; T10–12: 48 pedicles, 40% small).

Overall, the use of CT-IGS resulted in accurate screw placement in both small (good 100%, fair 0%, poor 0%) and large (good 96.6%, fair 0%, poor 3.4%) pedicles; the “poor” percentage was for a single screw. New cases resulted in 98.0% good placements (all but 1 screw), similar to the rate for revision cases (100%). Good screw placements among the small pedicles were similar across all thoracic levels (100%).

In the aggregate, good screw placements in small pedicles were performed with an extrapedicular in-out-in trajectory more often than in large pedicles (small 36.5%, $p < 0.0005$, Fisher exact test; large 6.8%). Screws in large pedicles were almost uniformly placed via an intrapedicular approach as the biomechanically preferred superior approach. Specifically, the extrapedicular trajectory in large pedicles was used in the high thoracic region 0% of the time, the midthoracic region 0%, and the low thoracic region 11%. When pedicles were small, the extrapedicular trajectory was used in the high thoracic region 31% of the time, midthoracic region 40%, and low thoracic region 37%. Subgroup analysis showed that this extrapedicular trajectory almost doubled to 69.2% of the time with very

small pedicles (≤ 2 mm; $p < 0.0001$), compared with large pedicles.

Discussion

The placement of thoracic pedicle screws can be especially challenging due to several factors. The relatively smaller diameter of thoracic pedicles, compared with pedicles in the lumbar spine, increases the risk for malpositioned pedicle screws. Radiographic and cadaveric studies have reported thoracic pedicle diameters ranging between 3.6 and 8.7 mm, with the smallest pedicles at T-4 to T-6.¹³ Additionally, the upper thoracic spine is frequently difficult to intraoperatively image with lateral radiography, contributing to the challenge of screw placement. Finally, there is a low margin of error given the minimal “safe zone” between the medial pedicle wall and the neural elements, increasing the risk for CSF leak or spinal cord injury. Some studies have reported the average distance between the medial pedicle wall and the spinal cord in the thoracic spine to range between 2 and 4 mm, with even less distance at the concave apex of a scoliotic curve.^{2,5} One study documented no space between the medial pedicle wall and the dura mater in the thoracic spine.³

As expected, the risk for inaccurate screw placement increases in patients with small thoracic pedicles. A breach through the medial wall of the pedicle would result in a screw in the spinal canal, which could cause a dural tear or neurological injury. A breach in the lateral wall, however, could cause the screw to lie in the posterior mediastinum or pleural space, and most of the time the screw would be contained in the costotransverse junction.^{2,13} A breach superiorly or inferiorly would cause the screw to lie in the neural foramen, resulting in radiculopathy.

In patients with significant spinal deformity, the risk of pedicle breach during screw placement is increased as the anatomy becomes more distorted, especially with freehand techniques that rely on anatomical landmarks. The use of fluoroscopic assistance still only provides information in one plane and requires an expert radiographer.

One technique to decrease the chance of a medial breach is the in-out-in technique, which has been especially useful in pedicles with a diameter smaller than that of the screw. In this technique the starting point for the screw trajectory is more lateral on the transverse process. The screw trajectory is then aimed medial through the transverse process, into the costotransverse junction, and through the lateral wall of the pedicle, into the vertebral body. Although this technically results in a lateral breach, the technique decreases the risk of a more serious medial breach in patients with especially small thoracic pedicles. This technique may be used judiciously in an instrumentation construct without significant sequelae, since in-out-in screws have approximately 80% of the pullout strength of true pedicle screws.

The accuracy of thoracic pedicle screw placement using conventional techniques has been reported in the literature.⁴ A landmark study from 2001 analyzed the ac-

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curacy of screw placement with fluoroscopic guidance and postoperatively measured accuracy with a CT scan.¹ The findings were as follows: 57% of screws were placed entirely within the pedicle; 14% of the inserted screws violated the medial border of the pedicle; 29% of the screws breached the lateral border, likely reflecting the fact that the medial pedicle wall is thicker than the lateral wall;⁷ the accuracy of screw placement was highest in the T9–12 region, consistent with the fact that pedicle diameters are relatively larger in this region; and 99% of examined screws were fully contained in the pedicle, were placed with less than a 2-mm breach of the medial pedicle wall, or laterally breached the pedicle via an in-out-in technique. A more recent study reported a 29.1% rate of medial or lateral breaching by thoracic pedicle screws using a freehand method, with 5.94% of screws having a more than 2-mm medial breach.¹⁵ Other more historical studies have documented a lower accuracy rate in thoracic pedicle screw placement ranging from 70% to 75% and medial cortical breach rates from 8% to 23%.^{5,11}

The advent of CT-IGS and 3D bony imaging has allowed the acquisition of intraoperative CT images and 3D image-guided navigation of pedicle screws. By placing a reference frame in the operative field and obtaining intraoperative CT images including this frame, the navigation system constructs a 3D space relative to the frame. Various instruments, including the drill, pedicle finders, and screws, can be registered into this space and navigated relative to the frame. This is an improvement over previous CT-based navigation techniques in which a preoperative CT scan was obtained and anatomical landmarks were intraoperatively registered to the scan. Since the relative position of the spine in the CT scanner would be different from that on the operating table, a significant amount of error in navigation accuracy would be incurred during registration.

We reported 100% and 96.6% good screw placements for the small and large thoracic pedicles, respectively, using intraoperative CT-guided navigation, with “good” defined as a breach less than 1 mm in any direction or placement of an in-out-in screw. Additionally, we reported no sighting of a medial breach. The one “poor” pedicle screw was placed in a 33-year-old woman undergoing a T-6 hemivertebra resection with T2–L1 posterior spinal instrumentation; the screw was placed in a right T-10 large pedicle (5.0 mm in diameter) with a 4-mm lateral pedicle wall breach farther into the costovertebral space than necessary for the pedicle diameter. Given the patient information and pedicle characteristics, we suspected this error was attributable to the learning curve associated with the O-arm, as this screw had been placed early in 2009 in one of the earliest O-arm cases done by the surgeons at our institution.

To our knowledge, this study is the only one to examine the feasibility of the accurate placement of screws in smaller-than-average thoracic pedicles. Our results seem to demonstrate an improvement over the accuracy reported in nonnavigated studies; however, a direct comparison cannot be made because of limitations described below. Nonetheless, our results are comparable with those in other studies examining the accuracy of pedicle screw place-

ment using intraoperative CT-guided navigation (Table 1). A recent study by Larson et al.⁸ revealed a 96.4% accuracy rate among 984 pedicle screws placed in the pediatric population, as confirmed by intraoperative CT following screw placement. This rate was compared with that in a meta-analysis reporting 94.9% accuracy in pedicle screw placement in the pediatric population using conventional methods.⁹ Interestingly, authors of this meta-analysis reported the highest screw revision rate for screws placed in the thoracic spine, where pedicle diameters were the smallest. Although all pedicle diameters were greater than 4 mm in that study, which would be classified as medium-sized pedicles in our study, the accuracy of thoracic pedicle screw placement was reported to be 95.5% in the pediatric group and 97.5% in the adult group. Lekovic et al.¹⁰ found increased difficulty in placing thoracic pedicle screws despite the advantages of navigation, with the highest rate of pedicle breach encountered in thoracic pedicles with diameters smaller than 4 mm.

Several studies and meta-analyses have demonstrated increased accuracy of pedicle screw placement using navigated systems as compared with conventional techniques. A review of prospective studies comparing various pedicle screw placement techniques indicated that screw insertion with CT navigation had a placement accuracy of 89%–100%.⁴ On the other hand, screws placements with fluoroscopy-based navigation had an accuracy of 81%–92%; screw placements with fluoroscopic guidance had an accuracy of 28%–85%; and screw placements performed with freehand techniques had an accuracy of 69%–94%.

A randomized trial by Rajasekaran et al.¹⁴ compared the accuracy of nonnavigated thoracic pedicle screw placement with that of a fluoroscopy-based navigation system in patients with thoracic spine deformities. They found a pedicle breach rate of 23% in the nonnavigated group versus 2% in the navigation group, in which a breach > 2 mm on postoperative CT was considered significant. Note, however, that the average diameter of the thoracic pedicles was not reported. A meta-analysis by Kosmopoulos and Schizas⁶ also revealed an increased mean accuracy of pedicle screw placement in the thoracic spine using navigated techniques (85.1%) compared with nonnavigated techniques (56%). Several retrospective studies have also demonstrated increased pedicle screw accuracy using intraoperative CT-based navigation versus conventional techniques.¹⁶

Study Limitations

This study has several limitations. First, the study was retrospective with no control group. A comparative analysis, preferably prospective, between screws placed with intraoperative CT-based navigation versus conventional methods would better demonstrate the efficacy of screw placement in small thoracic pedicles. It is quite possible that as the diameter of the pedicle decreases, the chance for inaccurate screw placement increases in a comparison between navigated and nonnavigated techniques, justifying and supporting the use of CT image-based navigation. Our intent in this study was to report our experience with the use of intraoperative CT-based

TABLE 1: Accuracy of pedicle screw fixation surgery using navigated and nonnavigated techniques*

Authors & Year	No. of Patients	Technique Used	No. of Screws	Age (yrs)/ Sex (no.)	Accuracy of Screw Placement	Criteria for Malpositioning	Complications	Miscellaneous
Amiot et al., 2000	NN: 100; Nav: 50	NN: biplanar fluoroscopy/Philips; Nav: Tomoscan helical CT	NN: 544; Nav: 294	NN: 47.3 ± 12.7; Nav: 50.7 ± 13.7/NR	NN: 84.7%; Nav: 94.6%	straight scale	misplaced screws: NN: 68, <2 mm; 10, 2.1–4 mm; 5, >4 mm; Nav: all 16, <2 mm	NN: 7 patients underwent reop
Belmont et al., 2001	40	fluoroscopy, violations of medial pedicle cortex used, in-out-in approach	279	24/13 M, 27 F	99%; 57% w/in cortical boundary	>2.0 mm medially; >6.0 mm laterally	14% medial penetration; 29% lat penetration	68% of perforations were lat
Gertzbein & Robbins, 1990	40	AO Fixateur Interne	167	NR	81.5%	>2.0 mm	2 patients w/ neuro complications; severe headaches, paresthesias in L-2	last 25% screw placements improved accuracy to 84%
Kosmopoulos & Schizas, 2007	NR	variable, Nav & NN approaches	37,337 total; in vivo: NN: 12,299; Nav: 3059	NR	total: 91.3%; in vivo: NN: 56%; Nav: 85.1%	variable; most common: screw present or absent w/in bony pedicle & 2.0-mm increment deviation from 0 to 6.0 mm	NR	meta-analysis; in vivo & cadaveric samples; 35 placement assessment methods used
Larson et al., 2012	50 pediatric, NR adult	O-arm intraop CT & Medtronic 3D Nav system	pediatric: 984; adult: 1511	14.4/21 M, 29 F	pediatric: 96.4%; adult: 98.2%	system alerts if screw has >1.0 mm error	27 screws redirected; 8 removed	malposition more common in thoracic levels
Lekovic et al., 2007	NN: 25; Nav: 12	NN: FluoroNav virtual fluoroscopy; Nav: Isocentric C-arm 3D Nav	NN: 183; Nav: 94	range: 35–81/ 20 M, 17 F	NN: 91.3%; Nav: 94.7% (excluding lat perforations)	excluded lat breaches; G1, <2 mm; G2, 2–4 mm; G3, >4 mm	unintended perforations: NN: 16; Nav: 5	perforation rate dependent on pedicle diameter; 3 patients excluded from NN
Modi et al., 2009	43	IPEP w/ freehand	854	17.6 ± 7.3/18 M, 25 F	93%	>2.0 mm medially & >4.0 mm laterally	268 misplaced; 10.3% medial penetration; 21% lat penetration	no significant difference in accuracy among vertebral levels
Rajasekaran et al., 2007	NN: 16; Nav: 17	NN: fluoroscopy; Nav: Isocentric C-arm (Vector Vision)	NN: 236; Nav: 242	17 ± 7.43/10 M, 23 F	NN: 77%; Nav: 98%	>2.0 mm = significant pedicle breach	NN: 54 breaches; Nav: 5 breaches; greatest error in NN ant/lat body penetration	blood loss: NN: 1100 ml; Nav: 950 ml; screw insertion time: NN: 4.61 ± 1.05 min; Nav: 2.37 ± 0.72 min
Sarlak et al., 2009	19	freehand technique	185	14.8/4 M, 15 F	70.8%	>2.0 mm medially; >6.0 mm laterally	10.8% medial, 18.3% lat breached screws	patients w/ suspicion of misplacement investigated out of 148 (1797 screws)

* ant = anterior; G1...G3 = Grade 1...Grade 3; IPEP = Ideal Pedicle Entry Point; Nav = Navigated technique; neuro = neurological; NN = nonnavigated technique; NR = not reported.

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navigation for this application given the paucity of studies investigating the role of navigation systems in small thoracic pedicle screw placement.

Although we did not have a control group, we compared our results to those of other studies that examined the accuracy of thoracic pedicle screw placement using navigated and nonnavigated techniques. However, this was problematic for several reasons. In our study we specifically looked at small-diameter thoracic pedicles. Many of the studies in the literature did not specify the diameters of the thoracic pedicles, or the pedicles were, on average, a larger diameter than the pedicles in our study. These factors preclude a direct comparison between studies when limiting the scope of the analysis to small-diameter thoracic pedicles.

Conclusions

Computed tomography image-guided surgical navigation is useful in instrumenting small thoracic pedicles in women and allows for safe, effective, and accurate placement of thoracic pedicle screws, even with the in-out-in technique when necessary. Although this study has shown that smaller-than-average thoracic pedicles can be accurately cannulated with O-arm guidance, a larger prospective study comparing results and the accuracy of navigated versus nonnavigated techniques would help to establish the efficacy and justification for increased use of the O-arm in small thoracic pedicles.

Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper. Dr. Kim is a consultant for DePuy.

Author contributions to the study and manuscript preparation include the following. Conception and design: Drazin. Drafting the article: Kim, Jeswani, Drazin, Hsieh, Shweikeh, Friedman. Critically revising the article: Kim, Pashman, Johnson. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Kim. Study supervision: Kim, Drazin, Johnson.

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