Mini-invasive Surgery

Review

Navigation, mixed reality, and robotics in endoscopic spine surgery

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Abstract

Endoscopic spine surgery (ESS) is an ultra-minimally invasive technique through which spinal pathology can be addressed via sub-centimeter incisions with negligible soft tissue disruption. However, concerns exist regarding the steep learning curve, operative time, and radiation exposure to the surgical team. The use of intraoperative navigation, mixed reality, and robotics in the setting of ESS is currently being explored, and the early evidence suggests that such technologies may help mitigate these issues. The application of these technologies in ESS as well as the associated literature is reviewed herein.

Keywords: Endoscopic spine surgery, navigation, mixed reality, robotics

INTRODUCTION

Minimally invasive spine surgery (MISS) aims to improve clinical outcomes while minimizing soft tissue damage, blood loss, recovery time, and pain. In recent years, there has been growing interest in and utilization of endoscopic spine surgery (ESS). Endoscopic techniques allow surgeons to approach the spine and neural elements via sub-centimeter incisions with negligible soft tissue disruption. Full ESS therefore offers several advantages over other MISS techniques, including tubular approaches[1]. Despite the potential advantages of ESS, concerns exist regarding surgical team radiation exposure, adequacy of decompression, and the associated learning curve[2-5].

ESS, particularly transforaminal lumbar discectomy via Kambin's triangle, requires highly accurate localization to afford access to the site of pathology and avoid iatrogenic neurological injury[6,7]. Traditional endoscopic localization techniques utilize biplanar fluoroscopy to navigate to the area of interest[8,9]. While fluoroscopy-based techniques have been widely adopted and utilized, authors have suggested that incorporating modern intraoperative image guidance systems could reduce the learning curve associated with ESS[4,6]. What follows is a review of the current state of intraoperative navigation, mixed reality, and robotics as applied to ESS.

THREE-DIMENSIONAL COMPUTED TOMOGRAPHY NAVIGATION

Three-dimensional (3D) computed tomography (CT) navigation allows for instrument tracking and localization and is frequently utilized in minimally invasive spine surgery. CT navigation allows for the accurate placement of percutaneous spinal instrumentation while decreasing radiation exposure to the surgeon and operating room staff compared to conventional fluoroscopic techniques[10,11]. It therefore stands to reason that combining this technology with ESS may be beneficial. For example, surgeons can use navigated instruments to guide them to the spine and to assess the extent of their decompression[4,12,13]. Furthermore, navigation may be of additional benefit in the revision setting where commonly used anatomic landmarks are distorted or absent. It is important to note that intraoperative CT navigation does increase radiation exposure to the patient compared to fluoroscopic techniques. Furthermore, movement of the fiducial or patient can compromise the accuracy of the CT navigation.

To date, the largest study evaluating CT navigation for lumbar ESS was published by Ao *et al.*[14] [Table 1] in 2019. The authors sought to assess the safety and efficacy of transforaminal endoscopic lumbar discectomy assisted by O-arm-based navigation (Medtronic Inc., Minneapolis, MN, USA). A total of 118 patients with symptomatic lumbar disc herniations were included in this prospective cohort study with 58 patients undergoing navigation assisted ESS and 60 patients undergoing ESS with the traditional biplanar fluoroscopic method. The use of navigation required placement of a reference frame into the contralateral iliac crest, followed by an intraoperative O-arm scan, and registration of that scan to the spinal anatomy and surgical instruments. In their technique, navigation was utilized to plan the appropriate trajectory and enabled the surgeon to perform the foraminoplasty using navigated instruments. The remainder of the procedure was performed under direct endoscopic visualization. Navigation use was found to ease the learning curve (13 cases *vs.* 32 cases), decrease cannula placement time and total operative time, and reduce radiation exposure to the surgical staff. There were no significant differences in clinical outcomes and no complications associated with the use of navigation. The authors concluded that the use of navigation in conjunction with transforaminal endoscopic lumbar discectomy was safe, accurate and efficient.

Zhang *et al.*[15] retrospectively evaluated the use of O-arm navigation when performing endoscopic posterior cervical foraminotomy with or without discectomy in 42 patients. Authors utilized navigation to plan their trajectory to the laminofacet junction at the level of interest. The remainder of the procedure was performed using direct endoscopic visualization. There were no perioperative complications or conversions to open surgery. At a mean follow-up of 15 months, patient reported outcome measures (VAS arm, neck, NDI) were significantly improved in all patients.

ULTRASOUND AND ELECTROMAGNETIC NAVIGATION

While CT-based navigation is already relatively pervasive within the field of spine surgery, other means of navigation exist that may reduce radiation exposure to the patient as well as the surgical team. Ultrasound (US) is a real-time imaging tool that does not produce ionizing radiation. It has been used as an aid in a variety of spinal procedures, including lateral lumbar interbody fusion[16], thoracic discectomy[17], resection

Table 1. Available clinical studies

Ref.	Design (*n*)	Techniques (*n*)	Surgery	Outcomes
Ao *et al.*[14]	Prospective cohort study (118)	CT Navigation (58) *vs.* biplanar fluoroscopy (60)	Transforaminal endoscopic lumbar discectomy	Decreased learning curve, cannula placement time, total operative time, radiation exposure to surgical staff with CT navigation; no difference in clinical outcomes
Zhang *et al.*[15]	Retrospective cohort study (42)	CT navigation	Endoscopic posterior cervical foraminotomy	No perioperative complications, significantly improved PROMS at last follow-up (mean 15 months)
Zhang *et al.*[20]	RCT (60)	Fluoroscopic guidance (30) *vs.* ultrasound guidance (30)	Transforaminal endoscopic lumbar discectomy	No differences in clinical outcomes, needle placement, cannulation, or operative times; significantly lower fluoroscopy shots and radiation with ultrasound technique
Lin *et al.*[21]	Retrospective cohort study (17)	Electromagnetic navigation	Transforaminal endoscopic lumbar discectomy	No perioperative complications, significantly improved PROMS at last follow-up (mean 20.6 months)
Liu *et al.*[24]	Matched cohort study (77)	Mixed reality (44) *vs.* matched controls (43)	Transforaminal endoscopic lumbar discectomy	No difference in clinical outcomes, significant reduction in operative time and radiation exposure to the surgeon with mixed reality; increased eye fatigue with mixed reality
Jin *et al.*[33]	Matched cohort study (117)	Robotic assistance (39) *vs.* fluoroscopic assistance (78)	Transforaminal endoscopic lumbar discectomy	More precise puncture, reduced fluoroscopy use, reduced operative time with robot; no difference in outcomes, length of stay or complication rates

RCT: Randomized controlled trial; PROMs: patient reported outcome measures.

of intradural mass lesions[18], and transforaminal epidural steroid injections[19]. Given the relative similarities between performing a transforaminal injection and localizing for a transforaminal endoscopic procedure, it stands to reason that ultrasound might be applied to ESS.

Zhang *et al.*[20] recently published their early experience using ultrasound guidance in transforaminal endoscopic lumbar discectomy. In this prospective randomized controlled trial, 60 patients with lumbar disc herniations undergoing discectomy via a transforaminal endoscopic approach were randomly divided between conventional fluoroscopic guidance and ultrasound guidance groups. A standard ultrasound machine and probe were used in the study with a physician specializing in ultrasound holding the probe while a surgeon performed the procedure. Spinal level identification, trajectory planning, and needle placement into the foramen were all accomplished using ultrasound; fluoroscopy was only used to confirm needle and cannula placement in this group. The remainder of the procedure was identical between the two cohorts. The authors observed no significant differences in needle placement, cannulation, or total operative times; and clinical outcomes were similarly positive with no complications in either group. However, the use of ultrasound was associated with significantly fewer fluoroscopy shots (2.13 ± 0.35 shots *vs.* 7.57 ± 2.99 shots, $P < 0.001$) and less radiation exposure (5.34 ± 0.63 mSV *vs.* 18.25 ± 10.52 mSV, $P < 0.001$) compared to traditional fluoroscopy alone.

Electromagnetic navigation can also provide real-time guidance without ionizing radiation. Such systems generate a magnetic field, which is used to receive and transmit electromagnetic signals to determine the position of a target in space. A retrospective pilot study of 17 patients undergoing electromagnetic navigation assisted transforaminal endoscopic foraminoplasty and discectomy demonstrated the feasibility and safety of this technique[21]. The described navigation system requires percutaneous placement of localizer into the spinous process of an adjacent vertebra, followed by anterior-posterior and lateral fluoroscopy shots for registration. No other X-rays are required after this point - the targeting needle, reamers, and endoscope can all be monitored via navigation alone.

Ultrasound volume navigation (UVN) is a technique that fuses preoperative CT or magnetic resonance imaging (MRI) data to real-time ultrasound. It has been used in conjunction with an electromagnetic tracker in early feasibility studies to facilitate localization and docking for transforaminal endoscopic lumbar discectomies[22,23]. While ultrasound alone may require specialized training and experience to interpret, a potential benefit of UVN is that surgeons view a more intuitive reconstructed MRI or CT image.

MIXED REALITY

Mixed reality technology merges the real and virtual worlds to produce new environments and visualizations in which the digital and physical objects coexist and can interact in real time. Such systems typically involve the use of head-mounted optical see-through displays through which images can be selectively projected over the viewer's normal vision. In contrast to other means of navigation, mixed reality allows surgeons to keep their gaze fixed on the surgical field rather than looking up at a monitor while navigating instruments and implants. The first spine surgery carried out in the United States using mixed reality was performed in 2020 using the xvision Spine System (Augmedics, Chicago, IL).

While pedicle screw placement has been an early focus of mixed reality technology, it could provide benefits in other realms of spinal surgery, including ESS. Liu *et al.*[24] evaluated the use of mixed reality for marking, needle insertion, foraminoplasty, and working cannula insertion during transforaminal endoscopic lumbar discectomy. Mixed reality was used in 44 such cases, and results were compared to 43 matched patients in whom conventional techniques were used. There were no differences in clinical outcomes, but the use of mixed reality was associated with significant reductions in operative time (18.48 ± 6.38 min *vs.* 23.87 ± 9.64 min, $P = 0.003$) and radiation exposure to the surgeon (13.59 ± 4.56 mGy *vs.* 18.62 ± 7.07 mGy, $P < 0.001$). The incidence of eye fatigue, as measured by a subjective questionnaire, was higher when mixed reality was used with visual discomfort, headache and blurred vision being noted.

ROBOTICS

In 2004, the Mazor Spine Assist (Medtronic, Minneapolis, MN) became the first robotic spine surgery platform to receive Food and Drug Administration approval[25-27]. Since that time, there has been a steady refinement of the technology. Presently available robotic systems incorporate CT-based navigation, which allows for instrument tracking. The rationale for incorporating robotics to ESS is similar to CT navigation - improved accuracy, reduced learning curve, and limited radiation exposure to the surgeon and staff. However, robotics may advance ESS even further given opportunities to standardize the workflow and enhance surgeon control[6,28-30].

Recent publications have asserted that robot-guided ESS is in its "earliest infancy" with limited supporting literature[6]. Liounakos and Wang[31] published their technique for endoscopic transforaminal lumbar interbody fusion using robotic guidance and an expandable interbody. The authors utilized the Mazor X robot (Medtronic, Minneapolis, MN) to cannulate pedicles and place percutaneous pedicle screws in the standard fashion. However, they also utilized the robotic software to plan trajectories through Kambin's triangle for endoscopic discectomy, endplate preparation and interbody delivery. The authors highlight the ability to quickly plan and move between different trajectories to the disc space. Their ideal trajectory was chosen based on triggered electromyography responses. A prior publication by Kolcun and Wang[32] detailed their experience using robotic guidance for disc space targeting in a case of thoracic discitis treated with endoscopic irrigation and debridement.

Table 2. Advantages and disadvantages of advanced technology in endoscopic spine surgery

Technology	Advantages	Disadvantages
CT navigation	Reduced learning curve, cannula placement time, total operative time, radiation exposure to the surgical team[14]	Requires placement of reference frame Increased radiation to patient Capital cost of navigation equipment Potential for reliance on technology to perform procedure
Ultrasound guidance	Reduced radiation exposure to patient and surgical team[20] Low cost	Requires advanced ultrasound training Potential for reliance on technology to perform procedure
Electromagnetic navigation	Reduced radiation to patient and surgical team	Requires placement of localizer on adjacent level spinous process Potential for reliance on technology to perform procedure Capital cost of equipment
Ultrasound volume navigation	Reduced radiation to patient and surgical team Can utilize preoperative MRI Does not require ultrasound-trained physician	Potential for reliance on technology to perform procedure Lack of clinical studies Capital cost of equipment
Mixed reality	Reduced operative time and radiation exposure to the surgical team[24]	Requires placement of reference frame Increased radiation to patient Capital cost of equipment Increased surgeon eye fatigue Potential for reliance on technology to perform procedure
Robotics	More precise single-shot puncture, reduced fluoroscopy, total operative time[33]	Requires placement of reference frame Increased radiation to patient Capital cost of equipment Potential for reliance on technology to perform procedure

MRI: Magnetic resonance imaging.

In March 2021, Jin *et al.*[33] published a match-paired study comparing robotic-assisted to fluoroscopy-assisted transforaminal endoscopic lumbar discectomy. The 39 patients in the robotic group and 78 patients in the fluoroscopy group were chosen on the basis of sex, age, surgical level, and herniated disc location. The authors utilized the TiRobot Orthopaedic Robotic System (TINAVI Medical Technologies Co. Ltd., Beijing, China) with an arm-mounted flat panel imaging system (Cios Spin, Siemens Healthineers AG, Erlangen, Germany) for intraoperative CT imaging. The robot was used to position a needle guide in the planned optimal trajectory, and the procedure was then carried out in the standard fashion. The authors found that a single-shot puncture in the robotic group was significantly more precise compared with 4.12 ± 1.71 trials in the fluoroscopy group ($P < 0.001$). There was an overall reduction of fluoroscopy use, time from first puncture to final working channel placement (13.34 ± 3.03 min *vs.* 15.03 ± 4.5 min, $P = 0.038$), and total operative time (57.46 ± 7.49 min *vs.* 69.40 ± 12.59 min, $P < 0.001$) using the robot compared to conventional fluoroscopy. However, there were no significant differences in patient-reported outcomes, length of stay, or complication rate between the two groups ($P > 0.05$).

While the aforementioned technologies present numerous advantages for performing ESS, a number of concerns exist regarding their widespread adoption [Table 2]. Some of the potential disadvantages exist with the incorporation of all advanced technology to ESS, while others are unique to specific techniques. For example, surgeons can potentially become reliant on each technology to perform ESS and therefore may be unable to complete the case if the technology becomes unavailable. This is obviously concerning as surgeons are now routinely performing ESS without them. CT navigation, robotics, and mixed reality reduce surgeon radiation exposure but require a preoperative CT scan, thereby increasing radiation exposure to the patient. These techniques also require the placement of a reference marker which increases the surgical morbidity of ESS. Ultrasound guidance does not increase radiation exposure to the patient, but current techniques

require a specialized physician to operate the ultrasound. Finally, all these techniques increase the cost of the procedure to varying degrees. While reduced operative time may offset some of these costs, many are not insignificant. The actual cost of each technology varies significantly based on region and healthcare setting. Nevertheless, capital costs for robotic navigation platforms can exceed $1 million USD and also require the purchase of disposables for each case[34]. More studies are needed to further analyze the advantages and disadvantages of advanced technology for ESS. Hopefully, as these technologies become more available, the costs will decrease and reduce the financial barriers to their adoption.

CONCLUSION

ESS is an ultra-minimally invasive technique with many advantages, but it has yet to achieve widespread adoption. The incorporation of navigation, mixed reality, and robotics could address some surgeons' hesitations about performing ESS by flattening the learning curve, increasing surgical efficiency, and limiting the use of fluoroscopy. However, the substantial capital costs of these auxiliary technologies in addition to that of the endoscopic equipment itself may prove prohibitive in certain settings (e.g., ambulatory surgery centers). Changes in reimbursement and/or pricing would reduce these financial constraints and likely help drive more pervasive use.

The evidence regarding the use of navigation, mixed reality, and robotics in ESS is currently limited and primarily focused on lumbar discectomies. Additional benefit may be realized should such technologies be applied to more advanced endoscopic applications such as endoscopic-assisted interbody fusions, where they can also facilitate disc space preparation and the placement of pedicle screws and interbody devices. Additional prospective, randomized studies are needed to fully delineate the impact that these technologies could have on the field of ESS.

DECLARATIONS

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