An Evaluation of Image-Guided Technologies in the Placement of Anterior Thoracic Vertebral Body Screws in Spinal Trauma: A Cadaver Study

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Abstract

Background: Image guidance provides additional anatomic information to the surgeon, which may allow more accurate insertion of spinal implants. Imprecise placement of anterior thoracic screws places the spinal cord and paraspinal structures at risk for injury. Image guidance may afford a safety benefit to patients when anterior thoracic screws are required in the setting of spinal stabilization after trauma.

Objectives: To compare the accuracy of anterior thoracic screw placement using standard fluoroscopy, computer-assisted fluoroscopic image guidance, Iso-C3D image guidance, and electromagnetic fluoroscopic image guidance.

Study Design: A surgical simulation study in human cadaver spine specimens.

Methods: After an open thoracotomy approach, anterior thoracic screws were placed by experienced spine surgeons using 4 different image-guided techniques in 4 human cadaver thoracic spines. Screws were placed in the 9th, 10th, and 11th thoracic vertebrae of each specimen. The specimens were then examined with thin-cut computed tomography (CT) scans, and with sagittal and coronal reconstructions. Measurements included the distance of the screw from the spinal canal, the angle of the screw path in relation to a perpendicular to a line that bisects the spinous process, and the angle of screw divergence from the superior endplate.

Results: There was no evidence of spinal canal penetrance with any of the image-guided techniques used to place anterior thoracic vertebral body screws. Screws inserted with standard fluoroscopy tended to aim anterolaterally by 18°. The image-guidance systems allowed more accurate placement of anterior thoracic screws in the transverse plane compared with standard fluoroscopy. There was no statistically significant difference in coronal plane screw angulation (angle of divergence with the superior endplate) between any of the imaging methods.

Conclusions: Spinal image-guidance systems may allow spine surgeons to place anterior thoracic screws more precisely, particularly in the axial plane. The improved accuracy of spinal implant insertion could ultimately provide a benefit to patient safety, especially in the setting of malaligned vertebral bodies after trauma.

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Key Words: Image-guided surgery; StealthStation; FluoroNav; Iso-C3D; Spinal instrumentation; Thoracic spine fixation; Anterior thoracic screws; Spinal cord injuries; Trauma

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INTRODUCTION

Unstable fracture dislocations of the thoracic spine often require circumferential reconstruction for adequate stability and optimization of neurologic preservation and return. Anterior vertebral spinal alignment and visual landmarks may be distorted after traumatic disruption, making placement of spinal instrumentation more technically challenging than in nontraumatic spinal disorders. The placement of anterior

spinal instrumentation carries the potential for specific surgical morbidities because of the intimate association of adjacent visceral and vascular structures. In the setting of spinal injury, patients in need of spinal stabilization are often in extremis and require timely and accurate surgical intervention. Surgeons use many intraoperative tools to assist in the safe and accurate placement of spinal instrumentation. Unfortunately, there is a recognized lack of precise anatomic visualization with the use of plain radiography and fluoroscopy. This led to investigations evaluating other technologies, such as computer-assisted spinal navigation and electrophysiologic monitoring, designed to safely assist in surgical instrumentation placement.

Anterior thoracic vertebral screws, which are joined by a longitudinal rod or plate connection, may at times have their starting points of insertion unintentionally too far anteriorly on the vertebral body surface rather than on the more preferred lateral surface. An inappropriately anterior starting point on the vertebral body increases the risk of implant malposition into the spinal canal because the screw is inserted in a posterolateral direction. Furthermore, prominent hardware or implant loosening and migration may result in soft tissue erosion of contiguous structures, such as the esophagus, aorta, or vena cava.

Although lateral insertion of screws is not without risk, there is theoretically less risk of spinal canal penetration if the screws are aimed transversely in the coronal plane, anterior to the vertebral canal (1). Furthermore, if the screws are aimed too far anteriorly or overpenetrate the contralateral vertebral cortex, there is the possibility of great vessel or esophageal penetration and its associated consequences (2).

Anatomical landmarks, such as the rib head, pedicle, and endplates are often used to guide placement of anterior thoracic screws. Deformity resulting from trauma, variation in patient anatomy, and patient positioning can all contribute to errant screw placement. Sucato and Duchene recently reported that the aorta may be directly lateral to the upper and middle thoracic vertebrae in cases of idiopathic scoliosis, as opposed to residing along its anterolateral surface, which is typically the case in spines with normal coronal plane alignment (3).

Image-guided spinal surgery is intended to improve surgical accuracy and minimize morbidity caused by soft tissue handling. Theoretically, the precise anatomic information provided by image-guidance technology should improve the safety and accuracy of spinal implant placement. However, the actual benefit to patient care has yet to be clearly delineated in the literature.

Fluoroscopy provides a 2-dimensional imaging tool that can assist in placement of anterior thoracic vertebral screws, but does not provide any information on the precise location of the nearby soft tissue structures. A computed tomography (CT) intra-operative axial image could provide important information in terms of distance of the screw from the spinal canal, great vessels, and esophagus. Computer-assisted image-guidance systems, once validated, could provide this additional information, which is of great value to the spinal surgeon.

Many recent studies have shown the improved accuracy of pedicle screw insertion throughout the spine with image-guidance technology (4–11). We hypothesize that these same technologies will also improve the accuracy of anterior thoracic vertebral screw insertion, especially in the setting of spinal trauma. This study was conducted to compare 4 methods of spinal imaging: standard fluoroscopy, computer-assisted fluoroscopic image guidance, Iso-C3D image guidance, and electromagnetic fluoroscopic image guidance (Figure 1).

MATERIALS AND METHODS

Four fresh-frozen cadavers were obtained, ranging in age from 51 to 79 years, with an average age of 67 years. Before instrumentation, all specimens were radiographed to exclude the presence of any structural lesions or pronounced spinal deformity. After thawing and positioning in the standard left lateral decubitus position, a standard right-sided thoracotomy approach was

Figure 1. The StealthStation TREON image-guided system (Medtronic Surgical Navigation Technologies, Louisville, CO).

performed on each cadaver, exposing the 8th to the 12th thoracic vertebrae, as confirmed radiographically. The spinal levels were identified using fluoroscopy and counting superiorly from the sacrum. Anterior screws were then placed in the 9th through 11th thoracic vertebrae of each cadaver by an experienced fellowship-trained spine surgeon using 1 of 4 imaging assisting modalities:

Standard Fluoroscopy

After confirmation of the desired thoracic level, the proper starting point on the lateral surface of the vertebral body was identified using anatomical landmarks and anterior/posterior and lateral fluoroscopy. Drilling trajectory was determined based on the same fluoroscopic images. After drilling, the screw path was tapped and a 6.5 mm × 35 mm screw was inserted under direct fluoroscopic guidance. The same steps were performed on the other 2 levels in the same manner.

StealthStation With FluoroNav

The StealthStation with FluoroNav (Medtronic Surgical Navigation Technologies, Louisville, CO) combines an optical tracking camera with the images from a standard C-arm. FluoroNav, coupled with intraoperative fluoroscopic imaging, allows for real-time navigation in multiple planes and reduces the length of radiation exposure while providing anatomical information to the surgeon. The camera tracks a fixed reference frame, which is attached to the cadaver's rib. Before performing the thoracotomy approach, each cadaver was automatically registered by using a C-arm target while obtaining fluoroscopic images. Vertebral levels were confirmed during the registration process and no further fluoroscopic views were obtained during screw insertion. The starting point and trajectory at each vertebral level was identified using FluoroNav (Figure 2). Each screw path was then drilled and tapped. Screws were then inserted at each thoracic level from T9 through T11.

Figure 2. The FluoroNav software, shown navigating the APT (Awl Probe Tap; Medtronic Sofamor Danek, Memphis, TN).

StealthStation With Iso-C3D

The StealthStation with Iso-C3D performs intra-operative 3-dimensional (3D) dataset acquisition and automatic registration of that dataset. It requires the use of a 3D fluoroscopic C-arm that is capable of generating an isotropic 3D dataset and sending these data to other devices via Digital Imaging and Communications in Medicine (DICOM) transfer. The system uses a patient reference frame and C-arm target to relate instrumentation to the patient's anatomy. In this case, the patient reference frame was attached to the cadaver's rib. Each cadaver was scanned before instrumentation with a 190° rotational Iso-C3D scanner (Siremobil Iso-C3D, Siemens Medical Solutions, Erlangen, Germany). Using the StealthStation, the starting points and proper screw trajectory were determined at each level. The screw paths were then drilled and tapped. Screws were then inserted under image guidance at thoracic levels T9 through T11.

StealthStation With FluoroNav EM

The StealthStation with FluoroNav EM uses a “field generator” that emits a low-energy electromagnetic field. The instruments detect these signals and measure their strength. This field is used in conjunction with a reference frame to relate instruments to the patient's anatomy. The reference frame was fixed to the cadaver's rib. This system was a prototype that built on the functionality of FluoroNav. Using FluoroNav EM, the starting point and proper screw trajectory were determined. Each screw path was then drilled and tapped. Screws were then inserted under image guidance at thoracic levels T9 through T11.

Figure 3. The shortest distance from the screw to the spinal canal is shown by the red line.

Figure 4. The angle of the screw to a line perpendicular to a line that bisects the spinous process determines the transverse plane angulation.

Determining Accuracy of Screw Position

Postoperatively, high-resolution CT scans were obtained through the instrumented levels. CT scans were analyzed to assess the position of the anterior thoracic vertebral body screws. Several variables were measured, including the minimum distance of the screw to the spinal canal (Figure 3), the angle of the screw with respect to a perpendicular to the spinous process (Figure 4), and the angle of divergence of the screw with respect to the superior endplate (Figure 5). Distance to the contralateral cortex was not measured because only one length screw

Figure 5. The angle of the screw (B) to a line parallel to the vertebral body endplates (A, C) determines the orientation in the coronal plane.

Table 1. Minimal Distance From Screw to Spinal Canal (in millimeters)

Thoracic Level	Standard Fluoroscopy	FluoroNav	Iso-C3D	FluoroNav EM
T9	8.3	9.0	5.8	6.8
T10	10.4	9.2	7.6	8.3
T11	14.3	10.2	7.2	9.3
Average	11.0	9.5	6.9	8.1

was used throughout the entire process. We defined ideal screw placement as follows: (a) the screw trajectory lies in the coronal plane or perpendicular to a line that bisects the vertebral body through the spinous process, (b) the screw should parallel the superior and inferior vertebral endplates, and (c) the screw should not violate the spinal canal. The screw should be at a safe distance from the spinal canal (5–15 mm) but not placed too far anteriorly to risk contact with contiguous soft tissue structures.

Analysis of variance (ANOVA) was used to compare the mean response of each outcome measurement across the 4 methods. Post hoc pairwise comparisons of individual methods were made using the Tukey approach to *P*-value adjustment for multiple comparisons. Statistical significance was determined using a 5% type I error rate. All analyses were carried out using the SAS statistical software system, version 8.2 (SAS Institute, Cary, NC).

RESULTS

Distance From Screw to Spinal Canal

There was no evidence of spinal canal screw penetration using any image-guidance method. The closest screw to the canal was placed at the T9 level using the Iso-C3D. The closest this screw came to the spinal canal was 5 mm. Screws placed the greatest distance from the spinal canal were placed using standard fluoroscopy (mean, 11.0 mm). The average minimal distances from the screw to the canal were 9.5, 6.9, and 8.1 mm for FluoroNav, Iso-C3D, and FluoroNav EM, respectively (Table 1). The differences among the 4 methods were not statistically significant using the available numbers.

Screw Divergence in Regards to the Transverse Vertebral Plane

Standard fluoroscopically placed screws demonstrated the largest mean angle (18°) of divergence in relation to

Table 2. Angle From Line Perpendicular to Spinous Process Bisector (in degrees)

Thoracic Level	Standard Fluoroscopy	FluoroNav	Iso-C3D	FluoroNav EM
T9	18	8	2	4
T10	19	3	3	5
T11	18	3	3	3
Average	18	5	3	4

Table 3. Angle From Superior Endplate (in degrees)

Thoracic Level	Standard Fluoroscopy	FluoroNav	Iso-C3D	FluoroNav EM
T9	< 5	< 5	< 5	< 5
T10	< 5	< 5	< 5	< 5
T11	< 5	< 5	< 5	< 5
Average	< 5	< 5	< 5	< 5

a perpendicular to a line bisecting the spinous process and anterior vertebral cortex (transverse plane). These screws were consistently angled anteriorly and away from the canal during their insertion. All 3 computer-assisted image-guidance systems allowed more accurate placement in the transverse plane compared with standard fluoroscopy. The average transverse angle of insertion was less than 5° using each of the spinal navigation systems. This was statistically significant when compared with standard fluoroscopy (Table 2).

Screw Divergence in Regards to the Coronal Vertebral Plane

All 4 image-guidance methods accurately assisted in placing screws in the coronal plane. The angle of screw insertion in relation to the superior vertebral endplate was less than 5° for all screws. No statistically significant difference was demonstrated between any of the methods with the numbers available (Table 3).

DISCUSSION

The consequences of a misplaced anterior thoracic screw can be catastrophic. Traditionally, thoracic screws were placed using limited intraoperative anatomical landmarks and palpation after the correct spinal level was identified. Important physical landmarks include the rib head, the pedicle, the neuroforamen, and the exposed endplates at each level. After thoracic trauma, many of these landmarks may be disrupted, removing visual cues to assist in accurate screw placement. Some surgeons, especially those with less experience, have a tendency to direct the screws in an anterior direction away from the spinal canal, to avoid canal penetrance. Although this trajectory does decrease the chance for spinal cord injury, it also increases the potential for soft tissue contact on penetrance of the contralateral vertebral cortex, and decreases the effective chord length of screw bone contact.

Spinal image-guidance systems are designed to decrease surgeon error during anterior thoracic screw placement by demonstrating an ideal screw path trajectory that achieves the best bony fixation and the least potential for injury to contiguous bony or neurovascular structures. The current study demonstrated that screws are often angled in an anterior direction in the transverse plane using standard fluoroscopy alone

(mean 18°). Each of the computer-assisted image-guidance systems provided enough information to enable the surgeon to accurately direct the screws more precisely in the transverse plane, decreasing the potential for great vessel injury while also maintaining a safe distance from the spinal canal. These navigation systems accurately provided information regarding the position of the screw tip relative to the far vertebral cortex and the location of the surrounding neurovascular structures. Image-guided references did not provide any real benefit over standard fluoroscopy in terms of coronal screw placement with regard to the superior vertebral endplate. This may be even less of an issue during open surgical cases after a complete discectomy, which provides an additional visual cue through exposed endplate reference. A discectomy was not performed in the research trial.

Some of the variation in results in this study may be related to anatomic variation between cadavers. Because each cadaver was screened preoperatively to exclude significant spinal deformity, the assumption is made that any effect related to anatomic variance in cadavers is small relative to that caused by the different guidance systems methods.

CONCLUSION

This study clearly demonstrated a benefit to using computer-assisted spinal image guidance for placement of anterior thoracic screws in terms of screw placement and the relation of the placement to the spinal canal as well as in terms of the transverse plane screw trajectory. A benefit could not be identified with regard to coronal screw placement. These findings are very important, because screw position relative to the spinal canal and contiguous soft tissue structures is extremely important in terms of patient safety, especially after trauma.

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REFERENCES

1. Ebraheim NA, Xu R, Ahmad M, Yeasting RA. Anatomic considerations of anterior instrumentation of the thoracic spine. *Am J Orthop*. 1997;26(6):419–424.
2. Matsuzaki H, Tokuhashi Y, Wakabayashi K, Kitamura S. Penetration of a screw into the thoracic aorta in anterior spinal instrumentation. A case report. *Spine*. 1993;18(15):2327–2331.
3. Sucato DJ, Duchene C. The position of the aorta relative to the spine: a comparison of patients with and without idiopathic scoliosis. *J Bone Joint Surg Am*. 2003;85A(8):1461–1469.
4. Kothe R, Matthias Strauss J, Deuretzbacher G, Hemmi T, Lorenzen M, Wiesner L. Computer navigation of parapedicular screw fixation in the thoracic spine: a cadaver study. *Spine*. 2001;26(21):E496–E501.
5. Assaker R, Reyns N, Vinchon M, Demondion X, Louis E. Transpedicular screw placement: image-guided versus lateral-view fluoroscopy: in vitro simulation. *Spine*. 2001;26(19):2160–2164.
6. Odgers CJ IV, Vaccaro AR, Pollack ME, Cotler JM. Accuracy of pedicle screw placement with the assistance of lateral plain radiography. *J Spinal Disord*. 1996;9(4):334–338.
7. Mirza SK, Wiggins GC, Kuntz C IV, et al. Accuracy of thoracic vertebral body screw placement using standard fluoroscopy, fluoroscopic image guidance, and computed tomographic image guidance: a cadaver study. *Spine*. 2003;28(4):402–413.
8. Ludwig SC, Kowalski JM, Edwards CC 2nd, Heller JG. Cervical pedicle screws: comparative accuracy of two insertion techniques. *Spine*. 2000;25(20):2675–2681.
9. Laine T, Lund T, Ylikoski M, Lohikoski J, Schlenszka 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(3):235–240; discussion 241.
10. Kamimura M, Ebara S, Itoh H, Tateiwa Y, Kinoshita T, Takaoka K. Cervical pedicle screw insertion: assessment of safety and accuracy with computer-assisted image guidance. *J Spinal Disord*. 2000;13(3):218–224.
11. Austin MS, Vaccaro AR, Brislin B, Nachwalter R, Hilibrand AS, Albert TJ. Image-guided spine surgery: a cadaver study comparing conventional open laminoforaminotomy and two image-guided techniques for pedicle screw placement in posterolateral fusion and nonfusion models. *Spine*. 2002;27(22):2503–2508.