Interactive frameless stereotaxy has been successfully applied to intracranial surgery. It has contributed to the improved localization of deep-seated brain lesions and has demonstrated a potential for reducing both operative time and morbidity. However, it has not been as effectively applied to spinal surgery.

The authors describe the application of frameless stereotactic techniques to spinal surgery, specifically pedicle screw fixation of the lumbosacral spine. Preoperative axial computerized tomography (CT) images of the appropriate spinal segments are obtained and loaded onto a high-speed graphics supercomputer workstation. Intraoperatively, these images can be linked to the appropriate spinal anatomy by a sonic localization digitizer device that is interfaced with the computer workstation. This permits the surgeon to place a pointing device (sonic wand) on any exposed spinal bone landmark in the operative field and obtain multiplanar reconstructed CT images projected in near-real time on the workstation screen. The images can be manipulated to assist the surgeon in determining the proper entry point for a pedicle screw as well as defining the appropriate trajectory in the axial and sagittal planes. It can also define the correct screw length and diameter for each pedicle to be instrumented.

The authors applied this device to the insertion of 150 screws into the lumbosacral spines of 30 patients. One hundred forty-nine screws were assessed to be satisfactorily placed by postoperative CT and plain film radiography. In this report the authors discuss their use of this device in the clinical setting and review their preliminary results of frameless stereotaxy applied to spinal surgery. On the basis of their findings, the authors conclude that frameless stereotactic technology can be successfully applied to spinal surgery.

KEY WORDS • spine • stereotaxis • operative technique • pedicle fixation
The wand can then be removed and a drill inserted through the drill guide. The drill is used during the orientation process. The drill guide is used during the orientation process to mark the location of the entry point and the angle of trajectory. The same wand can be used for the registration and orientation process.

Sonic Localization

The hand-held wand, which contains two spark-gap emitters, is interfaced with the sonic digitizer system and the computer workstation. When activated, the wand emits a series of sequential ultrasonic pulses. Localizing the emitters in space (by means of their Cartesian x, y, and z coordinates) is determined by triangulating the distances, or range values, measured by digitizer electronics. The range values are determined using the time delay between pulse emission and detection at an array of four microphones mounted on the operating table or a separate stand. For each digitization, an accuracy check is performed using the known distance between emitters on the wand and that obtained during each digitization process. The wand tip position and orientation are calculated from the determined coordinates of the two emitters. The shape of the wand, customized for spinal surgery, allows it to be used as a registration tool and, when combined with a hand-held drill guide, as an orientation tool as well (Fig. 1).

Neuroimaging and Display

A three-dimensional volume dataset of contiguous axial CT images throughout the proposed surgical field is obtained. Scan parameters include a 2-mm slice thickness, a field-of-view of 25.6 cm, and a 512 × 512-pixel image matrix yielding an inplane resolution of 0.5 mm. The images have their pixels averaged in each plane and are interpolated in the slice direction to yield a CT volume dataset consisting of cubic 1.0-mm isotropic voxels. The images are presented intraoperatively to the surgeon in a multiplanar reformatted fashion. In addition to the standard coronal, sagittal, and axial planes, a set of an armless, frameless stereotactic wand and sonic digitizer has been previously described. The main components of the system include an ultrasonic three-dimensional digitizer (Science Accessories, Stratford, CT) interfaced with an image processing workstation that consists of a powerful graphics supercomputer (Picker International, Highland Heights, OH). Customized, hand-held wands provide an interface between the surgeon and the workstation. The application of this technology to spinal surgery, however, differs from its use for localizing intracranial lesions in that skin-surface reference points (fiducials) are not used. The movement and variation of the skin surface overlying a bone landmark of the spinal column (for example, the spinous process tip) as well as the deformity of paraspinal tissues makes these fiducial markers unreliable reference points for spinal surgery.

The surface anatomy of the exposed spinal column provides a more reliable set of reference marks. Specifically, any bone landmark that can be identified intraoperatively as well as in a preoperative image dataset can be used as a frame of reference. Three reference points at a single exposed spinal level (for example, tips of the spinous process and the two transverse processes) are selected, or registered, intraoperatively and used as reference points to link the image dataset to the spinal anatomy. The wand and localization system can then be used intraoperatively to manipulate the image dataset and correlate it with the exposed spinal anatomy.

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three orthogonal views referenced to the orientation of the wand can be displayed. In most applications to spinal surgery, these views consist of a near-sagittal, near-coronal, and near-axial view. A cursor and a trajectory line with a diameter and width that can be adjusted in proportion to the selected screw diameter indicate the proposed location and the trajectory path through any point in the operative field. The length of the trajectory line relative to the imaged spine is displayed in millimeters, allowing screw length to be selected more accurately (Fig. 2 upper and center).

The images can be manipulated intraoperatively to show corresponding spinal anatomy in multiple planes and at a range of depths. By adjusting the length of the trajectory line so that its distal end lies at the midpedicle level in the near-axial and near-sagittal views, a near-coronal reconstructed image, corresponding to the end of the trajectory line, can be generated. With the correct entry point and trajectory selected, the near-coronal view will show a cursor lying within the boundaries of the pedicle on cross section. As the trajectory line is extended through the image set, the near-coronal plane will adjust accordingly to indicate the final position of a screw tip placed along that trajectory. Significant errors in sagittal angulation of the drill guide–wand assembly will place the cursor in either disc space adjacent to that pedicle. Errors in axial angulation of the drill guide–wand assembly or selected entry point in the coronal plane will place the cursor outside the boundaries of the vertebral body, the pedicle wall, or both (Fig. 2 lower).

Accuracy Analysis

A preliminary study of the practical accuracy and associated errors of the registration and localization procedure was performed on a plastic phantom using the sonic digitizer and the graphic supercomputer. Small nylon washers were attached to the phantom at six different positions covering an approximate volume of 1200 cc. A volumetric CT scan of the phantom was obtained with an inplane resolution of 1 mm at a slice thickness of 2 mm.

A three-point registration procedure was used to compute the transformation from the wand coordinate system to the CT coordinate system. Using the wand and this transformation, the position of each washer was determined in the CT coordinate system. The six different washer positions define 15 three-dimensional distances. The distances calculated from the wand and the transformation positions obtained were compared both to the distances calculated from the CT data and actual separations calculated using a digital caliper. The average difference for distances from wand–CT calculations was $1.1 \pm 0.8$ mm; from CT–caliper calculations, $1.4 \pm 1.2$ mm; and from wand–caliper calculations, $1.4 \pm 1.3$ mm. These average differences over 15 distances represent the combined error from digitization, registration, and image acquisition.

The frameless stereotactic system was initially applied to the insertion of pedicle screws in the lumbarosacral spines of cadaver specimens. The accuracy of screw insertion using frameless stereotaxy was documented by plain film radiography and axial CT imaging of the instrumented levels. A satisfactory placement of all inserted screws was noted.9

Fig. 2. Images appearing on the workstation screen during the procedures. Upper: Images indicating satisfactory trajectory of the wand. The trajectory line is set at 40 mm. The near-coronal and near-sagittal reconstructed computerized tomography images are viewed in the two upper quadrants of the screen. The cursor in the coronal view indicates the distal endpoint of the trajectory line. The near-axial view is shown in the lower left quadrant. The right lower quadrant shows the position of the wand tip in the true axial, coronal, and sagittal planes. Alternatively, a surface-rendered view of the imaged superolateral levels can be depicted. Center: Images indicating satisfactory trajectory of the wand with the trajectory line set at 15 mm. Note the position of the cursor within the cortical margins of the pedicle on cross section in the near-coronal plane (arrow). Lower: Images indicating an error in position of the hand-held wand. The appropriate adjustment of the wand would involve a more inferior and lateral inclination.
In the operating room, the patient is placed in the prone or kneeling position. The microphone detector array is mounted to the head of the table and tilted toward the operative field. Alternatively, the array may be mounted to a stand that can be positioned on either side of the table. In either case, the array lies approximately 1 to 1.5 m from the operative field (Fig. 3).

A standard exposure of the spinal levels to be instrumented is performed. A lateral radiograph is obtained to confirm the appropriate level. Three reference points previously selected from the CT image set are identified in the operative field and registered using the wand (Fig. 4). Registration involves moving the computer cursor to a specific bone landmark identified on the multiplanar CT images (for example, the spinous process tip). The wand is then placed precisely on the same point in the operative field and activated. This process is performed with two other reference points (for example, lateral tips of two transverse processes). After the coordinates of the three reference points are obtained, the relationship between the image data and the intraoperative anatomy is defined, allowing rapid mathematical conversion between the two using a three-dimensional coordinate transformation algorithm. The accuracy of this conversion can be assessed by localizing other bone landmarks in the operative field and comparing their location to the corresponding point identified on the image set. The registration and orientation processes are independent of changes in patient positioning between image acquisition (supine position) and surgery (prone or kneeling position) because the relationship of the three registration points selected at a given vertebral level is not altered by positional changes except theoretically in the setting of spondylolysis.

After registration, standard bone landmarks for pedicle localization are used to approximate the screw entry point (for example, intersection of the midtransverse process line with the facet joint). A drill guide is placed on this entry point and the wand is passed through the guide. The wand is activated and the appropriate multiplanar CT images through the localized point are generated. The near-axial and near-sagittal views can be manipulated with foot-pedal control to show the “extension” of the wand through the selected entry point. This involves a lengthening of the trajectory line through each of the two views. The near-coronal view will adjust accordingly to show a cursor in the CT image set at the distal extent of the trajectory line. Subtle adjustments of the inclination of the drill guide–wand assembly can be made after each set of images is generated until the optimum trajectory is obtained. The surgeon’s estimation of the pedicle’s orientation is thus readily confirmed.

The orientation of each pedicle to be instrumented can be assessed quickly and easily. Following each wand digitization, reformatted CT images through the selected anatomical point are generated within 1 to 2 seconds. Any errors in trajectory or entry point can be determined and corrected by minor adjustments of the drill guide–wand position. After the drill guide–wand assembly is satisfactorily aligned with the optimum trajectory, the wand is removed and a drill (3.2-mm diameter) is positioned through the guide. A pilot hole is drilled through the pedicle into the vertebral body. A pedicle sound instrument is placed in the hole to confirm satisfactory hole placement. The hole is tapped and the appropriate length screw is inserted. The process is repeated for each pedicle to be instrumented; C-arm fluoroscopy or serial radiographs are not required.

There are two options for using the system at a second spinal level. The preferred method is to select three new registration points at the second level and to register them.
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as previously described. This method eliminates any discrepancy in anatomical orientation, which may be related to a change in patient position between the preoperative CT scan and surgery.

The second method involves activating the wand on a bone landmark (for example, the tip of the spinous process) at the new level using the registration data of the previous level. If the computer screen cursor lies at this same point after activation, the correlation between image data and spinal anatomy is preserved, and the orientation of the second spinal level can proceed without entering three new registration points.

At any point during the orientation procedure, the accuracy of the system can be tested by placing the wand on a known bone landmark and confirming its location on the workstation screen. If there is any discrepancy between wand and cursor position, the registration process can easily be repeated. Accuracy is dependent on how closely the wand is placed to the exact site selected as a registration point as well as on the proper immobilization of the patient during the registration and orientation procedures. This ability to reregister points serially during surgery is not as easily performed with intracranial procedures but confirms and enhances the accuracy of the system during spinal surgery.

Patient Population

We applied the frameless stereotactic system to the insertion of pedicle screws in 30 patients (22 females and eight males ranging in age from 15 to 77 years). The mean follow-up period was 13 months with a range of 7 to 22 months. The indications for surgery included degenerative spondylolisthesis in 18 patients, spondylitic spondylolisthesis in five patients, vertebral body fracture in three patients, degenerative scoliosis in two patients, and vertebral body neoplasm in two patients.

Following exposure and radiographic localization of the spinal level to be instrumented, the appropriate registration points for each level were selected and registered. The bone landmarks for localizing each pedicle were identified. For each pedicle, the wand was placed over the approximated entry point for that pedicle. The wand was then angled to approximate the proper angle of screw insertion in both the axial and sagittal planes. From this position, the wand could be activated using a computer mouse (controlled by a technician) or a foot-pedal control. The appropriate selection of the entry point and the axial and sagittal angulations for screw insertion could easily be confirmed. The information derived from the frameless stereotactic system resulted in minor adjustments of these screw insertion parameters for each pedicle instrumented.

To confirm pedicle localization before screw insertion, Steinmann pins were placed in the drilled holes, and each patient underwent intraoperative lateral lumbar radiography. No significant adjustments in trajectory were required before screw insertion. Postoperatively, each patient underwent anteroposterior and lateral radiographs of the instrumented spinal levels as well as a limited CT scan to assess screw placement. The metallic artifact created by the screws on the CT image was reduced by using a high window setting during the scan (Fig. 5). The screws were determined to be in an optimum position (Grade 1) if they followed the appropriate entry point and trajectory through the pedicle into the vertebral body or sacrum without extending outside or beyond the cortical margins of these structures. A suboptimum but satisfactory placement (Grade 2) consisted of a proper screw entry point and trajectory with only minor elevation of the lateral cortical margin of the pedicle or the lateral or anterior cortical margin of the vertebrae or sacrum. An unsatisfactory placement (Grade 3) involved any screw insertion that elevated or perforated the medial cortical margin of the pedicle or perforated the lateral cortex of the pedicle or the lateral or anterior cortex of the vertebrae or sacrum.

A total of 150 pedicle screws were inserted after pedicle localization and orientation. The number of screws placed into each pair of pedicles in the lumbosacral spine included six at L-1, 10 at L-2, 18 at L-3, 45 at L-4, 49 at L-5, and 20 at S-1. Two screws were placed into the sacral ala. One patient had a single screw placed at the L-4 level because the other pedicle had been destroyed by a neurofibroma. One patient had a single screw placed at L-5.

Results

Intraoperatively, the system provided a rapid and relatively precise identification of the pedicle and its orientation to the exposed surface anatomy of the spinal column. This reduced the operative time for the screw insertion by approximately 20 to 30 minutes. It also eliminated the need for intraoperative fluoroscopy and serial lateral radiographs. It was most useful for identifying pedicles when traditional bone landmarks were absent (that is, in cases of previous lateral fusion with a fusion mass overlying the transverse processes).

An additional advantage of the system involved its use for preoperative planning. The width of the pedicle and the distance from the pedicle entry point to the anterior vertebral or sacral cortex could be determined so that a screw with the appropriate diameter and length could be selected preoperatively.
Of the 150 screws placed, 137 were determined to be in Grade 1 position. The position of 12 screws was assessed as Grade 2. Only one screw was rated as being in an unsatisfactory position. This screw perforated the lateral cortex of an L-4 pedicle in a patient with severe degenerative scoliosis. This placement was not clinically significant.

 Clinically, all 30 patients reported improvement in their preoperative back pain, although five patients continue to have some pain that limits their function. No patient reported significant leg pain postoperatively. There was no occurrence of nerve root injury secondary to screw insertion, and there were no postoperative wound infections.

Anteroposterior and lateral plain film radiographs of the instrumented levels were obtained at each subsequent follow-up visit in all patients. To date, there has been no incidence of pseudoarthrosis or fixation failure secondary to screw breakage or dislodgment.

Discussion

Frameless stereotaxy for intracranial localization was pioneered by Roberts, et al.,11 who used a stereotactic microscope, and by Watanabe and coworkers,14 who used a mechanical multiarticulated neuronavigation arm. Several groups have expanded this technology to localize intracranial lesions more effectively and directly.2,8,13,17 However, little exploration has been done regarding the application of this technology to spinal surgery. Nolte reported a preliminary use of an optical-based system for pedicle screw placement. Broadwater, et al.,9 reported using the stereotactic microscope for localization in the lumbar spine. However, using surface fiducials as a frame of reference, these authors found that their methodology was not sufficiently accurate to be clinically significant.

Although localization is important, a more substantial problem associated with spinal surgery is anatomical orientation. This factor is critical when placing screws into the pedicles of the lower thoracic and lumbosacral spine. In most cases, the surgeon does not directly view the pedicles. Instead, the approximate location of each pedicle is determined by identifying specific bone landmarks in the operative field. Before inserting the screws, the surgeon can only approximate the pedicles’ dimensions and exact angulation in the sagittal and axial planes.

In the past decade, pedicle fixation of the spinal column has gained greater acceptance as improved instrumentation and clinical effectiveness have become apparent.16 However, because of the complexity of the spinal anatomy involved as well as the need to individualize the construction to each patient, pedicle screw fixation has a significant learning curve. This results in varying incidences of neural injury and fixation failure secondary to suboptimum screw placement or fracture. These complications can be limited if the surgeon is properly oriented to each pedicle to be instrumented.

Currently, two methods are commonly used to obtain anatomical orientation before pedicle screw placement. Intraoperative C-arm fluoroscopy offers real-time imaging of the appropriate spinal structures that the screws will traverse. However, the fluoroscopic views generated are only two-dimensional images of a complex three-dimen-

sional structure. With manipulation of the fluoroscopic unit, the three dimensions can be visualized in a series of images, but these maneuvers can be cumbersome and time consuming. Furthermore, the surgical team is required to wear lead aprons during fluoroscopy.

The second method of obtaining anatomical orientation in the spine is serial intraoperative radiography. Before pedicle screws are inserted, metallic pins can be positioned in each pedicle and a lateral radiograph obtained to confirm the pins’ relationship to the surrounding spinal column structures. If the positions of the pins are not satisfactory, their trajectory is readjusted and a second radiograph obtained. Once the pins are satisfactorily positioned they are removed, and the pedicle screws are inserted along the same approximate trajectory. This technique can be time consuming and confusing because only lateral radiographs are obtained. Orientation of the screws in the axial and coronal planes is not feasible; oblique and anteroposterior views are difficult to acquire, and without these views screws may be improperly placed. Furthermore, the screw trajectory can change when the pins are removed, and the screws will not be passed along the selected path unless a cannulated screw system is used.

The practical problem of adapting stereotactic principles to spinal surgery is identifying a frame of reference in which improved three-dimensional imaging can be more directly applied to intraoperative anatomy. A frame system is not practical for spinal surgery. Furthermore, the use of surface landmarks or fiducials presents problems of spatial accuracy because of skin movement with respect to bone landmarks.3,4 This problem is less serious in intracranial applications because of the relatively fixed relationship of the overlying skin to selected bone landmarks.

For application of stereotactic technology to spinal surgery, the spine itself provides the reference points. The three-point registration process described earlier effectively “links” the formatted image set with the intraoperative anatomical structures. A sonic wand and localization system can then be used intraoperatively to manipulate the image set and correlate it with the exposed spinal anatomy. The appropriate screw entry point, angle of trajectory in the axial and sagittal planes, and depth of insertion can be determined by simultaneous analysis of the images.

However, unlike intraoperative ultrasonography or fluoroscopy, this system does not provide true real-time imaging. It will not show changes in the spinal anatomy as they occur. The system functions as a confirmation tool to assist the surgeon in identifying the pedicle and relating its position and orientation to the exposed spinal anatomy. It is an alternative method to the more conventional means of interpreting twodimensional images of the spine, relating them to the surgeon’s knowledge of the pertinent anatomy, and estimating the location of the pedicle. However, it is not intended to function as a substitute for an understanding of the appropriate spinal anatomy and the indications and techniques for insertion of pedicle screws.

Preliminary use of this system has shown that it provides useful and accurate information for identifying pedicles and their orientation. The device has been applied in other areas of spinal surgery, particularly posterior C1–2 transfacetual screw fixation, anterior odontoid screw fixation, and anterior spinal column decompression in the set-
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ting of vertebral body fracture or kyphotic deformity. Currently, the system is being assessed for use in these procedures.

Future enhancements of the system include modifications of the registration process and the transformation algorithm. These improvements will upgrade both the speed and accuracy of the system, allowing its application to spinal procedures to be more thoroughly assessed. By improving the accuracy and efficiency of pedicle screw insertion, the overall objectives of reduced operative morbidity, fixation failure, and length of procedure can be achieved.

Disclosure

Some equipment and technical support for this project were provided by Science Accessories Corp., Stratford, CT, and by Picker International, Highland Heights, OH.

References


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