Intraoperative image guidance for endoscopic spine surgery

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Abstract: Endoscopic spine surgery is a burgeoning component of the minimally invasive spine surgeon's armamentarium. The goals of minimally invasive, and likewise endoscopic, spine surgery include providing equivalent or better patient outcomes compared to conventional open surgery, while minimizing soft tissue disruption, blood loss, postoperative pain, recovery time, and time to return to normal activities. A multitude of indications for the utilization of endoscopy throughout the spinal axis now exist, with applications for both decompression as well as interbody fusion. That being said, spinal endoscopy requires many spine surgeons to learn a completely new skill set and the associated learning curve may be substantial. Fluoroscopy is most common imaging modality used in endoscopic spine surgery for the localization of spinal pathology and endoscopic access. Recently, the use of navigation has been reported to be effective, with preliminary data supporting decreased operative times and radiation exposure, as well as providing for improvements in the associated learning curve. A further development is the recent interest in combining robotic guidance with spinal endoscopy, particularly with respect to endoscopic-assisted lumbar fusion. While there is currently a paucity of literature evaluating these image modalities, they are gaining traction, and future research and innovation will likely focus on these new technologies.

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Introduction

The minimally invasive surgery (MIS) movement has revolutionized virtually all surgical specialties, including spine surgery. The goals of providing equivalent or better outcomes compared to conventional open surgery, while minimizing soft tissue disruption, blood loss, postoperative pain, recovery time, and time to return to normal activities is appealing to both surgeons and patients alike. In addition, the potential for reduction in cost-of-care has enormous implications for the economics of health care delivery (1). Today endoscopy within spine surgery is utilized to treat multiple degenerative pathologies including foraminal stenosis, disc herniation, and even assisting with end-plate preparation for fusion (2,3). As the tubular MIS approach removed the need to perform a painful subperiosteal dissection, the full percutaneous endoscopic technique allows surgeons to avoid potentially destabilizing laminotomy and medial facetectomy for appropriately selected pathologies (4).

Such benefits are not gained without overcoming challenges however. The learning curve for endoscopic spine surgery is steep, stemming in part from the need for highly accurate localization given the critical nearby neurologic structures. Several studies have attempted to quantify this learning curve with results ranging between 10 to 72 surgeries in order to achieve stable proficiency (5,6). While localization is not the only contributing factor to the learning curve, it stands to reason that the advancement

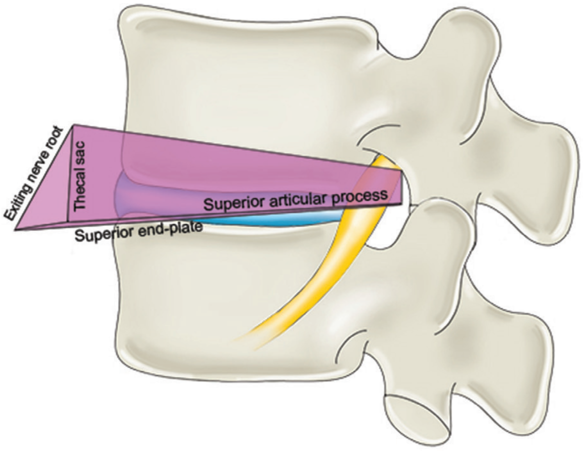

Figure 1 Kambin's triangle is a 3D space bounded anteriorly by the exiting nerve root, posteriorly by the superior articular process of the caudal vertebrae, medially by the thecal sac and traversing nerve root, and inferiorly by the superior end-plate of the caudal vertebrae.

of intraoperative image guidance for localization could improve the technique's learning curve and make spinal endoscopy more accessible.

Classically, percutaneous endoscopic access for lumbar discectomy is achieved via navigation of a spinal needle under fluoroscopic guidance to the area of interest, as discussed in the first section below. Advances in image guidance, paralleling the development of advanced image guidance techniques for the placement of spinal instrumentation, are now opening the doors to new methods of real-time localization. This article will review these techniques and their current support within the literature.

Fluoroscopic guidance

The advent of modern endoscopic surgery was made possible by the description of a safe working corridor to the disc space via the neural foramen by Parvis Kambin. This corridor, now referred to as "Kambin's triangle," is composed of four distinct anatomic structures: the exiting nerve root anteriorly, the superior articular process posteriorly, the thecal sac and traversing nerve root medially, and the superior end-plate of the inferior vertebral body inferiorly (*Figure 1*) (7-9).

Understanding the confines of this "safe" working zone lead to the development of novel surgical techniques such as transforaminal endoscopic discectomy which we will focus upon here. These techniques rely heavily upon fluoroscopic guidance to ensure appropriate localization (10,11). In this regard, the two most important structures to be avoided during access are the dorsal root ganglion (DRG) and the exiting nerve root rostrally, and the thecal sac medially (12,13). Additionally, the angle of approach is critical, and it must be tailored individually to allow access to the pathology being targeted. The approach must also consider the level of the pathology, as previous research has demonstrated a decrease in foraminal height and diameter when moving caudally throughout the lumbar spine (14).

Finally, before discussing appropriate landmarks for fluoroscopic localization, we must decide where the inner working of the endoscopic cannula should be docked. Specifically, one must decide whether to dock the cannula within the disc space or outside of the disc space, at the level of the annulus. These two approaches are often discussed as the "inside out" and "outside in" approaches, respectively (15-19). While there is no "one-size-fits-all" approach, many contemporary endoscopic practitioners utilize the "outside-in" technique and we will focus on this approach for the purposes of this discussion (15,20-22).

Considering each of these points collectively, we can establish some basic principles for endoscopic localization using the "outside-in" technique: (I) the safe working corridor is within Kambin's triangle (II) the maximum depth of the working cannula should be just superficial to the disc space at the level of the annulus (III) the working cannula should not be so medial as to jeopardize the descending nerve root or thecal sac but not so lateral as to be outside the foramen, and (IV) the angulation of the approach should be such that injury to the DRG is minimized while surgical exposure is maximized. These principles have guided the modern technique for approaching a transforaminal discectomy.

Based on these principles, the skin entry point for a percutaneous endoscopic discectomy is generally 8–14 cm off midline laterally and guided by preoperative imaging (23,24). Both the starting point and angle of approach will be guided by the pathology being treated, with a steeper approach for far lateral herniations and a more shallow approach for more midline herniations (13,25). The needle is advanced with the goal of docking at the level of the disc space rostro-caudally, at the edge of the posterior vertebral line on lateral fluoroscopy, and approximately at the mid-pedicular line on AP fluoroscopy (*Figure 2*) (23,24). Needless to say the

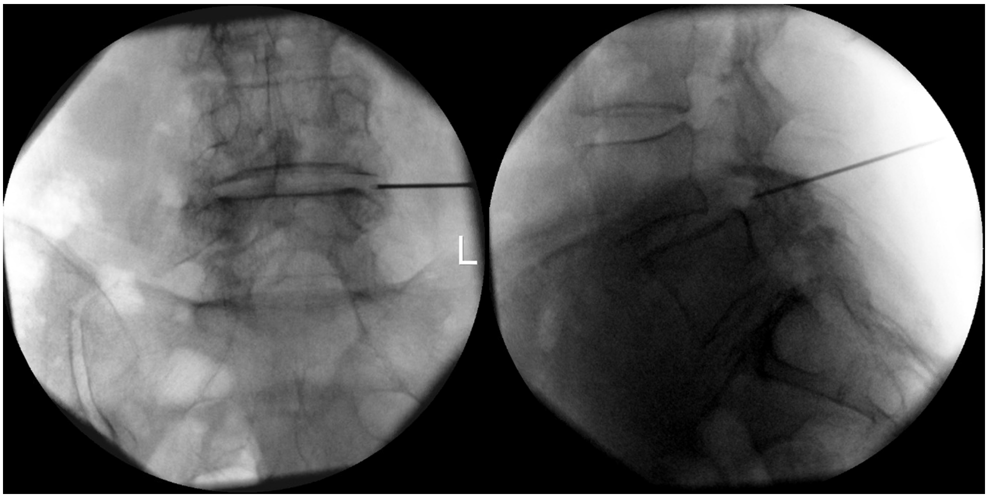

Figure 2 AP and lateral fluoroscopy demonstrating fluoroscopic guided localization of the disc space through Kambin's triangle. Ideally the needle should be at the mid-pedicular line on AP fluoroscopy and at the posterior vertebral line on lateral fluoroscopy. All figures submitted are original and prepared specifically for this submission.

laterality of this docking point can also be adjusted based on pathology, and may range anywhere from the lateral pedicular line to the medial pedicular line (13).

However, in addition to a detailed understanding of fluoroscopic localization, the use of local, rather than general anesthesia is critical to the safe completion of this procedure (26). While there are a myriad of reasons to avoid general anesthesia when possible, the use of sedation and local anesthetic without intubation or deep sedation is especially appealing in endoscopic spine surgery. Specifically, the performance of endoscopic spine surgery without general analgesia allows for immediate and direct patient feedback throughout the surgery (16,26). If a patient begins to have significant radicular pain during the surgery, this likely indicates close proximity to critical neural elements. This feedback should be viewed as synergistic with fluoroscopic localization in minimizing injury to the neural elements.

3-D computed tomography navigation

3-D CT navigation technology is widely used for the placement of spinal implants in both open and minimally invasive spine procedures. CT navigation allows for real-time visualization of the spinal anatomy in the axial, coronal, and sagittal planes and is associated with increased accuracy of pedicle screw placement, while potentially decreasing radiation exposure (27,28). An emphasis on obtaining the utmost accuracy lends this technology well to spinal endoscopy, which hinges on absolute accuracy and precision in localization. This fact is a major contributor to the steep learning curve associated with spinal endoscopy (6). Regardless of its potential for benefit, the literature contains only a handful of accounts of the combination of 3-D CT navigation with percutaneous endoscopic discectomy (29-31).

With respect to the lumbar spine, the largest published account is a prospective cohort study of 118 patients undergoing percutaneous endoscopic lumbar discectomy (PELD) utilizing either 3-D CT navigation (O-arm, Medtronic Inc., Minneapolis, MN, USA) or conventional fluoroscopic guidance (30). The surgical technique for the navigation group involves affixing a reference frame to the contralateral iliac crest, followed by an intraoperative O-arm scan, and finally registration of that scan to the spinal anatomy and surgical instruments. Utilizing real-time navigation, the appropriate trajectory through Kambin's triangle may be planned and executed upon. In addition, fully navigable instruments provide for the ability to perform foraminoplasty under live navigation. Once the endoscope is brought into the operative field, the remainder of the procedure proceeds in the typical fashion under endoscopic visualization. Mean operative times and radiation exposure times were significantly decreased in cases utilizing navigation as compared to fluoroscopy. Perhaps more importantly, navigation was associated with a significant improvement in the associated learning curve with an estimated 13 cases required to gain stable proficiency with regard to operative time, compared to 32 cases in the fluoroscopy cohort. One study by Zhang *et al.* has explored value of 3-D CT navigation in posterior endoscopic cervical foraminotomy and discectomy (31). This retrospective review of 42 patients undergoing O-arm navigated percutaneous endoscopic cervical foraminotomy with or without discectomy resulted in significant improvements in patient reported clinical outcome measures without complication nor the need to convert to open decompression. In similar fashion to the aforementioned technique described by Ao *et al.*, real-time navigation is used to precisely identify the skin entry point and trajectory to the laminofacet junction of interest. After docking the endoscopic working cannula, the procedure also proceeds under endoscopic visualization.

Robotic guidance

Robotically-guided endoscopic spine surgery remains in its earliest infancy at the time of this publication, but it is predicated on the same core principles as intraoperative navigation. These include, but are not limited to, improved overall accuracy of localization, tempered learning curve, and reduced radiation exposure. Unique to robotics however is the overarching goal to establish consistency and reproducibility amongst surgical techniques, in order to standardize surgical work flow. As expected, the published literature on this topic is minimal at the present time.

Liounakos *et al.* describe the utilization of robotic guidance for minimally invasive endoscopic transforaminal lumbar interbody fusion (32). In addition to guiding pedicle cannulation for percutaneous pedicle screw placement, the robotic guidance system (Mazor X, Medtronic, Minneapolis, MN, USA) allows the surgeon to plan multiple access trajectories to the disc space through Kambin's triangle for endoscopic discectomy, end-plate preparation, and expandable interbody delivery. Multiple trajectories may be planned and quickly toggled between, evaluating each with triggered electromyography in order to determine the most ideal trajectory. Following this decision, a guide wire is left in the neural foramen abutting the disc annulus and endoscopic discectomy proceeds. Utilizing a previous generation robotic platform (Renaissance, Mazor Robotics Inc., Caesarea, Israel), Kolcun *et al.* described another instance of robotic-guidance for disc space targeting for endoscopy, this time for the purpose of disc biopsy, culture, and washout for thoracic discitis (33). Next generation robotic platforms with integrated real-time navigation capabilities may serve to further refine these applications in minimally invasive spine surgery.

Conclusions

Endoscopic spine surgery is rapidly gaining traction as an alternative to traditional minimally invasive spine surgery techniques. Moreover, advancements in both endoscopic surgical applications and image-guidance and navigation are occurring in parallel. Currently the most tried-and-true method of image-guidance is fluoroscopy. However, as more surgeons adopt both endoscopy and real-time image guidance and navigation into their practice, we are likely to see a more fluid combination of these technologies. Current limitations to both 3-D CT and robotic image-guidance systems include the need for a reference array, or the robot itself, to be rigidly mounted to the patient. As it is ideal to perform endoscopic procedures under local analgesia in order to take advantage of patient feedback during the procedure, any patient movement in addition to pain from reference array placement poses an issue. While not currently validated in the scientific literature, electromagnetic tracking navigation may provide one solution to this. To be sure, high quality research studies evaluating each of these techniques will be necessary in order to validate these new and exciting technologies.

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