Image-guided spinal navigation: application to spinal metastases

IAIN H. KALFAS, M.D., F.A.C.S.
Section of Spinal Surgery, Department of Neurosurgery, The Cleveland Clinic Foundation, Cleveland, Ohio

Image-guided spinal navigation is an adjuvant surgical technology that has evolved over the past decade. It has been used as a replacement for conventional intraoperative imaging techniques to improve the spine surgeon’s spatial orientation to nonvisualized anatomy. The author will review the principles of image-guided technology in spinal surgery and focus on its application to the management of spinal metastatic disease.

KEY WORDS • metastasis • spine • image-guided navigation • stereotactic neurosurgery

Image-guided spinal navigation is a computer-based surgical technology that was originally developed to improve a spine surgeon’s orientation to the unexposed anatomy during complex spinal procedures.16,18 The modality evolved from the principles of stereotactic surgery used by neurosurgeons for several decades to help localize intracranial lesions. Stereotaxy is defined as the localization of a specific point in space by using 3D coordinates. The evolution of computer-based technologies has allowed for the more practical application of stereotactic principles to other surgery-related disorders.

The management of spinal metastasis has been greatly influenced by the increased acceptance and use of spinal instrumentation devices as well as the development of more complex operative exposures. Many of these surgical techniques place a greater demand on the spine surgeon by requiring a precise spatial orientation to that part of the spinal anatomy that is not exposed in the surgical field. In particular, the extent of tumor removal and the various reconstruction techniques that require placing bone screws into the pedicles of the thoracic, lumbar, and sacral spine require “visualization” of the unexposed spinal anatomy. Although conventional intraoperative imaging techniques such as fluoroscopy have proven useful, they provide only two-dimensional imaging of a complex 3D structure. Consequently, the surgeon is required to extrapolate the third dimension based on an interpretation of the images and a knowledge of the pertinent anatomy. This so-called “dead reckoning” of the anatomy can result in varying degrees of inaccuracy when placing screws into the unexposed spinal column.

The results of several studies have indicated that the use of routine radiography to assess pedicle screw placement in the lumbosacral spine is not reliable. The rate of penetration of the pedicle cortex by an inserted screw ranges from 21 to 31% in these studies.8,9,21 The disadvantage of conventional radiography in orienting the spinal surgeon to the unexposed spinal anatomy is that it displays only two planar images. Although the lateral view can be relatively easy to interpret, the AP or oblique view can be confusing because the single plane lacks the perspective of depth. For most screw fixation procedures, it is the axial plane that is critical for ensuring precise screw placement. Conventional intraoperative imaging cannot provide this view. Steinmann, et al.,20 however, using an image-based technique for pedicle screw placement that combined axial CT scans of cadaver spine specimens with fluoroscopy, were able to demonstrate a reduction of this screw insertion error rate to 5.5%.

Abbreviations used in this paper: AP = anteroposterior; CT = computerized tomography; LED = light-emitting diode; 3D = three-dimensional.
Image-guided spinal navigation minimizes much of the guess work associated with complex spinal surgery. It allows for the intraoperative manipulation of multiplanar CT scans, which can be oriented to any selected point in the surgical field. Although it is not an intraoperative imaging device, it provides the spine surgeon with superior imaging data compared with conventional (that is, fluoroscopy) intraoperative imaging technology. It can improve the speed, accuracy, and precision of surgery for spinal metastasis while, in most cases, eliminating the need for cumbersome intraoperative fluoroscopy.

PRINCIPLES OF IMAGE-GUIDED SPINAL NAVIGATION

The use of an image-guided navigational system for localizing intracranial lesions has been previously described.2,3,11 A variety of navigational systems have evolved over the past decade. The common components of most of these systems include an image-processing workstation interfaced with a two-camera optical localizer (Fig. 1). The optical localizer tracks infrared light emitted by a series of LEDs mounted on a customized handheld navigational probe or selected surgical instruments. Alternatively, the optical localizer itself can be the source of infrared light which is continuously reflected back to the camera by passive reflectors attached to the probe or selected surgical instruments. (Fig. 2)

The dimensions of each navigational probe or customized trackable surgical instrument is known by the computer workstation. The spacing of the LEDs or passive reflectors is also recognized. The infrared light that is transmitted from or reflected by these instruments is relayed to the computer workstation that calculates the precise location of the instrument tip in the surgical field as well as the location of the anatomical point on which the instrument tip rests.

Image-guided navigation functions by establishing a spatial relationship between preoperative imaging data and the corresponding intraoperative anatomy. Both the image-derived data and the anatomy can each be viewed as a 3D coordinate system with each point in that system having a specific x, y, and z cartesian coordinate. Using defined mathematical algorithms, a specific point in the imaging dataset can be “matched” to its corresponding point in the surgical field. This process is called “registration” and represents the critical step of image-guided navigation. A minimum of three points needs to be matched, or registered, to allow for accurate navigation.11

The initial application of navigational principles to spinal surgery was not intuitive. In early navigational technology applied to intracranial surgery practitioners used an external frame mounted to the patient’s head to provide a point of reference to link preoperative imaging data to the intracranial anatomy. This was not practical for spinal surgery. In the current generation of intracranial navigational technology reference markers or fiducials are glued to the patient’s scalp prior to imaging. The use of these surface-mounted fiducials for spinal navigation is also not practical because of the greater degree of skin movement over the spinal column yielding significant inaccuracies.4,5 This is less of a problem with intracranial applications because of the relatively fixed position of the overlying scalp to the attached fiducials.

The application of navigational technology to spinal surgery involves using the rigid spinal anatomy itself as a frame of reference. Two separate registration techniques can be applied. Paired-point registration involves selecting a series of corresponding points in a CT or magnetic resonance imaging dataset and in the exposed spinal anatomy. Bone landmarks on the exposed surface of the spinal column provide the reference points necessary for image-guided navigation. Specifically, any anatomical landmark that can be identified both intraoperatively and in the preoperative imaging dataset can be used as a refer-
ence point. Typically, the reference points are the tips of the spinous process and transverse processes at each spinal level to be fitted with hardware, although other bone landmarks such as facet joints or prominent osteophytes can also be used (Fig. 3). The registration process is performed immediately after surgical exposure and prior to any planned decompressive procedure. This preserves the spinal anatomical landmarks that facilitate an easy and accurate registration process.16

After a specific point in the imaging dataset has been selected, the tip of the probe can be placed on the corresponding point in the surgical field. When the system is activated, the coordinates of the two points are effectively linked. When a minimum of three such points are registered, the probe can be placed on any other point in the surgical field and the corresponding point in the imaging dataset will be identified on the computer workstation. Three separate reformatted images through any selected point are presented, providing the surgeon with a greater degree of orientation to the nonvisualized spinal anatomy.12–16

Alternatively, a second registration technique called “surface mapping” can be used. This technique involves selecting multiple nondiscreet points only on the exposed and debrided surface of the spine within the surgical field. This technique does not require the preselection of points in the imaging dataset, although several discreet points in both the dataset and in the surgical field are frequently required to improve the accuracy of surface mapping. The positional information of these points is transferred to the workstation, and a topographic map of the selected anatomy is created and matched to the imaging dataset.19

Typically, paired-point registration can be performed more quickly than surface mapping. The average time needed for paired-point registration is 10 to 15 seconds. The time needed for surface mapping is much longer; in difficult cases registration may require as much as 10 to 15 minutes. With the need to perform several intraoperative registration processes, this time difference can significantly affect the length of the navigational procedure as well as the surgery itself.

The purpose of the registration process is to establish a precise spatial relationship between the image space of the data with the physical space of the patient’s corresponding surgical anatomy. If the patient is moved after registration, this spatial relationship is distorted and creates inaccurate navigational information. This problem can be minimized by the optimum use of a spinal tracking device, which consists of a separate set of LEDs or passive reflectors mounted on an instrument that can be attached to the exposed spinal anatomy (Fig. 4). The position of the reference frame can be tracked using the camera system. Movement of the frame alerts the navigational system to any inadvertent movement of the spine. The system can then make adjustments to keep the registration process accurate and eliminate the need to repeat the registration process. The disadvantage of a tracking device is the added time needed for its attachment to the spine, the need to maintain a line of sight between it and the camera, and the inconvenience of having to perform the procedure with the device placed in the surgical field. Alternatively, image-guided spinal navigation can be performed without a tracking device.12–16 This involves acknowledging the effect of patient-related movement on the accuracy of image-guided navigation and maintaining reasonable stable patient position during the relatively short amount of time needed (that is, 10–20 seconds) for the selection of each appropriate screw trajectory. Several factors may cause this movement: 1) patient respiration, 2) the surgical team leaning on the table, or 3) a change of table position. Movement associated with patient respiration is negligible and does not require any tracking, even in
the thoracic spine. Although any of these three forms of movement will affect registration accuracy, inaccuracy can be easily avoided during the short navigational procedure. If inadvertent patient movement does occur, the registration process can be easily repeated. Repeating the registration process is far more practical with the shorter paired-point technique than with the more time-consuming surface-mapping technique.

**CLINICAL APPLICATIONS**

Metastatic tumors of the spinal column can produce varying degrees of vertebral instability and neural compression. These lesions can extend into the paraspinal region and encroach upon intrathoracic or abdominal structures. When approached via a posterior or posterolateral route, the anterior and lateral margins of these paraspinal lesions can be difficult to localize. This may result in an inadvertent injury to underlying soft-tissue structures. Spinal navigation can be used to identify these tumor margins, optimizing excision and minimizing soft-tissue injury. It can then be used to facilitate the placement of screw fixation devices if spinal stabilization is warranted.

Image-guided spinal navigation was initially evaluated for the insertion of pedicle screws in the thoracic and lumbosacral spine of cadaver specimens. The accuracy of screw insertion was documented by plain radiography and thin-section CT scanning of the instrumented levels. All inserted pedicle screws were satisfactorily placed. The clinical application of image-guided spinal navigation began with its use in lumbosacral pedicle fixation. Other spinal applications gradually evolved, including transoral decompression, cervical screw fixation, thoracic pedicle fixation, and anterior thoracolumbar decompression and fixation procedures.

The application of image-guided navigation to the management of spinal metastasis is directed by the complexity of the procedure and, specifically, by the need to visualize the unexposed spinal anatomy. Image-guided navigation can be used with or without standard intraoperative imaging such as fluoroscopy. In either case, image-guided navigation provides the surgeon with an improved orientation to the pertinent spinal anatomy, and this facilitates the accuracy and efficacy of the procedure.

**Pedicle Fixation**

Pedicle fixation has gained acceptance as an effective and reliable method of spinal stabilization following removal of a metastatic lesion. Because of the variations of pedicle anatomy within each patient, however, safe and precise placement of pedicle screws can be difficult. Suboptimum screw placement can result in varying degrees of neural injury and fixation-related failure. These complications can be minimized if, prior to screw placement, the surgeon is provided with accurate spatial orientation to each pedicle to be instrumented.

Image-guided spinal navigation can now be used routinely in place of fluoroscopy for the insertion of pedicle screws in both the thoracic and lumbosacral spine. Although fluoroscopy provides real-time imaging of spinal anatomy, the views generated represent only two-dimensional images of a complex 3D structure. Manipulation of the fluoroscopic unit can reduce this problem, but these maneuvers can be cumbersome and time consuming. Other disadvantages include the radiation exposure and the need to wear lead aprons during the procedure. Fluoroscopy can have difficulties visualizing certain spinal regions such as the upper thoracic spine and the lumbar spine in obese individuals. More importantly, fluoroscopy cannot provide an axial view of the spinal anatomy. It is this axial view provided by image-guided navigation that makes it superior to fluoroscopy for spinal screw fixation procedures.

The application of image-guided navigation to the spine involves obtaining a preoperative CT scan through the appropriate spinal segments undergoing placement of instrumentation. The images consist of a 3D volume dataset of contiguous axial CT scans. Alternatively, magnetic resonance imaging data may also be used. The imaging data are then transferred to the computer workstation via optical disk or a high-speed data link. If paired-point registration is to be used, three to five reference points for each spinal segment to be instrumented are selected and stored in the imaging dataset.

Intraoperatively, a standard exposure of the spinal levels to be instrumented is performed. A lateral radiograph can be obtained to confirm the appropriate level. The computer workstation and camera localizer are then positioned. The infrared camera detector is mounted at the foot of the table and aimed rostrally in cases in which thoracic and lumbosacral procedures are being performed (Fig. 5).
Image guidance and spinal metastases

Image-guided navigation is typically conducted prior to any planned decompression to take advantage of the intact posterior elements as registration points. The first spinal segment to be instrumented is then registered using either the paired-point or surface-mapping technique. When the registration process is complete, most navigational workstations will calculate a registration error (expressed in millimeters) that is directly dependent on the surgeon’s registration technique. The error value does not represent a linear error but rather a volumetric calculation comparing the spacing of registration points in the surgical field with the spacing of the corresponding points in the imaging dataset. This figure is, at best, a relative indicator of accuracy.

A better method of ensuring registration accuracy is the verification step, which is typically performed immediately after completing either of the two registration processes. The surgeon places the navigational probe on a discreet landmark in the surgical field. With the navigational system now tracking the movement and position of the probe, the trajectory line and cursor on the workstation screen will, if accurate registration has been achieved, move to the corresponding point in the imaging dataset (Fig. 6 upper). If registration accuracy has not been achieved, the cursor and trajectory line may be positioned a significant distance from the point selected in the surgical field (Fig. 6 lower). If this occurs, the registration process needs to be repeated. This verification step represents a more absolute indicator of registration accuracy and is important to perform prior to proceeding with navigation.

When an accurate registration of the first spinal level has been verified, standard bone landmarks for pedicle localization are used to approximate the screw entry point. A drill guide is placed on this entry point, and the navigation probe is passed through the guide. The navigational system is activated, permitting tracking of the probe in the surgical field. Three separate reformatted views are displayed on the workstation screen. Each view represents a separate plane passing through the selected point in the surgical field. In most cases of pedicle fixation, these views typically consist of a sagittal, axial, and coronal reconstruction. A trajectory line referenced to the long axis of the probe is superimposed on the sagittal and axial views. A round cursor, representing a cross section through the selected trajectory, is superimposed on the coronal view. As the probe is moved through the surgical field, the position of the trajectory line and cursor will change accordingly. Both the width of the trajectory line and the diameter of the cursor can be adjusted to match the relative diameter of the pedicle screws to be inserted. The length of the trajectory line can also be adjusted (Fig. 7).

As the probe is placed on each pedicle entry point, the images on the workstation screen are presented in real time. As the angle of the probe is adjusted in both the axial and sagittal planes, the images will be updated to show the corresponding trajectories. The depth of the coronal view can be adjusted to demonstrate the cross-sectional anatomy at any point along the selected trajectory. The orientation of each pedicle to be instrumented can be assessed rapidly and accurately. Any errors in trajectory or entry point selection can be determined and corrected by adjusting the position of the probe and the drill guide through which it passes.

When satisfactory screw entry point and trajectory have been selected, the images currently displayed on the workstation screen are frozen, the probe is removed from the drill guide, and a drill (3-mm-diameter) is positioned through the guide. The purpose of the drill guide is to preserve the physical trajectory and entry point data just acquired through the navigation of that pedicle. If a drill guide is not used, it may be difficult to position precisely a drill or pedicle probe on the same point and with the same trajectory as the removed navigational probe. The
drill guide also allows the surgeon to use a hand-held drill to place the small pilot hole instead of trying to recreate the navigational information by using a blunt and cumbersome pedicle probe. When the pilot hole is placed, a sound can be passed down the hole to ensure adequate positioning. Navigation is then performed for the contralateral pedicle.

For each additional vertebra requiring instrumentation, a new set of registration points at that level is selected. This method, termed “segmental registration,” eliminates any discrepancy in anatomical orientation that may be related to a change in patient position that may have occurred between the time of preoperative CT scanning and surgery. Because each vertebra is a fixed, rigid body, the spatial relationship of the selected registration points to the vertebral anatomy at a single spinal level is not affected by changes in body position.

After all pilot holes have been drilled, they are tapped and the appropriate-sized screws inserted. The use of C-arm fluoroscopy or serial radiography is not required. Typically, the mean time for registration, navigation, and the insertion of four pedicle screws is approximately 7 to 10 minutes when using a paired-point registration technique. Considerably more time is required when using a surface-mapping technique because of the longer time it takes to achieve satisfactory registration.

In addition to screw placement in the large pedicles of the lumbosacral spine, image-guided navigation can also facilitate screw insertion into the smaller pedicles of the thoracic spine (Fig. 8). Because of the increased precision it confers in this region, the fixation options for managing the unstable thoracic spine and cervicothoracic junction are greatly expanded.

**Posterior C1–2 Transarticular Screw Fixation**

Posterior C1–2 transarticular screw fixation can frequently be a valuable stabilization option for managing patients with spinal metastases of the upper cervical spine. This procedure involves the passage of a screw through the pars interarticularis of C-2, across the facet joint, and into the lateral mass of C-1. The risks of screw insertion include vertebral artery injury if the screw is placed too laterally or anteriorly, spinal cord injury if the screw is placed too medially, and failure to engage the lateral mass of C-1 if the screw trajectory is too anterior. The insertion of a screw on either side may be contraindicated if the pars interarticularis of C-2 is too narrow. The procedure is typically performed bilaterally using fluoroscopic guidance.

Selection of the appropriate screw entry site and trajectory requires a thorough understanding of the atlantoaxial anatomy. Although fluoroscopic guidance can be helpful, it does not consistently provide the millimetric precision necessary for this procedure. The application of image-guided navigation, however, confers significant additional accuracy.

Application of image-guided navigation to posterior C1–2 screw fixation requires first that a CT scan be obtained that depicts the area from the lower occipital region to C-3. Those visualized image data are transferred to the computer workstation and can be used to create a preoperative screw trajectory plan. A proposed entry point and target can be selected at the C-2 and C-1 levels, respectively. The imaging dataset can then be manipulated in multiple planes between these two points to demonstrate the position of a screw placed along the selected trajectory. In addition to displaying the sagittal plane, two separate planes that are perpendicular to the long axis of the screw trajectory are demonstrated. These views depict the position of the screw at each millimeric increment. Although this planning technique does not ensure safe screw placement intraoperatively, it can alert the surgeon preoperatively to avoid screw placement in patients with insufficient anatomy to accommodate such a procedure and to select an alternate intervention.

Intraoperatively, the patient is positioned and the posterior C1–2 complex is exposed. A wire (cable) and bone graft stabilization procedure at the C1–2 level is performed prior to undertaking navigation and screw inser-
tion. Performing this step first minimizes any independent motion between C–1 and C–2 during navigation and makes bone tapping and screw insertion easier.

After placement of the graft and cable, two to five registration points are selected at the C–2 level. It is not necessary to include registration points at C–1. Although the spatial relationship of C–1 and C–2 may change between the CT-demonstrated preoperative position and the intraoperative position, the ability of image-guided navigation to facilitate accurate screw placement is not significantly compromised. The technically difficult aspect of this procedure is the accurate passage of the screw through the narrow C–2 pars interarticularis. The lateral mass of C–1 is a relatively large target that can be easily reached provided there is a reasonably acceptable realignment of C–1 and C–2 as well as an optimum positioning of the screw within the appropriate C–2 anatomy. Whereas the relative position of C–1 and C–2 in both the preoperative imaging dataset and in the surgical field is important, it is not critical enough to interfere with the process of image-guided navigation.

Two separate stab incisions are made on either side of the midline at the C7–T1 level. A drill guide is placed through one of the stab incisions, passed through the paravertebral musculature, and passed into the operative field. A small divot is drilled at the proposed entry site to allow for secure placement of the drill guide. The registration process is performed at C–2, and the probe is passed through the drill guide. Intraoperative navigation through the C–2 pars interarticularis is performed, and the selection of an appropriate screw entry point and trajectory is confirmed (Fig. 9). The appropriate-sized screw length can also be determined. The probe is then removed from the drill guide and a drill is inserted. A hole is drilled along the selected trajectory, tapped, and the appropriate-length screw inserted. The process is repeated on the contralateral side.

Although image-guided navigation does not guarantee accurate screw placement, it does provide the surgeon with a greater degree of anatomical information than fluoroscopy alone. The addition of fluoroscopy to the navigational procedure provides the greatest degree of precision to the procedure. In this case, however, navigational technology significantly reduces the time of intraoperative fluoroscopic usage because it is typically only conducted as a final assessment of the selected trajectory in the sagittal plane.

**Transoral Surgery**

Although metastatic lesions involving the upper cervical spine are rare, their location in the anterior C1–2 region may require the use of transoral decompression. This procedure typically requires intraoperative fluoroscopy to help maintain proper anatomical orientation. Although orientation in the sagittal plane is easy to obtain using fluoroscopy, depth and mediolateral orientation are more difficult to assess. Image-guided technology can be used to orient the surgeon in multiple planes during transoral decompression of a metastatic lesion.

Unlike other spinal applications of image guidance, discreet registration points are not readily available during transoral surgery. In this setting, surface-mounted markers (fiducials) are applied in the patient. Typically, two fiducials are applied to the mastoid processes and two to the lateral orbital margins or to both malar eminences. The nasal septum can also be used as an anatomical registration point.

The patient is positioned in a three-point head holder. The registration process is conducted, and sterile draping is performed. Because the registration points will not be accessible intraoperatively, a reference frame is used for transoral navigation, which allows for changes in patient positioning during surgery without the need to undertake a reregistration process.

During the decompressive procedure, the probe is placed into the mouth and decompression site. Sagittal, axial and coronal CT reconstructions are generated through the selected point, providing the surgeon with a precise orientation to the pertinent surgery-related anatomy. In particular, orientation in the axial plane minimizes the risk of lateral deviation toward the vertebral artery during the decompressive procedure (Fig. 10).

**Anterior Thoracolumbar Surgery**

Image-guided spinal navigation can be applied in patients undergoing anterior thoracolumbar surgery to help orient the surgeon to the extent to which the anterior metastatic lesion must be decompressed and to facilitate the precise placement of fixation screws. Although the selection of reference points in cases of anterior spinal surgery is limited by the relative lack of prominent bone landmarks on the anterior aspect of the spinal column, the degree of accuracy required is less than that needed in most posterior screw fixation procedures. This degree of accuracy, termed “clinically relevant accuracy,” will change according to the procedure being performed. This term

---

**Fig. 9.** Workstation screen demonstrating a trajectory for insertion of a C1–2 transarticular screw. The lower-right screen shows the trajectory in the sagittal plane. The lower-left screen represents an orthogonal plane lying between the axial and coronal planes; it demonstrates the mediolateral trajectory. The upper-left screen depicts a plane that is perpendicular to the two other images; it demonstrates the location of the screw tip inserted along the selected trajectory at the indicated depth. Screw trajectory and tip location are indicated by arrows.
signifies the degree of accuracy needed to achieve a particular surgical task. For example, insertion of a C1–2 transarticular screw demands a higher degree of clinically relevant accuracy than placing an anterior fixation screw across a large thoracic or lumbar vertebral body. In both cases image-guided navigation provides clinically relevant accuracy more consistently than fluoroscopy alone.

Potential registration points in anterior thoracolumbar surgery include selected landmarks on the vertebral end-plates, pedicles, head of the rib, and prominent anterior osteophytes. In general, higher registration errors can be tolerated because of the lower degree of accuracy required in most anterior thoracolumbar procedures compared with posterior screw fixation procedures. The accuracy verification step performed immediately after registration can further confirm the achievement of clinically relevant accuracy before proceeding with navigation.

During anterior procedures involving a spinal metastasis, the probe can be placed into the partially decompressed site to orient the surgeon to the contralateral margin of the spinal column and, more importantly, to the location of the epidural space (Fig. 11 upper). Following decompression, image guidance can be used to guide the placement of anterior fixation screws across the vertebra at either end of the corpectomy site (Fig. 11 center).

Other Applications in the Spine

Image-guided navigation has several other applications in the management of complex spinal disorders. Any procedure in which intraoperative imaging is required to improve a surgeon’s orientation to nonexposed spinal anatomy can benefit from image guidance. Other procedures in which image guidance has been applied include anterior screw fixation for nondisplaced odontoid fractures, cervical lateral mass screw fixation, cervical corpectomy and the resection of spinal neoplasms via a posterior approach (Fig. 11 lower). The navigational workstation also provides superior image manipulation capabilities. This al-

Fig. 10. Workstation screen demonstrating navigation during transoral decompression. Probe tip location and trajectory are indicated by arrows.

Fig. 11. Upper: Workstation screen demonstrating navigation during removal of an L-2 metastasis. Orientation to the contralateral side and the epidural space can be obtained. Arrows indicate probe tip location and trajectory. Center: Workstation screen demonstrating a selected trajectory for an anterior lumbar fixation screw. Arrows indicate screw trajectory and tip location. Lower: Workstation screen demonstrating intratumoral navigation during resection of a thoracic metastasis via a posterior approach. Cursor in upper-left quadrant (white arrow) indicates the tip of probe within tumor bed.
Image guidance and spinal metastases

allows the surgeon to scroll through reformatted CT scans in multiple planes, providing for optimum preoperative planning and improved intraoperative anatomical assessment.

PITFALLS OF IMAGE-GUIDED SPINAL NAVIGATION

Like any other computer-based modality, image-guided navigation is highly dependent on the quality of the information imported into the system. Although properly formatted CT scans need to be obtained and the data correctly transferred to the navigational workstation, the critical step in image guidance is actually the registration process. If the surgeon takes too casual an approach to registration, inaccurate information will be displayed during intraoperative navigation.

Another important facet of image guidance is the correlation of the navigational data with the surgeon’s own knowledge of the anatomy and the appropriate screw trajectories through that anatomy. Image-guided navigation is not a replacement for the surgeon’s knowledge of pertinent spinal anatomy and surgical technique. Rather, it merely serves to help confirm his or her estimation of the nonexposed anatomy by providing imaging data that typically exceeds those yielded by intraoperative fluoroscopy.

Depending on the features of the system used, image-guided navigation also has varying degrees of intraoperative functionality. This can either simplify or complicate the overall procedure. Typically, the use of the surface-mapping registration technique and a reference frame adds time to the navigational procedure, frequently making it a longer and more complicated procedure than fluoroscopy alone. The use of the paired-point registration technique without a reference frame simplifies the navigation process, because the insertion of four pedicle screws typically takes no more than 7 to 10 minutes. By optimizing the ease of use of navigational technology, standard fluoroscopy becomes unnecessary in most screw fixation spinal procedures.

FLUOROSCOPIC NAVIGATION

In fluoroscopic navigation standard fluoroscopy and image-guided navigational are combined. This technology was developed to counter the user difficulties posed by certain earlier image-guided systems that typically required considerably more time to use than standard fluoroscopy. Its primary advantage is that it reduces intraoperative fluoroscopic time. With the patient positioned prior to surgery, AP and lateral fluoroscopic views of the pertinent spinal anatomy are obtained. This is performed using a customized reference frame attached to the C-arm or to the patient. This frame serves to superimpose a specific grid on the two images obtained. The navigational workstation can then import two images and relate the spatial position of the imaged anatomy to a navigational probe. A navigational trajectory line and a cursor can then be superimposed on the lateral and AP images, respectively. As the probe is moved over the exposed spinal anatomy during surgery, the trajectory line and cursor will adjust their position on the stationary fluoroscopic images.

The disadvantage of fluoroscopic navigation is that it is still only fluoroscopy. The same difficulties encountered with standard fluoroscopy are present using this technology. Specifically, only AP and lateral images are provided. The critical plane for most spinal screw fixation procedures, however, is the axial plane, which is the only plane that can definitively demonstrate violation of the spinal canal by a medially displaced screw. Only CT-based image-guided navigation can demonstrate this view, although current developments in standard fluoroscopy will eventually allow for axial reconstructions. Furthermore, any region of the spinal column that is difficult to visualize with standard fluoroscopy (that is, upper thoracic) will likewise be difficult to image when using fluoroscopic navigation.

The early goals of image-guided spinal navigation were to improve the surgeon’s orientation to the intraoperative spinal anatomy, in a time- and cost-efficient manner, and ultimately to replace fluoroscopy. Although earlier image-guided systems were difficult to use intraoperatively, several advances have made some systems much easier to use. Because of several years of clinical experience, navigational techniques have been modified and improved. The use of paired-point registration and the optional use of a reference frame have both been found to reduce significantly the difficulties of using image-guided technology for spinal procedures.12,13 Advances in computer and localizer technology have also contributed to the improved functionality of these systems. This improved ease of use of the advanced image-guided systems, coupled with superior accuracy, image manipulation, and orientation capabilities, provides image-guided technology with a clear advantage over any fluoroscopy-based technology.

CONCLUSIONS

Interactive frameless stereotactic technology has been successfully applied to spinal surgery and, in particular, the surgical management of spinal metastases. By linking digitized imaging data to spinal surface anatomy, image-guided spinal navigation facilitates the surgeon’s orientation to unexposed spinal structures and improves the precision and accuracy of the surgery. Typically it is used to optimize the placement of spinal fixation screws and to monitor the extent of complex decompressive procedures. Additionally it can be used as a preoperative planning tool.

Although image-guided spinal navigation is a versatile and effective technology, it does not replace the surgeon’s thorough knowledge of the pertinent spinal anatomy and his or her correct surgical techniques. Rather, it merely serves as an additional source of information used to make selected decisions intraoperatively. In this way, it is similar to more conventional intraoperative imaging techniques (that is, fluoroscopy) except that it provides considerably greater information to the surgeon.

Despite the advantages of image guidance, the surgeon must ultimately assess the information provided by these systems and determine if it correlates with his or her estimation of the nonexposed anatomy and the proposed surgical plan. If good correlation exists between the two, the surgical procedure can be performed. If sufficient correlation is not present, however, the surgeon needs to reassess...
both the spinal anatomy and the image-guided registration accuracy before proceeding.

Ideally, the clinical application of this technology to spinal surgery should reduce operative time, morbidity rates, and costs. It should be capable of minimizing or eliminating the need for conventional intraoperative imaging. It should be fast, easy to use, reliable, and capable of being used briefly to provide accurate intraoperative information while minimizing any disruption to the standard routine of each surgical procedure. Ultimately, beyond each individual surgical application, image-guided navigation technology needs to be clinically versatile. It is the routine use of this technology by numerous surgical specialists that will drive its continued evolution and development as well as establishing it as a cost-effective surgical tool.

References

Manuscript received November 2, 2001. Accepted in final form December 3, 2001.
Address reprint requests to: Iain H. Kalfas, M.D., F.A.C.S., Department of Neurosurgery (S80), The Cleveland Clinic Foundation, 9500 Euclid Avenue, Cleveland, Ohio 44195.