Intraoperative image-guided spinal navigation: technical pitfalls and their avoidance

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Spinal instrumentation has made significant advances in the last two decades, with transpedicular constructs now widely used in spinal fixation. Pedicle screw constructs are routinely used in thoracolumbar-instrumented fusions, and in recent years, the cervical spine as well. Three-column fixations with pedicle screws provide the most rigid form of posterior stabilization. Surgical landmarks and fluoroscopy have been used routinely for pedicle screw insertion, but a number of studies reveal inaccuracies in placement using these conventional techniques (ranging from 10% to 50%). The ability to combine 3D imaging with intraoperative navigation systems has improved the accuracy and safety of pedicle screw placement, especially in more complex spinal deformities. However, in the authors' experience with image guidance in more than 1500 cases, several potential pitfalls have been identified while using intraoperative spinal navigation that could lead to suboptimal results. This article summarizes the authors’ experience with these various pitfalls using spinal navigation, and gives practical tips on their avoidance and management.

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**Key Words** • intraoperative spinal navigation • pitfall • avoidance • image guidance

**ABSTRACT**

Transpedicular instrumentation has become the favored tool of the spine surgeon for a wide variety of spinal stabilization procedures. The goals of any spinal procedure may include decompressing neural elements and preventing or correcting deformity if necessary, using spinal fixation that results in earlier mobilization and rehabilitation. Using standard insertion techniques, the rate of misplaced pedicle screws ranges from 14% to 55%, with as many as 7% of these misplaced screws resulting in neurological injuries. Spinal navigation was introduced in 1995 with a goal of improving the accuracy of pedicle screw insertion and thereby minimizing the risk of neurovascular injuries. As a result, there has been a substantial increase in the use of spinal navigation with ever-improving image capture devices and registration platforms. The advantages of using spinal navigation for accurately placing pedicle screws have been reported in a multitude of studies. In a cadaveric study by Weinstein et al.,73 pedicle screws violated the cortex in 21% of the specimens when inserted using anatomical landmarks. A number of other studies have described pedicle violations ranging from 10% to 50% in the cervical and thoracic spine, where the size, shape, and orientation of these pedicles makes it more challenging to insert pedicle screws when guided by anatomy or fluoroscopy. Other authors have found that freehand placement of pedicle screws may be safe in very experienced hands. The use of image guidance has been reported to consistently reduce pedicle breaches to less than 5% in a number of published studies. Shin et al. have shown a decrease in pedicle perforation rates from 15% in nonnavigated screws to 6% in navigated pedicle-screw insertions. These findings have resulted in the increased use of image guidance for spinal fusion. However, spinal navigation should be thought of as an adjunct to thorough knowledge of spinal anatomy, and not be used as a substitute for it. It is therefore critical to recognize the limitations of this technology.

The purpose of this article is to review the most recent literature and discuss various pitfalls in the use of intraoperative spinal navigation, thereby providing insights into avoiding common errors and their associated complications during spinal fusion procedures.

**Preliminary Concepts**

The most commonly used forms of image-guided navigation in spine surgery presently include 2D images, in which a fluoroscope or plain radiography is used, and 3D navigation, making use of cone-beam CT or CT scans. The 3D systems provide projections of the operative field and instruments with imaging in 3 axes. The principle goal is to track surgical instruments and anatomy in the operative field relative to a registered reference point. The most commonly used method is by optical tracking using cameras that project and detect reflected infrared light from reflecting spheres or light-emitting diodes. This technology enables the surgeon to navigate the patient’s spine anatomy using a visual image that shows the position of...
tracked instruments relative to the surgical field. Various methods used to register the surgical space with image guidance have included material fiducials, anatomical fiducials, and surface-based registration techniques. The use of material fiducials in spine surgery had drawbacks because it required the attachment of fiducials prior to surgery, resulting in inaccuracy when used with spinal navigation, and is not currently used. Anatomical fiducials required certain anatomically accessible targets to be exactly identified by the surgeon, and then these points in the intraoperative space were matched to CT-based imaging. However, this process, known as paired-point matching, was the least accurate because the surgeon had to identify the exact anatomical location, which remains a difficult task. A variant of the anatomical registration includes surface-based point-pairing techniques. Once registration has occurred, various instruments with reference markers can be appropriately localized in the surgical field, and the tool tips and projections in the axial, coronal, and sagittal planes are computed and projected for the surgeon. A number of possible sources from which errors arise have been documented in early publications on spinal navigation and image-guided registration accuracy. The introduction of cone-beam CT brought about a change by enabling intraoperative registration of the surgical space to take place following surgical exposure and delineation of bone anatomy.

The 2D imaging systems use anteroposterior and lateral fluoroscopic images obtained during the case and combine them with the preoperative CT images on the navigation system. The advantages of 2D-based systems were speed, decreased radiation exposure, and ease of use, but these systems were not as accurate as the next generation of 3D-guided navigation systems. The introduction of cone-beam CT enabled multiple fluoroscopic image acquisition by a device that rotated isocentrically around the patient. The images are reconstructed into a cone-beam CT scan that can be used for navigation once it is transferred to an image-guided system. As the reference arc is tracked with the patient imaging, the computer-generated 3D image of the patient’s operative field is already registered and ready for use with navigation. Advantages with the use of this technology include the ability to image multiple levels in a single sequence, imaging accuracy in patients who had undergone prior spine surgeries at the same levels, decreased radiation exposure to the operating room (OR) staff, improved accuracy because the patient’s anatomy is registered in the surgical position, and portability of the system so it can be easily transported between ORs.

The present cone-beam CT-based systems include the Arcadis Orbic 3D isocentric C-arm (Siemens AG), the Ziehm Vision FD Vario 3D (Ziehm), and the O-arm (Medtronic). In addition to these systems, more recent 32-slice mobile intraoperative CT scan platforms that can be integrated with navigation systems for use in spinal navigation have been released and include the Airo (BrainLAB) and BodyTom (NeuroLogica Corp.).

The benefits of spinal navigation have been described in minimally invasive surgical procedures, as well as in the treatment of complex deformities, tumor, and trauma of the spine when the anatomy is distorted and visual and tactile landmarks are not readily available to the spine surgeon.

Literature Review and Author Experience

For this review, a PubMed-based literature search was performed to identify any published studies regarding the errors, technical pitfalls, and complications when using spinal navigation pedicle-screw insertions in the cervical and thoracolumbar spine. The keywords used while searching the database included “spinal navigation pitfalls” and “navigation complications.” There have been numerous articles published on the efficacy and advantages of intraoperative navigation utilization, but to date no publications have addressed the technical issues and pitfalls that occur while using intraoperative navigation. The intraoperative navigation pitfalls could eventually lead to a loss of OR time, prolonged anesthesia, blood loss, intraoperative pedicle screw errors, and inadvertent neurological complications. Poor planning in the pre- and intraoperative stages will obviate any advantage of an intraoperative navigation system.

At our institution we obtained the O-arm (Medtronic) combined with Stealth navigation in April 2008, prior to which time the authors had used alternative systems (BrainLab, Iso-C) for image-guided spine surgery. The authors in this paper have a combined experience of having used image-guided navigation for spine surgery in more than 1500 cases. Based on this vast experience with image-guided spine surgery, we have attempted to classify and categorize these pitfalls with the use of intraoperative spinal navigation. We will describe these pitfalls along with an illustrative case, showing how to avoid these problems. The most important factor remains the time and technical nuances with spinal image guidance that can be further subcategorized into preoperative, intraoperative, and postoperative considerations. The inability to develop a smooth workflow and plan ahead decreases the efficiency of the operating team. To simplify any spinal procedure we have implemented a checklist (Fig. 1) depending on the region where the surgery is to be performed, the type of procedure, and OR requirements. This measure helps to keep the OR staff prepared for the procedure and all the equipment appropriately arranged in the work environment on the day of surgery. Our OR setup with the arrangement of various equipment has been outlined (Fig. 2); the implementation of this setup minimizes confusion for any spinal case using intraoperative navigation.

Preoperative Considerations

Prior to starting a spinal fusion procedure, various operative considerations such as positioning, neuromonitoring, and equipment require appropriate selection. The surgical team is responsible for dissemination of information to OR personnel, who will in turn organize the OR.

Obese Patients

Preoperative patient factors include the potential difficulty of performing adequate imaging on obese and morbidly obese patients. The increased soft tissue in patients with morbid obesity may create difficulty with positioning, beam penetration, and the ability to maneu-
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![Diagram of Region of surgery]
- Cervical
- Thoracic
- Thoraco-lumbar
- Lumbar
- Lumbo-sacral

![Diagram of Operating room requirements]

**Operating table**
- Radiolucent Wilson frame
- Regular OR table
- Jackson table (decide on short vs. long board requirement)

**Patient position**
- Supine
- Prone
- Lateral
- Sitting
- Partial lateral
- Additional requirements (Gel rolls / hip pads / blanket rolls)
- Arm position (tucked by the side / flexed & upwards)

**Image guidance & fluoroscopy**
- O-arm and Stealth (our Institute)
- Intraoperative fluoroscopy & navigation
- BrainLab
- Stryker

**Head fixation**
- Cervical sling
- Mayfield head frame
- Gardner Wells tongs

**Intraoperative neuromonitoring: SSEPs/MEPs/EMGs**

**Instrumentation**
- Special requirements (navigation attachments)
- Interbody cage
- Iliac crest harvesting tools
- Others

**Headlights / loupes/microscope**

**Intermittent pneumatic compression device on legs**

**Appropriate instruments for surgery**

**Local hemostatic agents / pulse irrigation**

**Body warming system**

**Intraoperative cell salvage machine**

**Surgeon preference**
- Type of case: deformity vs. other
- O-arm for spinal navigation

**Level of surgery and type of pathology**
- Deformity vs. non-deformity

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**Surgical Learning Curves**

Surgeon learning curves when new technology emerges have been reported in robotic and laparoscopic surgery.\textsuperscript{34,37} For spine surgery, the learning curve for adopting...
image-guided technology has been reported by Bai et al. and Sasso et al. The components of the learning curve include the ability to direct instruments based on imaging visualized on a screen, the ability to replicate in-line maneuvers while placing instrumentation, as well as adopting and developing proper technique while using image-guided technology. The ability of surgeons to adapt to the use of this technology may depend on a generation of surgeons who grew up playing video games. Rosser et al. was able to correlate faster completion and reduced errors in laparoscopic surgeries when the surgeons had a background of more than 3 hours per week of video game play.
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Surgical Table Selection

Appropriate selection of an OR surgical table for image guidance is important. Modern spine surgical ORs have a variety of equipment at the surgeon’s disposal. Different operating tables have advantages and disadvantages for surgical positioning, exposure, and intraoperative imaging. The dimensions and designs of regular OR tables may hinder one’s ability to perform imaging with modern cone-beam CT–based imaging systems. Two-dimensional fluoroscopy is compatible with many OR tables as long as the patient is positioned appropriately. The Jackson table enables greater deformity correction and correction of alignment along the entire neuraxis, making it ideal for complex spinal fusions. The design of the O-arm allows it to work ideally with the Jackson table, which does not have a base obstructing movement along the long axis of the patient and table. The Jackson table enables the O-arm to be positioned along any level of the spinal axis. The table is well designed for imaging purposes, with its core structure such that the table has minimal radiodense metal resulting in minimal radiographic artifact.

Sterile Draping

Sterile draping is a consideration. Current draping of the fluoroscope is simple and standardized such that the OR staff is able to perform this seamlessly. However, the sterile cover for O-arm use remains cumbersome, at times getting caught between the shields. This has occurred during our initial learning curve with spinal navigation using the O-arm. Once the drape is caught, the failsafe prevents it from opening in an automated manner and manual maneuvers have to be used to open out the O-arm (Fig. 3). In our experience, an alternate draping of the patient in a 360° circumferential manner is more efficient and avoids problems while the O-arm opens and closes around the patient and operating table (Fig. 4). This method of draping could also be adopted for the new intraoperative CT scanners as well.

Registration Process

The registration process following patient positioning is crucial. Inaccurate registration with the use of image guidance and computer-assisted navigation potentially has multiple sources of error. This necessitates frequent validation and accuracy assessment on a continuous basis. Early computer-based navigation systems required registration of preoperative images with the surgical intraoperative space. The margin of error for insertion of a pedicle screw depends mainly on the size of the pedicle, size of the screw, and distance to the isthmus or narrowest point on the pedicle. Rampersaud et al. evaluated error margins and demonstrated very small tolerances, with less than 1 mm permissible for translation and less than 5° for rotational changes in the cervical, thoracic, and thoracolumbar junctions.51 Glossop et al. demonstrated a clinical utility error range of 2–3 mm of translation and 4°–7° of rotation using image-guided navigation.44

Intraoperative image acquisition and registration should therefore be performed after surgical access is completed. This avoids angular and translational movements that may alter the image registration. With conventional open midline access, image acquisition and registration should be performed after completing the approach to eliminate motion-related inaccuracy. In contrast, percutaneous minimally invasive instrumentation may begin immediately after the intraoperative registration procedure without prior anatomical landmark dissection, as significant manipulation of the surgical field and landmarks do not occur in these procedures.59

Errors during image registration can occur. Patients undergoing surgery have 2 body warmers to prevent hypothermia, I placed over the upper body and the other over the lower body. During image acquisition for registration with cone-beam CT scans, the upper body warmer has to be turned off to avoid increasing imaging artifacts and creating registration errors. Additionally, movements during respiration and image acquisition can cause significant changes and inaccuracies with registration. The anesthesiologist has to specifically hold the patient’s respiration during this step, minimizing errors secondary to motion artifact. Image acquisition is also performed after the dissection, and afterward the deep retractors are left in situ, especially for mobile cervical spine segments. The surgeon should avoid changing the position of the table (Trendelenburg position or the reverse) and attempt to avoid any potential movements with instruments that may cause distortion of anatomy, such as drilling and tapping all holes prior to instrumentation.

There is potential inaccuracy with increasing distance of screw placement from the reference arc. Quiñones-Hinojosa et al. analyzed 3D fluoroscopy–identified errors of accuracy at different distances from the reference arc and different time points when used in lumbar spine fusion surgery.47 They identified increasing distance from the reference arc and increased duration of surgery as the main factors, with inaccuracy of 3 mm in 7% of the patients when surgery was 3 levels away from the reference arc, and inaccuracy of 3 mm in 17% about 1 hour into surgery. Scheufler et al. performed pedicle screw instrumentation using a single-registration sequence in 32 (91.4%) of their 35 patients, with as many as 12 vertebrae instrumented after a single registration sequence. They identified a statistically insignificant increase in misplaced screws by about 2 mm at distances 10 segments between the instrumented segment and reference arc.58 Interestingly, Holly et al.58 demonstrated that navigation error is an interaction between technology and human factors, remaining the same independent of registration techniques.67

Considerations Based on the Region of the Surgical Spine

Cervical Spine

For posterior cervical spine surgery (occipitocervical fusions), the reference arc can be placed on the Mayfield headholder,54 with some surgeons preferring the arc on the most distal spinous process exposed in the surgical field. Additionally, to minimize intersegmental movement in the upper cervical spine, imaging should be performed following dissection up to the bone anatomy and placement of retractors to minimize movement after image acquisition and registration. Drilling of pilot holes must be completed
prior to tapping and placing screws, the patient’s respiration must be held (by the anesthesiologist) during image acquisition, and changes in table position must be avoided. In rare cases in which image-guided navigation needs to be used for anterior cervical cases, the cranial reference arc is attached to the Mayfield headholder.\textsuperscript{44,46} Navigation is beneficial in identifying complex bone anatomy, maintaining midline orientation in rotary scoliosis, and locating the vertebral artery foramen in complex tumor cases where this structure may be involved or displaced. Key landmarks need to be marked out prior to bone removal as this segment of the spine is mobile, resulting in positional changes and distortion, with navigation becoming inaccurate after beginning spinal manipulation.

**Thoracic Spine**

We have found that in patients positioned for anterior and lateral approaches to the thoracic spine, the surgeon is...
limited in his or her ability to place the reference arc in an ideal position near the surgical field and obtain clear images. The size and depth of the bore, patient positioning, and orientation are limiting factors for the use of fluoroscopic systems as well as cone-beam CT–based systems. In these cases, it is ideal to perform fluoroscopy-based imaging, utilizing surgical landmarks and imaging landmarks as guides for the procedure. We have found an alternative location, placing the reference arc percutaneously in the iliac crest. However, the caveat remains that the access surgeon helping in the exposure should be comfortable using a Jackson table. Ideally, use of radiolucent retractors avoids imaging artifacts, but if these are not available, standard retractors have to be removed to obtain clear images without distortion. The spine surgeon should keep in mind that navigation is useful for bone anatomy and not useful in delineating the adjacent vascular anatomy or soft-tissue structures.

**Lateral Thoracolumbar Surgery**

Recently there has been increasing interest and use of lateral approaches to the lumbar spine to perform interbody fusions in patients with spinal deformity, spondylosis adjacent to a previous fusion, or degenerative disc disease. Spinal navigation systems have been adapted to these procedures and the dissection, discectomy, and implant tools can be currently paired to navigation to help increase the safety and efficiency of these procedures. Navigation simplifies patient positioning, enabling patients to be easily placed laterally on a Wilson frame, on top of a flat table rather than maneuvering the operative table to perfectly align with anteroposterior and lateral fluoroscopy. The navigated dissection and discectomy tools help to confirm appropriate passage through the tissues and disc space. Preoperative planning with proper placement of the reference arc is crucial. The reference arc must be placed in a position that can be seen by the camera, close enough to the operative field to maintain accuracy, and out of the line of sight to the operative tools. We have found that placing a percutaneous reference arc into the posterior iliac crest serves better than placement into the lateral iliac crest. The lateral crest site may obscure visualization of the arc, and because of the proximity to the surgical site, interferes with the operative tools as they are placed into the disc space (Fig. 5).

**Intraoperative Considerations**

**Operating Room Setup**

Operating room setup and line-of-sight issues can lead to significant delays. Proper setup of the OR is essential for efficient implementation of spinal imaging guidance. In open spinal fusion cases, the camera is placed at the head of the OR table above the anesthesiologist, with the computer monitor placed across the OR table from the surgeon to allow the surgeon easy visualization of the monitor. In minimally invasive spinal fusion cases, in which the reference arc will be placed percutaneously on the iliac crest, the camera is placed at the foot of the bed to keep the reference arc between the camera and the working field in which the image-guided instruments will be used. All image-guided instruments are registered by the OR staff prior to the start of the case.

Additionally, the type of spinal fusion case and surgeon preferences are entered into the image-guided system. The ability to view the reference arc, and the image-guided instruments within this surgical field, requires a linear trajectory between the infrared camera, the reference arc, and the instruments. This direct line of sight requires appropriate placement of the infrared camera and the reference arc (Fig. 6). Incorrect reference arc positioning, as well as placement of objects that block the line of sight between the infrared camera and the reference arc, will result in line-of-sight issues with a resultant inability to navigate (Fig. 7A and B). Subsequently, time and frustration will be added to the case. The reference arc should always be placed between the camera and the area in the surgical field where the image-guided instruments are being used (Fig. 7C). In open cases, the reference arc is placed on the most superiorly exposed spinous process with the camera placed at the head of the bed. In minimally invasive cases in which a percutaneous reference arc is being used, the camera is placed at the foot of the bed as described above. The infrared camera has to be placed at an optimal distance from the reference arc, and the image-guided system has a function that will guide the OR staff in accomplishing this task. Direct light (overhead lights, head lights) shining on the reference arc will affect its ability to reflect the infrared light back to the camera and result in the inability to navigate. If the line of sight is clear between the camera, the reference arc, and the instruments, and the image-guided system still does not visualize the image-guided instruments or reference arc, then the most likely cause is blood or other debris on the reflective spheres of the reference arc and/or image-guided instruments. In this scenario, the spheres should be cleaned with a wet towel or gauze pad and then dried. Bending of the instruments after registration can be problematic because remote instrument tracking relies on the stiffness and nondeformity of surgical instruments. Intru-

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**Fig. 5.** Intraoperative photograph showing the reference arc inserted on the lateral iliac crest adjacent to the surgical site. The proximity of the arc to the surgical instruments results in errors while using image guidance and instrumentation.
ments that are optically tracked and thin such as K-wires or drill bits could bend and result in inaccurate navigation. We have found that while using potentially flexible instruments it is vitally important to make sure that the surgeon does not bend the tool to correct the trajectory down the pedicle that is visualized on the image-guided system, as this deformity of the instrument gives the surgeon a false interpretation of instrument position on the image-guided system with resulting erroneous insertion of the implant.

Wrong-Level Surgery

Wrong-level surgery is another potential pitfall. The absence of visual anatomical landmarks, a steep learning curve, and tactile feedback readily available in open surgery, make the risks of wrong-level screw insertion higher with minimally invasive techniques. Our technique in these cases is to try to include the lumbosacral junction in lumbar cases to provide a point of reference. If the case involves the thoracic spine, then the reference arc placed on the spinous process serves as a marker to localize the appropriate level, and its location should be confirmed by counting levels from the lumbosacral junction using the fluoroscopy function on the cone-beam CT device prior to implementing the scan for cone-beam CT registration. Additionally, the reference arc should always be included in the cone-beam CT scan in these cases to always serve as a point of reference for confirmation of appropriate levels. During navigation, the image-guided platform will allow the field of view to be expanded for visualization of the lumbosacral junction and/or reference arc to confirm appropriate levels. Once appropriate levels are confirmed, the field of view can be zoomed in to allow better visualization of the spinal anatomy for instrumentation placement.

Maintaining Navigation Accuracy

Maintaining navigation accuracy following cone-beam CT registration must be constantly monitored throughout
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The surgery. It is essential to firmly fixate the reference arc to the bone anatomy in lumbar and thoracic cases to ensure that the arc does not move relative to the patient's spine after cone-beam CT registration. In cervical cases, we attach the reference arc to the Mayfield head clamp. We believe the most stable reference fixation in the thoracolumbar spine occurs on the spinous process. It is important that the spikes on the clamp of the reference arc penetrate the cortical bone of the spinous process to prevent the clamp sliding on the bone. Interspinous placement of the reference arc has to be avoided. We gently pull on the reference arc after it is fixated, and before cone-beam CT registration, to confirm that fixation is secure. It is also important to apply counter traction on the reference arc stem when screwing the clamp onto the spinous process to prevent fracture of the spinous process. After cone-beam CT registration, it is essential that the surgeon and assistant do not bump the reference arc, which could move the arc relative to the patient's spine and result in navigation inaccuracy. Additionally, suction tubing and wires for the cauterezation instruments should be positioned so that they do not contact or put traction on the arc when being used. At the skin level, placement of the reference arc at the apex of the incision should also be performed with caution if retractors are not in place at the time of reference arc placement, as retracting the wound will result in inferior movement of the incision apex resulting in applied force to the reference arc stem, which could result in movement of the reference arc relative to the spinal anatomy. Navigation accuracy is best immediately after cone-beam CT registration, so this is when instrumentation placement should occur. Complete exposure of the spine should be accomplished prior to cone-beam CT registration.

In long-level fusions, we still prefer reference arc placement on the most superiorly exposed spinous process. In these cases we will place instrumentation beginning distal to the arc and moving proximal, as instrumentation placement does result in some movement of the spine and the image-guided system is less accommodating in maintaining navigation accuracy at the levels most distal to the reference arc. As a result, the surgeon is moving closer to the reference arc with each subsequent level of screw placement in multilevel cases and this allows the image-guided system to better accommodate the spinal movement that occurs with instrumentation placement in multilevel fusion cases. Caution should be employed, however, in flexible spines (adolescent scoliosis and trauma cases) as the movement in the spine with instrumentation placement in these cases may supersede the ability of the image-guided system to accommodate for this movement, resulting in navigation inaccuracy. Furthermore, it is essential for the surgeon to confirm navigation accuracy prior to placement of each screw, which can be easily and quickly accomplished by touching the spine anatomy and confirming accuracy on the image-guided system. We typically use the transverse process for confirming navigation accuracy by quickly dragging the image-guided probe over the transverse process in the superior-inferior and medial-lateral planes. Avoiding excess force and torque on the spine will also help maintain navigation accuracy. In small or corticated pedicles, drilling the initial hole with an image-guided drill guide will prevent excessive banging of probes down the pedicle and the resulting movement of the spine associated with those maneuvers. Avoiding Trendelenburg and rotational changes in bed position after cone-beam CT registration will also help limit movement of the spine relative to the reference arc and will also help to maintain navigation accuracy in these long-level fusion procedures.
Postoperative Considerations

Radiation Exposure

Minimizing radiation exposure to the staff and patient are essential components taken into account while using imaging guidance. Spinal instrumentation using active fluoroscopy remains cumbersome because of the necessity to maneuver around the fluoroscope while performing surgery and the need to use heavy protective lead shielding. Fluoroscopy can increase the radiation exposure to the surgeon by 10- to 12-fold in comparison with nonspinal procedures, and more so with complex multisegmental fusions, deformity corrections, and reoperations on the spine. With the use of low-dose helical CT techniques, a resulting 20-fold decrease has been noted in patients’ radiation doses compared with standard CT. Nottmeier et al. demonstrated the absence of any radiation exposure to OR personnel using cone-beam CT–guided imaging systems with absence of any radiation scatter if the surgeon stood more than 10 feet away from the system and behind a lead screen. It is important to keep in mind that the surgeon will perform a large number of these procedures in a year, whereas the patient may not require further imaging in the postoperative period once intraoperative imaging confirms appropriate implant insertion following surgery.

Complication Rates

Following the introduction of cone-beam CT–guided spinal navigation, numerous reports in the literature have been published demonstrating its utility in increasing the accuracy of pedicle screw placement and, at the same time, decreasing the incidence of neurological injury from misplaced pedicle screws. Scheufler et al. reported the accuracy of cervical (99.3%), thoracic (97.8%), and lumbar (94.4%) pedicle-screw placement using CT-based neuronavigation systems. Silberman et al. compared freehand with navigation-guided pedicle screw insertion and found a breach rate of 5.9% with the freehand technique and a breach rate of 1% using navigation for lumbar screw placement. Several systematic reviews and meta-analyses comparing the accuracy of navigated versus nonnavigated pedicle-screw placement reported that the pedicle-screw placements using navigation resulted in less pedicle breach (6% vs 15%, respectively) as well as less neurological injury (3 vs 0 cases, respectively). Furthermore, Shin et al. found no statistically significant difference in operative time and estimated blood loss between navigated and nonnavigated cases. These publications support the use of image guidance in aiding surgeons in the placement of pedicle screws. Tow et al. recently published their results on accuracy of pedicle-screw placement using spinal navigation. They found a higher rate of misplaced screws (37.5%) when the reference arc was placed more than 3 levels above their instrumentation level, and a rate of 13.89% when the arc was within 2 levels of their surgery. However, the importance of spinal navigation lies in its adjunct value to enhancing the accuracy of the spine surgeon in complex revision cases with distorted anatomy, and minimally invasive cases in which there is no landmark visualization.

Illustrative Case

This 65-year-old woman presented with severe canal stenosis at the L4–5 levels with disc extrusion, degenerative changes, and moderate spondylolisthesis. She was symptomatic with neurogenic claudication and radiculopathy. She underwent a minimally invasive transforminal lumbar interbody fusion. During the procedure there was movement in the reference arc, which was caused by either tugging by entangled suction tubes or inadvertent table movement after registration. While inserting 1 of the screws, tactile feedback felt incorrect and the angled trajectory seemed to be lateral, although it appeared appropriate on the imaging screen. On confirmatory imaging we found the pedicle screw was placed lateral and outside the pedicle (Fig. 8). We reregistered, found our starting point, tapped and reinserted the screw into the pedicle, and then confirmed this with imaging.

The authors present this case example to illustrate one of the key tenets of spine surgery with navigation. Surgeons must always be cognizant that the images on the screen are not shown in real time. Polyaxial screwdrivers will have some inherent movement at the instrument tip, and thinner-diameter taps may have some flexibility. Care must be taken to insert these tools as straight as possible so that the surgeon does not get “fooled” into thinking the implant is in the proper location when it actually is not.

Discussion

The absence of numerical data in the published literature makes it difficult to perform a systematic or meta-
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Fig. 8. Axial (left) and sagittal (right) cone-beam CT scans used for confirmation of pedicle screw positioning at the L4–5 levels following a minimally invasive transforaminal lumbar interbody fusion. In this image the pedicle screw has been placed lateral to the pedicle due to movement of the reference arc or operating table following image registration. This placement required reimagining and re-registration followed by correct repositioning of the misplaced pedicle screw. The sagittal image reveals the proximity of the L-4 and L-5 pedicles in the sagittal plane, making wrong-level insertions possible if the image is extremely magnified. Thus, we prefer larger fields of view for localization and initial drilling and pedicle tapping, followed by magnified imaging for final pedicle screw insertion.

The sources of potential error thus include imaging errors, surface model generation errors, tracking device fixation errors, registration errors, and inaccurate surgical tools or actions. Any of these alone or in combination result in cumulative errors.7,51 Zwingmann et al. performed a retrospective analysis using data from the German pelvic trauma registry and evaluated the intraoperative complications using navigated and conventional techniques for percutaneous iliosacral screw fixations in pelvic fractures.75 In this prospective multicenter study, they found a similar number of intraoperative and postoperative complications when comparing navigated and conventional techniques for percutaneous iliosacral screw fixation, but had a significantly higher rate of neurological complications. They could not analyze their data to identify the cause of higher neurological morbidity in the navigated group, but identified technical mistakes in the use of navigation or secondary dislocations as a cause of this increased morbidity.74

In a global survey by Härtn et al. regarding the use of navigation, only 11% of surgeons in North America and Europe used navigation in spite of its widespread availability.15 The users of navigation cited increasing accuracy, facilitating complex surgery, minimizing radiation exposure, performing a high volume of surgeries, and its use for minimally invasive surgeries as advantages. For the nonusers of navigation, the high cost of these systems, lack of adequate training, equipment issues, steep learning curve, and disruption of workflow were cited. In the survey these surgeons wanted valid data to prove precision, cost effectiveness, radiation exposure, and training to integrate workflow and technical issues associated with spinal navigation.

With an increasing number of intraoperative imaging analysis on this topic. However, we have summarized the key points that need to be taken into account to avoid potential errors with image-guided navigation using cone-beam CT (Table 1). Integrating the above preoperative checklist system48 and incorporating these steps while using cone-beam CT may help reduce the learning curve, avoid duplicating unwanted steps, achieve better preoperative planning, minimize the potential for misplaced pedicle screws, reduce OR time, and diminish radiation exposure by minimizing frequent intraoperative imaging.

The use of image-guided spinal navigation has been gradually increasing among the surgical spine community. A recent global survey on the use of computer-aided spine surgery by Härtn et al. provided interesting data on the use of spinal navigation.15 With numerous publications demonstrating the time effectiveness of image-guided surgery and the reduction of radiation exposure to OR personnel, the number of centers utilizing imaging guidance is gradually increasing.7,55,40,57,68 Although approximately 80% of the respondents in the survey of Härtn et al. were favorable to the use of spinal navigation, the cost, training, time efficiency, and integration into the OR workflow, as well as the lack of adequate training for surgeons, were cited as reasons for nonutilization of this technology.40,42 There is a consensus among a majority of spine surgeons regarding the significant benefits when imaging guidance and navigation are used in minimally invasive spine surgery, deformity correction surgery, and revision spine cases in which the anatomical landmarks have been distorted.

The sources of potential error thus include imaging errors, surface model generation errors, tracking device
TABLE 1: Summary of key points in cone-beam CT-based image-guided spine surgery

<table>
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<tr>
<th>Step</th>
<th>Key Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>setup</td>
<td>position camera to maximize line of sight&lt;br&gt;position monitor so easily visualized by surgeon&lt;br&gt;patient positioning&lt;br&gt;tuck patient's arms for mid- to high-thoracic &amp; cervical cases to allow positioning of cone-beam CT device around patient&lt;br&gt;use radiolucent/Jackson table&lt;br&gt;Mayfield head clamp; radiolucent head clamp does not have to be used, but angle head clamp superiorly out of the cone-beam CT field of view</td>
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<tr>
<td>registration</td>
<td>reference arc placement&lt;br&gt;firmly affix reference arc to spinous process or iliac crest&lt;br&gt;cone-beam CT registration&lt;br&gt;drape patient, not cone-beam CT device</td>
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<tr>
<td>maintaining navigational accuracy</td>
<td>perform cone-beam CT scan w/ retractors in place (cervical)&lt;br&gt;hold patient respirations during cone-beam CT scan&lt;br&gt;insert instrumentation immediately after registration&lt;br&gt;insert instrumentation starting at the most distal level from the arc &amp; work towards the arc&lt;br&gt;briefly check navigation accuracy on patient anatomy prior to placement of each screw&lt;br&gt;avoid changing Trendelenburg position of bed after registration&lt;br&gt;avoid excessive banging on instruments &amp; movement of spine&lt;br&gt;be aware of flexible spines (adolescent scoliosis patients &amp; trauma patients)&lt;br&gt;do not bump or adjust reference arc after cone-beam CT registration&lt;br&gt;do not bend image-guided instruments&lt;br&gt;always remember that the images on the screen are not in real time</td>
</tr>
<tr>
<td>maintaining line of site</td>
<td>place reference arc between the camera &amp; the working space for image-guided instruments&lt;br&gt;avoid placing objects (suction, clamps) in front of reference arc&lt;br&gt;avoid shining light (headlight, overhead lights) directly on reference arc</td>
</tr>
<tr>
<td>computer-surgeon interface</td>
<td>surgeon or qualified OR staff interfaces &amp; drives computer&lt;br&gt;consider intraoperative planning function of image-guided system during screw placement&lt;br&gt;helps to maximize screw size&lt;br&gt;helps to guide tapping of pedicle &amp; placement of screw down the pedicle to prevent pedicle breach</td>
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<tr>
<td>confirming accurate instrumentation placement</td>
<td>perform cone-beam CT scan prior to leaving OR</td>
</tr>
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</table>

and navigation options being made available to surgeons, integrating effective training and shortening the learning curve are essential to making this technique cost-effective and safe. However, if the surgical team is aware and takes into account the above pitfalls, image-guided systems enable safe and accurate placement of spinal instrumentation in both routine and challenging situations.

**Conclusions**

Image-guided surgery and the tools associated with spinal navigation add a significant value to the armamentarium of the spine surgeon. Image-guided navigation cannot replace the technical expertise and training of spine surgeons, but is a useful adjunct to increasing the accuracy in training, and various complex surgical cases. Spine surgeons using this technology need to be aware of the pitfalls associated with the use of these systems and use good surgical judgment to achieve safe surgical outcomes.

**Disclosure**

Dr. Nottmeier has received speaking fees from Medtronic Navigation and BrainLAB, and serves as a consultant to K2M and Excelsius Surgical.

Author contributions to the study and manuscript preparation include the following: Conception and design: Rahmathulla, Nottmeier, Deen. Acquisition of data: Rahmathulla, Analysis and interpretation of data: Rahmathulla, Nottmeier, Pirris, Deen. Drafting the article: Rahmathulla, Nottmeier. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Rahmathulla. Statistical analysis: Rahmathulla. Administrative/technical/material support: Pirris, Deen, Pichelmann. Study supervision: Pirris, Deen, Pichelmann.

**References**

Pitfalls in image-guided spinal navigation


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