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Stereotactic Navigation in Complex Spinal Surgery: Tips and Tricks

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Stereotactic navigation has become an indispensible tool for accurately inserting spinal instrumentation and localizing hidden anatomy. The first-generation navigation systems used slow, and relatively inaccurate methods to synchronize (register) the surgical anatomy with computed tomography images obtained preoperatively. Newer systems overcome these limitations by using 3-dimensional images obtained intraoperatively to register the workstation. They also employ robust software to display the anatomy in orthogonal planes with superimposed images of surgical instruments. These innovations have dramatically improved the effectiveness of stereotactic navigation and allowed image guidance to be a routine and nearly seamless adjunct to spine surgery. The purpose of this article is to provide a brief overview of stereotactic navigation in spine surgery, describe our methods for registration and direct referencing and share lessons learned for best practice use of this promising technology.
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KEYWORDS stereotactic navigation, posterior, spinal instrumentation, spinal fusion, referencing, O-arm

Introduction

The intent of surgeons practicing spine surgery is to perform each operation in the safest and most effective manner possible. This principle has driven innovation in all realms of spine surgery over the last several decades. The wide introduction of pedicle screws and rigid segmental instrumentation techniques in the 1990s prompted an exponential growth in instrumented spinal fusion procedures. With each new innovation in spine surgery, new challenges are introduced. Accurate placement of spinal implants is one of these challenges. Since Gertzbein's initial assessment and grading of pedicle screw placement, surgeons have sought ways to use 3-dimensional (3-D) spinal imaging to place instrumentation more precisely.[1] The introduction and optimization of stereotactic navigation in spine surgery over the last 2 decades is an example of innovation overcoming such challenges. Against this backdrop, this article is written to describe the history and basic tenets of stereotactic navigation in spine surgery and details of our technique for using intraoperative stereotactic navigation in complex spine surgery.

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What Is Stereotactic Navigation and When Is Most Useful?

The term stereotactic is derived from the Greek root stereo- (means solid or having structure) and the Latin root –tact (mean to touch). In the case of stereotactic navigation, the touch in space is performed virtually, through the use of a 3-D image set and a navigation computer system that allows one to use instruments in surgery that are tracked with a camera and mapped to an acquired image. The final outcome is that a 3-D image can be acquired preoperatively, or more recently intraoperatively, the working ends of guided instruments can be tracked on a computer monitor and the surgeon can have real-time understanding of the anatomy at the working end of the implant and beyond. When digital images and intraoperative data are integrated via a computer system to assist or guide

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surgery, the terms computer-assisted surgery and image-guided surgery, are often used and are synonymous with stereotactic navigation surgery. Although stereotactic navigation was originally described and designed for use in skull-based neurosurgery, its uses outside of the skull have blossomed, especially in the spine.

The prototypical use of stereotactic navigation in spine surgery is in the placement of pedicle screws or other implants into the spine. Although there are many described methods for the safe placement of pedicle screws, ranging from freehand to fluoroscopically assisted techniques, all have been associated with a pedicle wall violation rate that is relatively high when evaluated radiographically. Although misplaced screws are infrequently symptomatic ($<5\%$), they can have significant consequences.[2-6] Stereotactic navigation has been shown to improve the accuracy of screw insertion and decrease the rate of returning to the operating room (OR) to revise misplaced instrumentation.[7,8]

The original stereotactic navigation systems relied on images that were obtained before surgery. A key requirement for stereotactic navigation is a referencing method. The referencing method is the process that correlates 3-D images to real anatomical structures. Without accurate referencing one cannot have accurate navigation. In the setting of cranial surgery, the skull was rigidly captured in an external frame that was worn during image acquisition. The images and the patient were then transferred to the operative suite where a first-generation navigation station married the images to points on the frame that were tracked with an infrared camera or by other means. The navigation station was able to compute in real-time, through trigonometric conversions, the angle and the projection of the approach between surgical instruments and the intracranial target. This system allowed for accurate targeting of deeper portions of the brain for neurosurgical procedures like tumor resection and more recently deep brain stimulation surgery for movement disorders. Although the use of framed stereotactic navigation remains a prominent and expanding aspect of brain surgery, translation of intraoperative navigation technology to the spinal column required the use of a frameless approach.

In addition to a frame, earlier stereotactic navigation systems required the placement of external fiducial markers. A fiducial marker, from the Latin word for trust, is a defined point in space that acts as a trusted reference. It must be detectable on imaging and by the navigation camera. Historically external fiducial markers were affixed to the patient's skin via adhesive. They were placed in specific locations based on the planned surgery. At least 4 fiducials must be placed at the time of the image acquisition and these must remain in place, undisturbed throughout the surgical use of navigation. The process of correlating the fiducial markers to the acquired image is called "referencing," and the first time in which this process is performed in an operative case, it is called "registration." To perform this process, a guided probe, which has at least 3 passive reflector spheres that are trackable by the navigation camera, is used to touch the center of each fiducial mark. The accuracy of the navigated image, which is the married 3-D image displayed on the navigation station, and reality is confirmed through this process of referencing. In addition to fiducial marking, unique and obvious portions of the anatomy are probed before and during navigated surgery to continually reconfirm the accuracy of the navigated image. When superficial adhesive markers are used, it is easy for the fiducials to shift, resulting in loss of navigated image accuracy. Overall this referencing method is quite accurate in cranial surgery, since a single osseous structure, the skull, is used as the anchor point for the referencing method. However, the articulated nature of the spinal column posed a new challenge for the concept of stereotactic navigation and more specifically the method for referencing the navigated image.

The Dawn of Frameless Stereotactic Navigation for Spine Surgery

The first-generation spinal surgery navigation systems relied on images that were acquired before surgery.[9-11] Computed tomography (CT) scan images using a specific protocol (ie, 1 mm slice thickness) were obtained in a radiology suite. These images were then loaded to the navigation station. Intraoperatively, referencing was performed by taking a guided probe and touching specific anatomical landmarks (ie, a portion of a spinous process) or externally applied fiducial markers, termed the "point merge technique" and this required the use of at least 4 reference points. This disconnect between image acquisition and use in the surgical theater, introduced room for registration error.[12] In addition, each vertebra had to be registered individually since the position of the spine on the operating table typically did not match the position of the spine at the time of the preoperative scan. In response to these limitations, navigation platforms that could obtain images within the operative suite for stereotactic navigation was the leap forward that progressed this technology from a novelty, reserved for unique cases, to mainstream spine surgery. Minimally invasive techniques for placing spinal implants have further accelerated the acceptance of this technology. Zhang et al have shown that in adolescent idiopathic scoliosis, the use of intraoperatively acquired images for navigation vs those acquired preoperatively, results in significantly decreased rates of medial perforation and significant (ie, >2 mm) pedicle breaches (5% vs 11%, $P = 0.035$). The advantage of real-time, continuous image guidance affords greater confidence in placing implants using minimal access approaches, especially for those earlier in the learning curve.[1,4,5,12] Further, the frameless, integrated registration processes used in current navigation systems has reduced in half the time required to place an image-guided pedicle screw compared to previous techniques which relied on preoperatively acquired images.[12] The improved implantation accuracy achievable with current systems has led to a significant reduction in reoperation rate for screw malposition.[7,8]