

Frameless stereotaxy for anterior spinal procedures

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Object. Intraoperative image guidance provides real-time three-dimensional visualization and has been successfully applied in many posterior spinal procedures. The feasibility of applying these techniques to anterior spinal surgery has not been studied systematically because the anterior spine, in contrast to the posterior spine, lacks distinct anatomical landmarks for registration. The authors sought to evaluate the practicality of performing stereotaxy in the anterior spine in a cadaveric model.

Methods. Unilateral C4–L4 pedicle screws were placed posteriorly in three cadaveric specimens to serve as unknown markers within each vertebral body. The specimens then underwent computerized tomography (CT) scanning, and the CT data were transferred to an optical tracking system. The anterior surface of the spine was registered for use with the stereotactic system by using a paired point–matching technique. Attached to a surgical drill, K-wires were placed under stereotactic guidance in a tip-to-tip orientation with the posterior pedicle screws. A second postoperative CT scan was obtained, and accuracy was determined by measuring the distance between the tips of the K-wire and pedicle screw.

The K-wires were placed tip to tip with pedicle screw markers in 57 vertebral levels. The mean registration error was 1.47 ± 0.04 mm, and when combined with the universal instrument registration error of 0.7 mm yielded an overall registration error of 2.17 ± 0.04 mm. The mean tip-to-tip distance for all K-wires placed was 2.46 ± 0.23 mm. The difference between the mean tip-to-tip distance and overall registration error was not statistically significant ($p > 0.05$), indicating that the K-wires were placed within the expected range of error.

Conclusions. The results of this study confirmed the feasibility of performing anterior stereotactic procedures throughout the spine. The accuracy of the findings in this study indicates that anterior stereotaxy should be applicable in clinical practice.

KEY WORDS • anterior approach • stereotaxy • spine

INTRAOPERATIVE image guidance has been successfully applied in many posterior spinal procedures such as C1–2 transarticular¹⁰ and lumbar pedicle screw placement.^{5,8} Anterior spinal procedures are very common in the cervical spine, and anterior thoracic and lumbar procedures are also increasing in frequency in the era of modern spinal reconstruction. The feasibility of applying these techniques to anterior spinal surgery, however, has not been well studied because of the paucity of distinct anatomical landmarks for registration. In this study we evaluate the practicality, efficacy, and accuracy of anterior spinal stereotaxy in a cadaveric model.

Materials and Methods

Three embalmed adult cadavers were used for this study. Following posterior soft-tissue exposure, unilateral pedicle screws were placed posteriorly from C-4 to L-4 to serve as unknown mark-

ers within each VB. The specimens then underwent CT scanning (General Electric, Milwaukee, WI). Data were obtained in 1-mm slices in the cervical region and 3-mm slices in the thoracic and lumbar regions on data-acquisition tapes and then transferred to the Radionics OTS (Radionics; Burlington, MA) workstation. The cadavers were placed supine for cervical and semilateral for thoracolumbar exposures on the operating table. A dynamic reference frame was attached to a Caspar distraction pin placed in the VB immediately superior to the level of interest (Fig. 1 *upper*). The vertebral level of interest was then registered using standard paired point–matching techniques with five points to correlate the position of the patient in the operative space with the CT scan data featured on the OTS workstation (Fig. 1 *center and lower*). In the cervical and lumbar regions all five points were chosen from the VB surface. In the thoracic region, the pleura was reflected, and two points were obtained from the rib head, one from the inferior rib head, and two from the VB surface.

A K-wire was placed in a pneumatic surgical drill mounted with an array of light-emitting diodes for the OTS. This was then calibrated for use with the frameless stereotactic system by using UIR techniques.⁶ An entry point was selected contralateral to the previously placed pedicle screw, and the K-wire (2.4-mm diameter for cervical, and 2.8-mm diameter for thoracic and lumbar regions) was drilled under real-time image guidance along this trajectory until the K-wire appeared to be in a tip-to-tip orientation with the pedicle

Abbreviations used in this paper: CT = computerized tomography; OTS = optical tracking station; UIR = universal instrument registration; VB = vertebral body.

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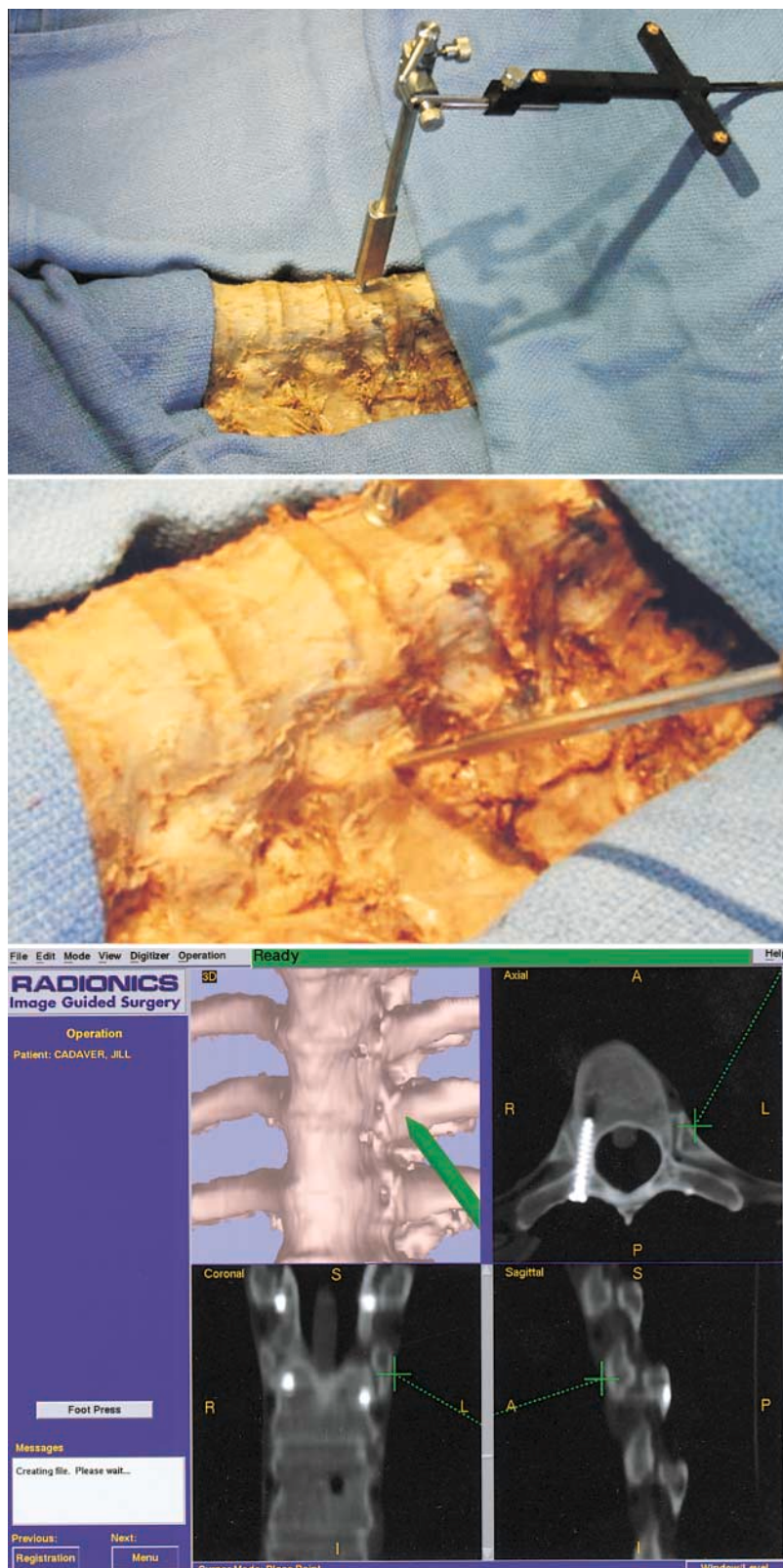


FIG. 1. *Upper:* Dynamic reference frame with an array of light-emitting diodes attached to the VB by a Caspar distraction pin. *Center:* The standard probe is being used to identify the rib head to verify the accuracy of registration. *Lower:* Computer workstation printout showing the probe touching the rib head, demonstrating good correlation between the specimen anatomy in the operative space and the CT data.

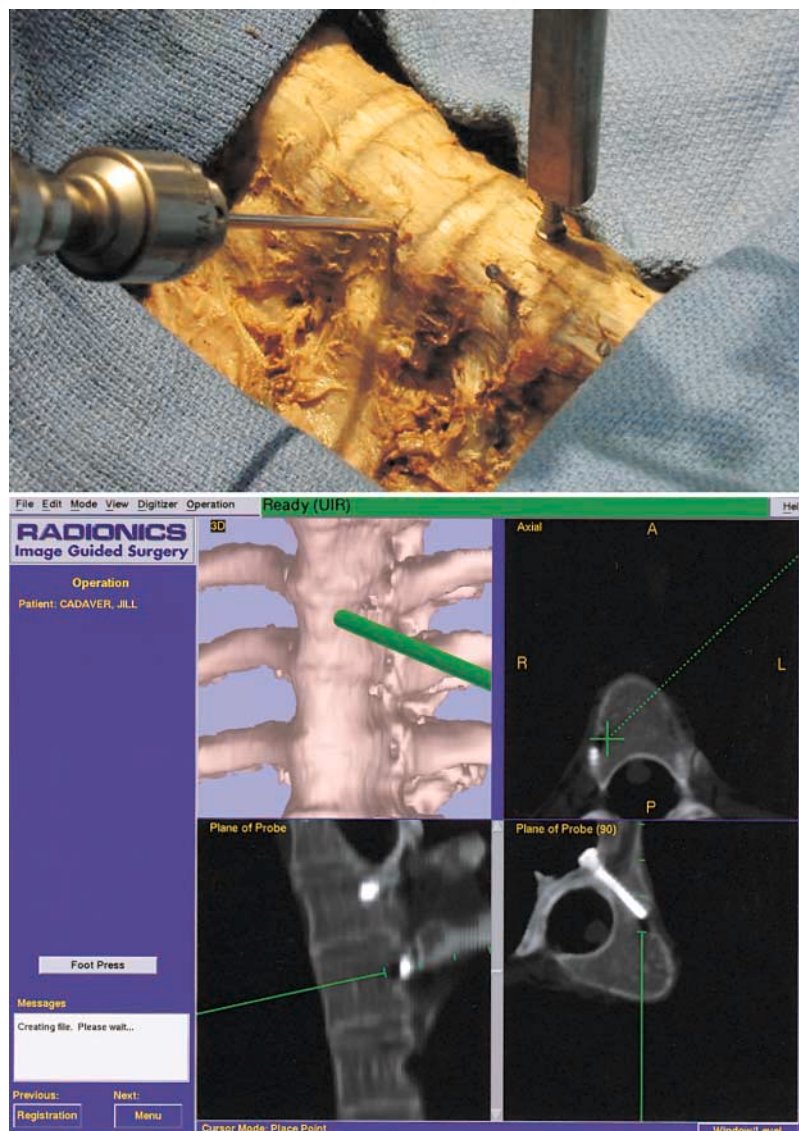


FIG. 2. Upper and Lower: A K-wire being stereotactically drilled into the VB.

screw on the OTS workstation (Fig. 2). The K-wire was then carefully detached from the drill and left in place in the VB (Fig. 3). The dynamic reference frame attached to the Caspar pin was then moved to the next caudal level, and the registration process was repeated at the adjacent inferior VB.

The accuracy of K-wire placement was determined by evaluating postoperative CT scans (Fig. 4). The spatial distance from the tip of the K-wire to the tip of the pedicle screw was measured using the OTS workstation and compared with the computer-reported registration error. The statistical significance of the difference in measurements was determined using a paired-point Student t-test.

Results

The K-wires were placed tip to tip with posterior pedicle screw markers in a total of 57 VBs (Table 1). Three levels were excluded because of suboptimal pedicle screw placement. The mean registration error was 1.47 ± 0.04 mm, with a mean of 3.9 attempts per VB level at registration by using the paired point-matching technique. Be-

cause UIR was used to calibrate the drill with the K-wire for stereotactic use, the inherent error in the technology was included in the overall registration error. The authors of previous studies have indicated that the UIR calibration increases registration error by 0.7 mm.⁶ Therefore, the overall mean registration error resulting from paired-point registration and UIR calibration was 2.17 ± 0.04 mm. The mean tip-to-tip distance for all 57 K-wires placed was 2.46 ± 0.23 mm. The difference between the mean tip-to-tip distance and overall registration error was not statistically significant ($p > 0.05$). The K-wire trajectory through the VB from entry point to end point was an average distance of 25.6 mm.

Discussion

Evolution of Frameless Stereotaxy

Frameless stereotaxy was initially developed for in-

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FIG. 3. Cadaveric specimen following K-wire placement in cervical and thoracic spine.

tracranial surgery and has recently been adapted for spinal applications.³⁻⁵ The initial transition from intracranial to spinal surgery was difficult because the skin surface fiducials were subject to significant errors from movement in

reference to the fixed bone anatomy, resulting in unacceptable rates of inaccuracy. Brodwater, et al.,³ reported mean error rates of 6 mm superficially on the skin surface, which increased to 28 mm when attempting to localize the disc space. Based on their experience with spinal stereotaxy in which skin fiducials were used, Roessler, et al.,⁹ concluded that the poor accuracy of spinal stereotaxy precluded its clinical usage.

Foley and Smith⁴ described the use of easily distinguishable anatomical landmarks on the posterior aspect of the spine as fiducial points. These anatomical fiducials obviated the need for superficial fiducial markers and significantly improved accuracy of the technique. Furthermore, these internal registration markers provided increased flexibility with the ability to change or add markers at the time of surgery. Kalfas, et al.,⁵ similarly used the exposed spinal column for registration and determined that frameless stereotaxy could be safely used to guide lumbar pedicle screw placement. This technology has continued to evolve, and frameless stereotaxy is now routinely used for other posterior spinal procedures such as C1-2 transarticular and thoracic pedicle screw placement.

Frameless Stereotaxy in the Anterior Spine

Despite the emergence of posterior spinal frameless stereotaxy and the increasing frequency of anterior spinal surgery, very little information has been reported regarding the application of stereotaxy to the anterior spine. The relevant literature is essentially limited to studies involving the cervical spine.^{1,2,7} Albert, et al.,¹ performed lateral anterior corpectomy in four cadavers, using an image-guided burr on one side and non-image guided burr on the other side. The troughs at each level were planned so that the lateral border of the trough would be 4 mm medial to the transverse foramen. They measured the distances and concluded that image guidance tended toward improved accuracy ($p = 0.08$) and less variability when compared with the standard technique, suggesting potentially useful clinical applications. Klein, et al.,⁷ using an image guid-

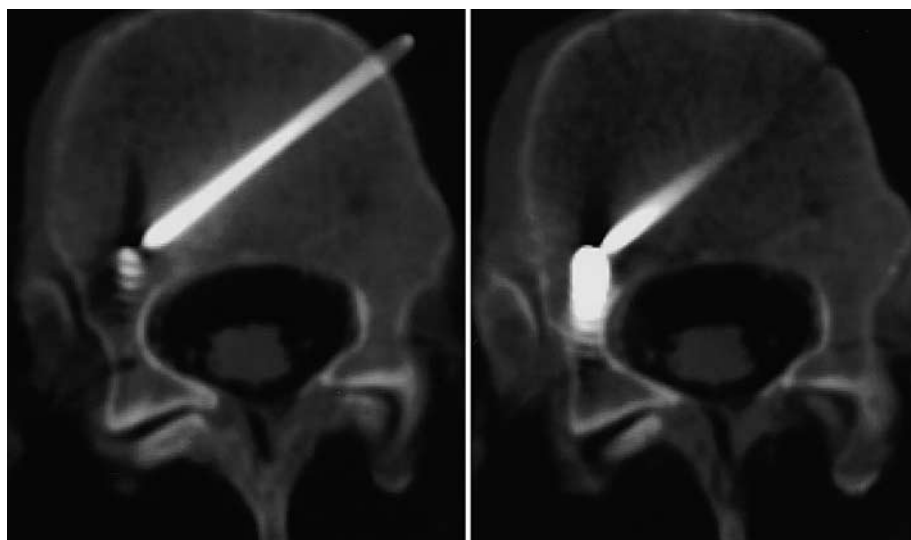


FIG. 4. Two contiguous postoperative axial CT scans demonstrating accurate placement of the K-wire.

TABLE 1
Summary of mean registration and measured errors
in the cadaveric specimens

Spinal Region	No. of VBs	Registration Error (mm)*	Measured Error (mm)†
cervical	10	1.26 ± 0.15	3.18 ± 0.63
thoracic	35	1.49 ± 0.06	2.03 ± 0.24
lumbar	12	1.55 ± 0.06	3.12 ± 0.61
total	57	1.47 ± 0.04	2.46 ± 0.23

* Obtained using paired-point matching of the five selected registration points.

† Determined by measuring the distance between pedicle screw tip and K-wire tip.

ed Kerrison instrument, performed anterior cervical foraminotomies in 12 cadavers without causing vertebral artery injury. In a series of 40 patients with cervical spondylosis, Bolger, et al.,² described the use of anterior cervical frameless stereotaxy to guide successful osteophyte resection and screw insertion for anterior cervical plate fixation.

The registration procedure posed the most significant difficulty to these authors primarily because of a paucity of distinct landmarks for registration on the relatively smooth VB surface.² Albert, et al.,¹ were only able to use a paired point-matching technique on three of 16 levels, and they relied mostly on surface matching to provide accurate registration. The process of surface matching added significant time to the procedure because, in some instances, approximately 100 points were required. Klein, et al.,⁷ similarly found registration inaccuracies with paired-point registration and often used surface matching, which also prolonged the procedure. Bolger, et al.,² were unable to obtain acceptable levels of registration (that is, < 2 mm) in their first seven patients. They then performed a more extensive anterior cervical exposure and used the medial margins of the transverse process as distinct landmarks, which resulted in improved registration accuracy.

Although, as in our study design, a K-wire is not stereotactically aimed at a hidden target in humans, the issues of landmark registration on the anterior spine and the accuracy of anterior spinal stereotaxy are clinically relevant. This is particularly true in the thoracic and lumbar spine, where image guidance has not been previously studied systematically. Using a five paired point-matching technique, we were able to obtain mean registration errors of less than 1.5 mm with an average of fewer than four attempts at registration. Our experience indicates that it is feasible to register the anterior spine with acceptable error rates while not significantly prolonging the procedure time. The registration error and number of attempts both improved with operator experience, suggesting that both of these results improve with the learning curve. The UIR error associated with converting from the standard probe to the customized instrument (the drill with K-wire) for this system is 0.7 mm and is combined with the registration error to yield the overall registration error.⁶

The lack of a statistically significant difference ($p > 0.05$) between tip-to-tip distance and the overall registration error (2.46 ± 0.23 mm and 2.17 ± 0.04 mm, respectively) indicates that the stereotactic system is sufficiently

accurate to be used in anterior spinal procedures. It is evident, however, that the mean tip-to-tip distances were quite similar and slightly higher in the cervical and lumbar regions (3.18 ± 0.63 mm and 3.12 ± 0.61 mm, respectively) than in the thoracic (2.03 ± 0.24 mm). This likely corresponds to the similar smooth contour of the anterior spinal surface found at the cervical and lumbar levels. Although the overall registration errors were not significantly different among these regions, it is likely that the rib heads provided the thoracic vertebrae with distinct landmarks, which likely improved the accuracy of registration.

Furthermore, in clinical applications registration may not be as accurate in the cervical and lumbar regions because there is more movement between adjacent VBs than in the thoracic region. This allows for the possibility that the relationship between the vertebral levels in the operative position is different from that demonstrated on the preoperative CT scan. Specifically, in an anterior approach to the lumbar spine performed with the patient in a decubitus position, the relationship would be different from that depicted when the patient was supine in the CT scanner. Presently this concern is dealt with through careful registration until the workstation image best correlates with the patient's anatomy. Future advances in image-guided technology will likely provide independent registration and tracking of adjacent vertebrae, allowing intraoperative alterations to the preoperative CT scan data to reflect the intraoperative position of the patient.

As anterior spinal surgery becomes more prevalent in the treatment of spinal disorders, the role of image guidance may become more important and better defined. Presently, the most common indication appears to be anterior spinal decompression for cervical spondylosis. Image guidance may decrease the risk of two significant complications from this procedure—vertebral artery injury and incomplete decompression. Another application is in cases of ossification of the posterior longitudinal ligament in which residual bone can be missed. Frameless stereotaxy may also improve the safety of anterior decompression and placement of spinal instrumentation in the surgical management of tumors, spinal deformity, and trauma within the thoracic and lumbar region.

Conclusions

The results of this study confirm the feasibility of performing anterior spinal stereotactic procedures. Despite the lack of distinct anatomical landmarks, there was no statistically significant difference between the overall registration error and the actual measured error in any region of the spine. These findings validate the accuracy of our study and indicate the potential use of anterior spinal stereotaxy in clinical practice.

Disclosure

The authors have no financial interest in the instrumentation or methodology described in this manuscript.

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