The development of transpedicular instrumentation has provided the spine surgeon with a multitude of options when planning posterior instrumentation strategies. Although the technique of such instrumentation is becoming commonplace in the everyday practice of spine surgery, it still carries the risks of neural element or vascular injury associated with misplacement. Furthermore, the biomechanical strength of the construct is directly related to the accuracy of instrumentation placement.

The evaluation of the accuracy of transpedicular thoracolumbar instrumentation is a subject of great interest in the spine community as we attempt to limit complications and improve patient outcomes. This has led to numerous published evaluations of the accuracy of pedicle screw placement and the development of innovative techniques to improve the accuracy of instrumentation.

Currently, several techniques are used to assist the surgeon with placement of posterior instrumentation. These include free-hand techniques using anatomical landmarks, fluoroscopy, and image-guided navigation systems that typically use intraoperative fluoroscopy or preoperative CT scanning. The use of image-guided navigation systems has been shown to improve accuracy and safety in the placement of posterior instrumentation.

We present a novel application of image guidance technology combined with intraoperative CT scanning. The technique is performed in a new operative suite equipped with a CT scanner interfaced with the operative table, allowing rapid CT scanning of the sterile surgical field.

Intraoperative computed tomography image–guided navigation for posterior thoracolumbar spinal instrumentation in spinal deformity surgery

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Object. Placement of thoracolumbar pedicle screws in spinal deformity surgery has a reported inaccuracy rate as high as 30%. At present, image-guided navigation systems designed to improve instrumentation accuracy typically use intraoperative fluoroscopy or preoperative CT scans. The authors report the prospective evaluation of the accuracy of posterior thoracolumbar spinal instrumentation using a new intraoperative CT operative suite with an integrated image guidance system. They compare the accuracy of thoracolumbar pedicle screw placement using intraoperative CT image guidance with instrumentation placement utilizing fluoroscopy.

Methods. Between December 2007 and July 2008, 12 patients underwent posterior spinal instrumentation for spinal deformity correction using intraoperative CT-based image guidance. An intraoperative CT scan of the sterile surgical field was obtained after decompression and before instrumentation. Instrumentation was placed, and a postinstrumentation CT scan was obtained before wound closure to assess the accuracy of instrumentation placement and the potential need for revision. The accuracy of pedicle screw placement was later reviewed and recorded by independent observers. A comparison group of 14 patients who underwent thoracolumbar instrumentation utilizing fluoroscopy and postoperative CT scanning during the same time period was evaluated and included in this analysis.

Results. In the intraoperative CT-based image guidance group, a total of 164 thoracolumbar pedicle screws were placed. Two screws were found to have breached the pedicle wall (1.2%). Neither screw was deemed to need revision due to misplacement. In the comparison group, 211 pedicle screws were placed. Postoperative CT scanning revealed that 11 screws (5.2%) had breached the pedicle. One patient in the fluoroscopy group awoke with a radiculopathy attributed to a misplaced screw, which required revision. The difference in accuracy was statistically significant (p = 0.031).

Conclusions. Intraoperative CT-based image guidance for placement of thoracolumbar instrumentation has an accuracy that exceeds reported rates with other image guidance systems, such as virtual fluoroscopy and 3D isocentric C-arm-based stereotactic systems. Furthermore, with the use of intraoperative CT scanning, a postinstrumentation CT scan allows the surgeon to evaluate the accuracy of instrumentation before wound closure and revise as appropriate. (DOI: 10.3171/2010.1.FOCUS09275)

Key Words • neuronavigation • image guidance • spinal deformity • spinal instrumentation • intraoperative computed tomography
field. This application increases accuracy and safety of instrumentation while allowing the surgeon an intraoperative assessment of instrumentation placement.

Methods

Patient Population

Between November 2007 and July 2008, 12 patients underwent posterior spinal instrumentation using intraoperative CT-based image-guided navigation for spinal deformity. All screws were placed under the direction of the senior surgeon (D.O.O.). A comparison group of 14 patients who underwent thoracolumbar instrumentation utilizing fluoroscopy during the same time period and who had postoperative CT scans was evaluated and included in this analysis. All patients in the comparison group underwent surgery for correction of scoliosis.

Operative Technique

In the image guidance group, patients underwent intraoperative CT-based image guidance of spinal instrumentation in a newly installed intraoperative suite at UPMC Presbyterian Hospital (Fig. 1). Patients underwent induction of general anesthesia and were then placed prone. Surgical exposure was carried out in routine fashion. If removal of hardware was planned, this was carried out prior to CT scanning. Reference fiducials were then placed in rigid bone landmarks. An intraoperative CT scan of the operative field was then obtained using a 64-slice multidetector CT scanner (GE LightSpeed). Contiguous 0.625- or 1.25-mm images at 120 kVP and 240 mA were obtained. Image acquisition time was < 1 minute in all cases.

Because of the design and movement of the CT scanner table, intraoperative CT scanning of the sterile field is possible. Patients are draped using 4 sterile drapes in a square block-drape fashion. Prior to beginning the scan, the wound is covered with an antimicrobial adhesive dressing. The entire operative field is then covered with another sterile drape, and all operative instruments placed on a sterile table away from the field (Fig. 1). Following CT scanning, the drape is removed and the adhesive dressing is incised to expose the wound. A new adhesive drape and 4 sterile drapes are used to recreate the sterile operative field. Using this method, no patient in this series suffered a wound infection. A 3D volume set of contiguous axial CT images was uploaded to an image guidance workstation (Stryker). Reference fiducials in the surgical field were registered after securing the image guidance tracker to a spinous process. System accuracy ranged between 1.0 and 1.8 mm.

Coronal, axial, sagittal, and trajectory views are available to the surgeon in real time during drilling, tapping, and placement of instrumentation (Fig. 2). Prior to placement of screws, the pedicle tract is palpated using a ball-tipped “feeler” probe. This was performed in both the image guided and fluoroscopy groups. Triggered electromyography was used in the non–image guidance cases to assess for potential pedicle breeches by lumbar pedicle screws. A threshold of 10 mA is used. Any screw with nerve root stimulation at < 10 mA is removed and revised.
Intraoperative CT image–guided navigation for deformity surgery

as necessary. Triggered electromyography was used in an early subset of the CT image guidance cases. Rods and set screws were placed on each side to complete the screw-rod construct. A final intraoperative CT scan through the region was obtained to confirm proper placement, trajectory, and length of all screws before wound closure.

Patients in the fluoroscopy group underwent similar procedures for induction, exposure, and decompression. Instrumentation was placed with serial lateral fluoroscopic images. Anatomical landmarks and direct visualization were used to confirm the mediolateral trajectory. Following surgery and extubation, the patients underwent CT scanning to assess accuracy of instrumentation placement, as is our standard postoperative protocol in patients with spinal deformities.

Postoperative Evaluation

The postoperative CT scans were reviewed by 2 independent observers. The main objective was to determine if any screws were malpositioned. Once malpositioned screws were identified, the spinal level, positioning, and the presence of impingement or invasion of adjacent neurovascular structures were recorded. Follow-up radiographs were evaluated for the presence of instrumentation failure and pseudarthrosis.

Results

Image Guidance Group

One-hundred sixty-four pedicle screws were placed in 12 patients via a posterior approach using the aforementioned intraoperative CT guidance protocol. Of these screws, 85 were placed in the thoracic spine and 79 in the lumbosacral spine.

Independent, blinded review of postinstrumentation CT scans revealed that 2 screws (1.2%) breached the pedicle cortex. Both screws were located in the thoracic spine. We reviewed the operative reports of these 2 patients after unblinding the data. In 1 patient, a right-sided T-5 screw broke through the cortex medially. Notation was made to leave the screw in place, as less than half of the screw diameter had penetrated the pedicle wall and there was no impingement on adjacent neural elements. The second patient had a left-sided T-8 screw minimally breach the medial pedicle wall. Again, it was noted that

**Fig. 2.** A screen capture from the image guidance screen during pedicle probing. Coronal, axial, sagittal, and trajectory views are available to the surgeon in real time during drilling, tapping, and placement of instrumentation.
the spinal canal and adjacent structures were not at risk, so the decision was made to leave the screw in its initial position. The overall accuracy for the image guidance group was 98.8%.

No intraoperative instrumentation-related complications (that is, screw breakage, pedicle fracture, or neurovascular injury) were encountered during any of these procedures. Following postinstrumentation intraoperative CT scanning, the surgeons determined that all screws were in a satisfactory position and no screws were revised during the initial procedure. The mean follow-up for patients undergoing CT-based image guidance was 16.8 months (range 14–21 months). During the follow-up period, no patient showed evidence of instrumentation failure or pseudarthrosis. No patient required reoperation for revision of instrumentation.

**Fluoroscopy Group**

In the comparison group, 211 screws were placed in 14 patients. Ninety-one screws were placed in the thoracic spine, and 120 were placed in the lumbar spine. Eleven screws were found to breach the pedicle wall. The overall accuracy for the fluoroscopy group was 94.8%. The difference in accuracy between the 2 systems was found to be statistically significant (p = 0.031).

Postoperatively, 1 patient awoke with a radiculopathy attributable to a medially misplaced screw. This patient returned to the operating room for revision of this screw. Two patients in the comparison group had postoperative wound infections that required operative debridement.

**Discussion**

Intraoperative CT-based spinal navigation is an effective and accurate means of achieving complex instrumentation of the thoracolumbar spine. Its use improves the accuracy of instrumentation placement and decreases the risk to adjacent neurovascular structures. Furthermore, with intraoperative CT-based image guidance, the operating room staff is spared the radiation exposure of traditional procedures that use fluoroscopy.

The accuracy of intraoperative CT-based image guidance is maximized because the images off of which the guidance is performed are obtained with the patient in the same position as that during placement of the instrumentation. Fiducial reference markers are placed after exposure and within millimeters of the intended starting points for the instrumentation, further enhancing accuracy of the image guidance.

The use of intraoperative CT-based spinal navigation allows real time feedback to the surgeon of instrumentation placement in the coronal, sagittal, and axial planes. Any errors in starting point, trajectory, screw size, or anatomical relationships may be corrected through adjustment of the drill. Final instrumentation placement is assessed by a second intraoperative CT scan such that any suboptimal screw may be replaced at the surgeon’s discretion if necessary.

A major concern of spine surgeons when placing instrumentation is the accuracy with which the instrumentation has been placed. A recent meta-analysis on pedicle screw placement accuracy found a median accuracy for thoracolumbar instrumentation without navigation to be 86.6% (range 27–100%) when compared with a navigation-assisted median accuracy of 93.7% (range 72–100%). In our series, all lumbar/lumbosacral instrumentation was accurately placed within the pedicle 100% of the time. An analysis of our thoracic instrumentation showed 2.4% of our thoracic pedicle screws (1.2% of all screws placed) were outside of the pedicle. However, neither screw had more than half of its diameter outside of the pedicle. No neurovascular structures were impinged on, and no significant change in spinal canal diameter resulted. In our series, image guidance was superior to fluoroscopy. Three patients in the fluoroscopy group required a second surgery, including a patient who required instrumentation revision for neurological impingement.

The use of 3D image guidance software also allows not only for placement of instrumentation within the boundaries of the pedicles but also with the desired axial and sagittal angles required to maximize construct strength. Surgical correction of spinal deformity requires that implants withstand the force necessary to achieve the correction. Increasing biomechanical stiffness will lead to higher arthrodesis rates. Maximizing bone-implant interface assists in resisting pullout. In the thoracic and lumbar spine, triangulation of pedicle screws has been shown to significantly increase pullout strength in in vitro studies. The surgeon may maximize convergence, as well as screw size, via surgical planning on the axial images provided by the navigational software. Further strength may be added to the construct by choosing an optimal sagittal trajectory. A biomechanical study by Lehman et al. showed an increase in pullout strength if transpedicular instrumentation was placed parallel to the endplate rather than down the axis of the pedicle. The sagittal reconstructions afforded by intraoperative image guidance allow the surgeon to capitalize on real-time imaging to place instrumentation parallel to the endplate and maximize pullout strength.

Current image guidance systems can be classified by the imaging they use and include standard fluoroscopy and 3D C-arm fluoroscopy systems. A weakness of a standard C-arm image guidance system is the lack of coronal and sagittal reconstructions that allow the surgeon a real-time visual feedback regarding the trajectory of instrumentation.

Three-dimensional C-arm fluoroscopy is able to account for many of the limitations of fluoroscopy-based systems. The systems rely on an isocentric C-arm fluoroscope combined with a navigational computer. The images can be reconstructed in 3D to provide axial, coronal, and sagittal reconstructions. In addition, intraoperative and postinstrumentation imaging can be obtained to assess accuracy. Application of this technology to spinal instrumentation has provided encouraging results and it is readily available. While image quality of 3D C-arm fluoroscopy is an improvement, it is not on par with thin-slice CT scanning. In the face of complex deformity, image quality allows for improved accuracy during utilization of image-guided navigation systems. The new intraoperative CT scanner at our institution provides for
Intraoperative CT image–guided navigation for deformity surgery

Improved image quality, and the accuracy of instrumentation reported herein confirms that.

The introduction of intraoperative CT in the 1980s enabled surgeons to adapt their operative plans with up-to-date high-resolution imaging. While the use of intraoperative CT scanning in spinal surgery is not new, we believe we are the first to report its marriage to imaging guidance for instrumentation placement in complex spinal deformity. Our use of intraoperative CT scanning with spinal neuronavigation eliminates the disadvantages of other navigational systems. The image-guidance CT scan is obtained with the patient in the operative position and takes into account operative decompression or surgical landmark manipulation. The images obtained are thin-slice CT images of the same quality as those obtained using diagnostic CT scanners. This resolution is absolutely necessary when attempting to maximize screw length, diameter, and trajectory in the vicinity of neurovascular structures.

A criticism of this technology is the cost required to install and use an intraoperative CT suite. The debate rests between the cost of installation of this system and the cost of reoperation in patients with misplaced screws. Our current investigation is not able to address a cost-benefit analysis as sample size and length of follow-up are insufficient to power such a study. As our experience grows, we hope to make this a focus of future analyses.

An important issue is whether intraoperative imaging may lead to unnecessary replacement of radiographically suboptimal screws that are otherwise not clinically significant. Unnecessary repositioning of screws places the patient at an increased risk for complications related to screw placement and runs the risk of biomechanically weakening the construct. Of the 164 screws placed in the image guidance group, none were revised following the second intraoperative scan. This includes the 2 screws that were deemed suboptimal. The surgeon must judge whether the risks of replacing a screw outweigh the potential clinical implications of its misplacement. For each of the 2 misplaced screws in the CT image–guided group, the surgeon made a conscious decision not to revise the screws as neither vascular nor neural elements were at risk.

Conclusions

Intraoperative CT-based spinal navigation for the placement of thoracolumbar pedicle screw instrumentation improved accuracy to 98.22%. It also allowed for revision of misplaced instrumentation before closure. When compared with standard fluoroscopy, intraoperative CT-based spinal navigation significantly improves the accuracy of instrumentation placement.

Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author contributions to the study and manuscript preparation include the following. Conception and design: DO Okonkwo, PA Gardner, RM Spiro. Acquisition of data: DO Okonkwo, MJ Tormenti, PA Gardner, AS Kanter, RM Spiro. Analysis and interpretation of data: DO Okonkwo, MJ Tormenti, DB Kostov. Drafting the article: DO Okonkwo, MJ Tormenti, DB Kostov. Critically revising the article: DO Okonkwo, MJ Tormenti, AS Kanter, RM Spiro. Reviewed final version of the manuscript and approved it for submission: DO Okonkwo, MJ Tormenti, DB Kostov, AS Kanter.

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