Current Navigation Modalities in Spine Surgery

With a Focus on the Use of the O-arm in Deformity Surgery

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Expert Commentary

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Image guidance in spine surgery has evolved from static modalities such as the plain radiograph to navigation systems such as the O-arm. Commonly used modalities include CT scan based navigation systems, 3D fluoroscopy, and most recently the O-arm. Each of these navigation systems improved on the capabilities of its predecessor with the O-arm being the most recent system. The O-arm obtains multiplanar images of the spine intra-operatively. These images can be used for navigation or for rapidly assessing the safety of implants within the spine. We currently use the O-arm for image guided instrumentation during deformity surgery.

Advances in spinal instrumentation such as the use of pedicle screw fixation has improved the mechanical rigidity of various constructs used for spinal stabilization and deformity correction. However, instrumentation of the spine remains challenging because a significant portion of spinal anatomy is not visible with traditional exposures. Instrumentation therefore requires inference of spinal anatomy from surface landmarks. This "blind" method of instrumentation poses a risk to adjacent neurovascular structures. Historically, intra-operative serial plain radiographs and fluoroscopy were used to facilitate instrumentation of the spine. These modalities, however, have several deficiencies that limit their utility. Radiographs provide static uniplanar images of the spine and require a significant delay between acquiring and processing of the images. This delay prevents instantaneous monitoring of tools and implants within the spine[1,2].

The use of fluoroscopy addressed a primary limitation of X-rays by providing rapid instantaneous imaging of the spine. The fluoroscope is able to image sequential positions of instruments and implants within spine. However, like the plain radiograph, images can only be obtained in a single plane. Multiplanar imaging requires frequent repositioning of the fluoroscope or simultaneous use of a second fluoroscope. In addition, continuous use of fluoroscopy exposes the surgeon to significant radiation[3,4]. Finally, use of a fluoroscope for navigation may significantly limit access to the surgical field by the surgeon. Modern day intra-operative imaging has evolved from the use of fluoroscopy to advanced navigation systems such as the O-arm (Medtronic Surgical Technologies, Louisville, CO), isocentric C-arm, and several CT-scan based navigation systems. These systems are able to provide multiplanar imaging of complex anatomy and allow tracking of surgical instruments and implants within the spine when supplemented with specialized software programs. Though different, these navigation systems consist of similar components. The central component of each system is a workstation that processes 2-D and 3-D images. These systems also have a referencing device, the dynamic reference array (DRA), which is attached to the patient during navigation (Figure 1). The DRA has attached LEDs (light emitting diodes) and can be tracked by an electro-optical camera. The DRA enables accurate navigation even in the presence of motion. Instrumentation is accomplished by specialized instruments (screw drivers, probes, drill guides, etc.) with attached LEDs. The relative position of the instruments and DRA is tracked by an optical camera to facilitate navigation[2,5]. These navigation systems are frequently used at many centers during spine surgery, and the improved safety of instrumentation provided by these imaging modalities has been demonstrated by various authors[6-8]. Below is a brief description of commonly used navigation systems in spine surgery.

CT-based Navigation Systems

There are several CT-based navigation systems available in the market with very similar protocols. They all require obtaining a CT scan of the appropriate levels prior to surgery. Typically, a fine cut (1-2mm) CT scan of the surgical levels to be instrumented is obtained pre-operatively and transferred to a computer workstation where it is reformatted into coronal, sagittal, and axial views. The images obtained can be used for pre-operative planning such as determining the feasibility of instrumentation and also estimating the size and trajectory of selected implants. These images can also be used for navigation. In the OR, easily identifiable anatomical landmarks (tips of the transverse process, spinous process etc) are chosen on the images obtained. After adequate exposure of the spine, a DRA is attached to a fixed point on the spine away from the surgical field. Thereafter, a probe with

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Figure 1. A DRA (dynamic reference array) attached to the posterior elements of the exposed spine during an O-arm navigated posterior instrumentation. A probe with attached LEDs is used to complete registration by placing the probe on the DRA as shown above.

attached LEDs is used to identify the pre-selected points on each vertebrae to be instrumented (paired point matching). This registration process correlates the patient's anatomy to that of the image obtained pre-operatively. The accuracy of the registration process is calculated by the workstation and errors of <1.5mm are typically acceptable[9]. Accurate registration is confirmed by the surgeon by verifying that a probed point on the exposed spine correlates with a similar location on the image. A mismatch should prompt repetition of the registration process. When accuracy is acceptable, navigation ensues with use of specialized instruments[1, 2, 5].

A major disadvantage of traditional CT-based navigation systems is the need for pre-operative CT scans**.** This is problematic in routine deformity surgery (i.e. idiopathic scoliosis) where a CT scan is not a routine part of the pre-operative workup. Moreover, in settings where a pre-op CT scan is obtained as a part of the pre-operative evaluation, the images may not be compatible with the navigation system, consequently requiring additional imaging. The additional radiation exposure and cost that may be required with this navigation system limits its utility[1, 2]. Another problem that results from obtaining images preoperatively is the possibility of a change in intersegmental relationships between vertebral segments during positioning for imaging and actual positioning during surgery. This can occur in the setting of traumatic or degenerative instability. These differences can affect the registration process and accuracy of navigation. Some authors have investigated the role of registering each vertebral segment individually (single-level registration) to avoid errors caused by intersegmental stability. This time consuming method has not been shown to improve accuracy compared to the standard method of multilevel registration[10, 11]. Finally, the need for a manual registration process can be time consuming, has a steep learning curve, and its accuracy is surgeon dependent.

3D Fluoroscopy

Several disadvantages of CT-based systems are addressed by the 3D-fluoroscope. The isocentric C-arm (Siemens AG Medical Solutions, Erlangen, Germany) obtains multiplanar images of the spine as the fluoroscope automatically rotates about the patient through a 190 degree arc (Figure 2). These images are transferred to a workstation and reformatted into sagittal, coronal, and axial views. The scanning process takes approximately 2 minutes for high resolution images and 1 minute for lower resolution images. Unlike the CT- based systems, images are acquired intra-op while the DRA is attached to the patient. An electro-optical camera tracks the position of the DRA while the image is obtained thereby automating the registration process. The automated registration process minimizes the inherent limitations associated

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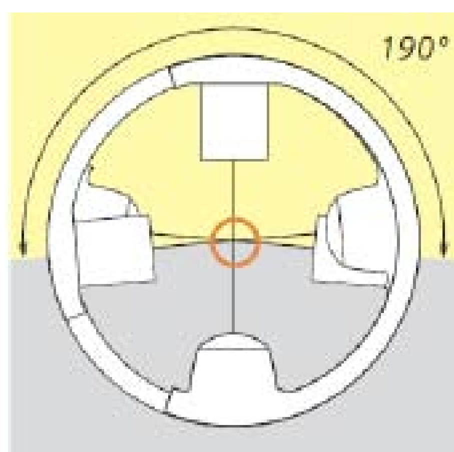

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Figure 2. (A) Siemens SIREMOBIL® Iso-C3D C-arm with 3D imaging capabilities. (B) The Siemens SIREMOBIL® Iso-C3D is automatically rotated through a 190 degree arc about the patient to obtain 3D images.

with manual registration as illustrated above. After registration is completed, specialized surgical instruments can be tracked real time in relation to the reconstructed images. The isocentric C-arm has several advantages over CT-based systems. First, it avoids the need for expensive, time consuming pre-operative CT scan. Second, a surgeon dependent registration process is not required prior to navigation. Because imaging is obtained after the patient is positioned in the operative table, differences in anatomy due to intersegmental instability does not affect the accuracy of navigation, as occurs with traditional CT- based navigation systems[5, 12, 13].

O-arm

The O-arm (Medtronic Surgical Technologies, Louisville, CO) is the most recent navigation system. As with the Iso C-arm, images are obtained intra-operatively while a DRA is attached to the patient thereby automating the registration process. However the O-arm provides image qualities similar to that of a CT scan with lower radiation exposure[14].

The O-arm consists of an oval telescopic gantry that obtains images in a 360 degree arc. The O-arm gantry is automatically adjusted in space by a motorized robot (Figure 3). The x-ray tube and a flat panel are located within the oval housing unit. Its field of view, at approximately 30 x 40 cm, is relatively larger than that of most C-arms. This maximizes the amount of vertebral segments that can be imaged within a single frame. The image obtained is rapidly transferred to a workstation where a multiplanar reconstruction of the anatomy is generated. The resolution of the images generated is determined by the amount of exposures obtained during each scan. Higher resolution images can be obtained with 750 pulses over 25 seconds while lower resolutions images require 391 pulses over 13 seconds[15].

The intra-operative imaging obtained by the O-arm can be linked to a computerized tracking system allowing for surgical navigation. At our institution the O-arm is predominantly used for deformity surgery. Navigation with the O-arm begins with complete exposure of the posterior elements. A DRA is subsequently attached to a spinous process that is within the levels to be instrumented. Because the instrumented levels during pediatric deformity surgery often exceeds the field of view of the O-arm, two scans, and therefore 2 DRAs, are often needed (Figure 4). Before imaging the patient, the surgeon must verify that the location of the DRAs on the patient can be detected by the optical cameras typically positioned above the head of the OR table. Next, the O-arm is draped and positioned over the patient. A scan of the patient is obtained while the surgical team leaves the OR. To optimize image quality, the patient's ventilation may be stopped transiently by the anesthesia staff while the scan is obtained. As mentioned above, two scans are often required to image the entire segments instrumented in deformity surgery. After the scan is obtained, the images are reviewed on the display screen to ensure all segments to be instrumented have been scanned. As mentioned above, registration is automated because images are obtained with the DRA attached to the patient. Navigated instrumentation using the O-arm is accomplished by a probe with attached LEDs. The probe is used to confirm the starting point of pedicle screw fixation at the posterior elements (Figure 5). The estimated trajectory and recommended size of the implant is superimposed on multiplanar images of the

Figure 3. The draped O-arm is shown enclosed over the patient.

Figure 4. Two DRAs attached to the posterior elements. This is often needed for long fusions.

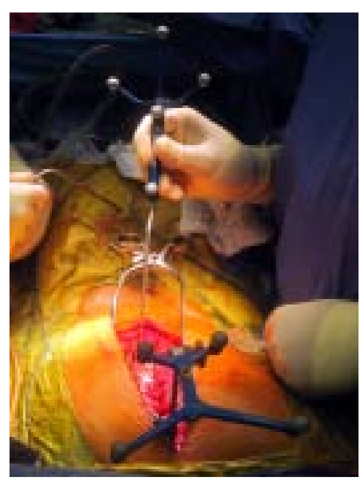

Figure 5. A probe with attached LEDs is placed on the starting point.

Figure 6. The estimated screw size, length and trajectory are superimposed over axial, sagittal and coronal reconstructed views of a thoracic vertebra.

selected level (Figure 6). The surgeon makes a mental note of this trajectory and instrumentation begins using standard techniques. At each stage of instrumentation that precedes insertion of the pedicle screw, the trajectory of the implant can be confirmed with the specialized probe. After all levels are instrumented, a repeat scan can be obtained to ascertain optimal screw placement prior to correction of the deformity.

The O-arm has several advantages over the aforementioned systems. Like the Iso C-arm, imaging is obtained intra-op while the patient is positioned consequently eliminating errors caused by changes in intersegmental relationships. Furthermore, the registration process is automated because imaging is obtained intra-operatively with a DRA attached to the patient. This saves time and improves accuracy of navigation. However, imaging provided by the O-arm is superior to those provided by the Iso-C arm. The O-arm can also be used to rapidly obtain relatively high quality post-operative imaging while the patient remains anaesthetized. In deformity cases where pedicle screws are utilized, safety and accuracy of pedicle screws can be confirmed prior to attempted correction[15].

To date, there are no published well controlled large series evaluating the safety and efficacy of navigated screw placement with the O-arm in spinal instrumentation. That being said, the O-arm has been used at our institution for deformity surgery since 2007**.** We intend to assess our data and ascertain any improvement in accuracy of pedicle screw placement with O-arm navigation.

Conclusion

Use of navigation in spine surgery has improved the safety of spinal instrumentation. Improvement in navigation technology will continue to expand its applications in spine surgery. This technology however should not substitute for a thorough knowledge of spinal anatomy and traditional methods of instrumentation.

Ask the Expert

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Have you noticed an overall reduction in the duration of surgery for instrumented fusions using the O-arm?

After the learning curve, we now can instrument the spine more safely and more quickly that without image guided navigation.

Do you think obtaining intra-op CT scans to confirm screw accuracy with modalities such as the O-arm will become standard of care?

Standard of care is a loaded term with substantial medico-legal implications. I would predict wide adoption of post-implant imaging. I suspect it will be part of spine deformity patient safety just like neurologic monitoring

How has navigation affected resident/fellow education? Is training adversely affected if residents/fellows are trained exclusively with navigation?

It's safer and more fun. Training is enhanced because residents and fellows can actually see (on the navigation images) the substantial and unpredictable pedicle morphology changes commonly present in severe spine deformity. Trainees are taught to use image guided navigation not as a ôcrutchö, but as a way to better understand and deal with the anatomic variability in the deformed spine.

References

1. **Holly LT.** Image-guided spinal surgery. *Int J Med Robot.* 2006 Mar;2(1):7-15.
2. **Holly LT, Foley KT.** Image guidance in spine surgery. *Orthop Clin North Am.* 2007 Jul;38(3):451-61; abstract viii.
3. **Smith HE, Welsch MD, Sasso RC, Vaccaro AR.** Comparison of radiation exposure in lumbar pedicle screw placement with fluoroscopy vs computer-assisted image guidance with intraoperative three-dimensional imaging. *J Spinal Cord Med.* 2008;31(5):532-7.
4. **Rampersaud YR, Foley KT, Shen AC, Williams S, Solomito M.** Radiation exposure to the spine surgeon during fluoroscopically assisted pedicle screw insertion. *Spine (Phila Pa 1976).* 2000 Oct 15;25(20):2637-45.
5. **Gebhard F, Weidner A, Liener UC, Stockle U, Arand M.** Navigation at the spine. *Injury.* 2004 Jun;35 Suppl 1:S-A35-45.
6. **Rajasekaran S, Vidyadhara S, Ramesh P, Shetty AP.** Randomized clinical study to compare the accuracy of navigated and non-navigated thoracic pedicle screws in deformity correction surgeries. *Spine (Phila Pa 1976).* 2007 Jan 15;32(2):E56-64.

7. **Kotani Y, Abumi K, Ito M, Takahata M, Sudo H, Ohshima S, et al.** Accuracy analysis of pedicle screw placement in posterior scoliosis surgery: comparison between conventional fluoroscopic and computer-assisted technique. *Spine (Phila Pa 1976).* 2007 Jun 15;32(14):1543-50.
8. **Austin MS, Vaccaro AR, Brislin B, Nachwalter R, Hilibrand AS, Albert TJ.** Image-guided spine surgery: a cadaver study comparing conventional open laminoforaminotomy and two image-guided techniques for pedicle screw placement in posterolateral fusion and nonfusion models. *Spine (Phila Pa 1976).* 2002 Nov 15;27(22):2503-8.
9. **Rampersaud YR, Simon DA, Foley KT.** Accuracy requirements for image-guided spinal pedicle screw placement. *Spine (Phila Pa 1976).* 2001 Feb 15;26(4):352-9.
10. **Takahashi J, Hirabayashi H, Hashidate H, Ogihara N, Kato H.** Accuracy of multilevel registration in image-guided pedicle screw insertion for adolescent idiopathic scoliosis. *Spine (Phila Pa 1976).* 2010 Feb 1;35(3):347-52.
11. **Papadopoulos EC, Girardi FP, Sama A, Sandhu HS, Cammisa FP, Jr.** Accuracy of single-time, multilevel registration in image-guided spinal surgery. *Spine J.* 2005 May-Jun;5(3):263-7; discussion 8.
12. **Foley KT, Simon DA, Rampersaud YR.** Virtual fluoroscopy: computer-assisted fluoroscopic navigation. *Spine (Phila Pa 1976).* 2001 Feb 15;26(4):347-51.
13. **Holly LT, Foley KT.** Three-dimensional fluoroscopy-guided percutaneous thoracolumbar pedicle screw placement. Technical note. *J Neurosurg.* 2003 Oct;99(3 Suppl):324-9.
14. **Zhang J, Weir V, Fajardo L, Lin J, Hsiung H, Ritenour ER.** Dosimetric characterization of a cone-beam O-arm imaging system. *J Xray Sci Technol.* 2009 Jan 1;17(4):305-17.
15. **Eric L. Lin DKP, Peter G.** Whang, Howard S An, Frank M. Philips. O-Arm Surgical Imaging System. *Semin Spine Surg.* 2008;20:209-13.