Augmented reality–mediated stereotactic navigation for execution of en bloc lumbar spondylectomy osteotomies

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En bloc spinal tumor resections are technically demanding procedures with high morbidity because of the conventionally large exposure area and aggressive resection goals. Stereotactic surgical navigation presents an opportunity to perform the smallest possible resection plan while still achieving an en bloc resection. Augmented reality (AR)–mediated spine surgery (ARMSS) via a mounted display with an integrated tracking camera is a novel FDA-approved technology for intraoperative “heads up” neuronavigation, with the proposed advantages of increased precision, workflow efficiency, and cost-effectiveness. As surgical experience and capability with this technology grow, the potential for more technically demanding surgical applications arises. Here, the authors describe the use of ARMSS for guidance in a unique osteotomy execution to achieve an en bloc wide marginal resection of an L1 chordoma through a posterior-only approach while avoiding a tumor capsule breach. A technique is described to simultaneously visualize the navigational guidance provided by the contralateral surgeon’s tracked pointer and the progress of the BoneScalpel aligned in parallel with the tracked instrument, providing maximum precision and safety. The procedure was completed by reconstruction performed with a quad-rod and cabled fibular strut allograft construct, and the patient did well postoperatively. Finally, the authors review the technical aspects of the approach, as well as the applications and limitations of this new technology.

https://thejns.org/doi/abs/10.3171/2020.9.SPINE201219

KEYWORDS augmented reality; mixed reality; computer-assisted spine surgery; spine navigation; spine tumor; chordoma; en bloc; deformity; surgical technique

Augmented reality (AR)–mediated spine surgery (ARMSS) via a tracking camera–integrated head-mounted display (HMD) is a stereotactic computer navigation modality that has demonstrated high accuracy and precision with spinal instrumentation.1,2 Conventional computer-assisted spine navigation systems have two major disadvantages: line of sight (LOS) interruption and attention shift.3,5 LOS interruption impairs workflow efficiency and occurs when computer navigation is interrupted by obstruction of the remote tracking camera (RTC) field of view (FOV).8–10 This inhibits visualization of tracking markers by the RTC—resulting in the loss of navigation until the obstruction is cleared. It should be noted that we are referring specifically here to interruption of the LOS of the navigation tracking camera, not the human operator’s view. Attention shift is a source of technical error in surgical navigation and occurs when operators must shift attention away from the patient to the remote screen for guidance.5 The present AR-HMD system minimizes LOS interruption by employing an integrated tracking camera (ITC) (Fig. 1A) that excludes external LOS obstruction sources. In addition, it eliminates attention shift by projecting 3D- and 2D-reconstructed models (Fig. 1C) along with tracking information directly onto the operator’s retina, using a transparent near-eye display (Fig. 1B) head-set. This enables visualization of both the surgical field and navigation data in the same FOV (Fig. 1C). Clinical grade cadaveric benchmark data led to the recent FDA approval of this technology, and we recently described the successful execution of the first in-human clinical use of this technology for lumbar pedicle instrumentation.11 A positive workflow and precision performance experience with this novel navigation system revealed the potential for more technically demanding surgical applications. Here, we describe the first use, to our knowledge, of ARMSS for guidance in unique osteotomy execution to achieve an en bloc wide marginal resection of an L1 chordoma through a posterior-only approach.

ABBREVIATIONS AR = augmented reality; ARMSS = AR-mediated spine surgery; FOV = field of view; HMD = head-mounted display; ITC = integrated tracking camera; LOS = line of sight; RTC = remote tracking camera.


INCLUDE WHEN CITING Published online March 5, 2021; DOI: 10.3171/2020.9.SPINE201219.
**Case Description**

**Clinical Presentation**

This 69-year-old male patient had a history of low-grade lymphoma initially diagnosed in 1990. He underwent a series of chemotherapy and radiation therapy cycles for recurrence, with complete remission since 2010. Approximately 6 months prior to surgery, he developed new left-sided low-back pain and paresthesia. Pain was constant and worsened in the evening. Further workup revealed an intraosseous lesion at the posterior half of the L1 vertebral body with extension into the spinal canal (Fig. 2). A transpedicular biopsy was performed and demonstrated chordoma. The patient elected to undergo a posterior-only en bloc L1 corpectomy followed by adjuvant proton beam radiation therapy.

**General Operative Technique**

The patient was positioned prone on a Jackson table (Mizuho OSI) and prepped and draped in standard sterile fashion. A lateral plain radiograph and a 22-gauge spinal needle were used to plan and confirm the level of the incision. A 15-cm incision was made overlying the T11–L3 lumbar vertebral levels, permitting visualization of the rostral aspect of the L3 spinous process. It should be noted that the xvision system (Augmedics) was not used to plan the incision, given that navigation and registration in this open setting occur following subperiosteal exposure. Subperiosteal dissection was used to expose posterior T11–L3 bony anatomy from a mediolateral direction until visualization of the superior articulating facet, pars interarticularis, and transverse process confluence was achieved at each level. A registration clamp and marker were then placed over the spinous process of L3 (Fig. 3). Intraoperative 3D imaging and registration were acquired (O-arm, Medtronic). The registration marker on the registration clamp was exchanged for a tracking marker positioned contralateral to the working side (i.e., the tracking marker was positioned to be prominent on the left side when working on the right side and flipped to be prominent on the right side when working on the left side) (Fig. 3). Surgeons were then fitted with an AR-HMD display (xvision, Augmedics) that provided direct retinal projection of the relevant 2D and 3D navigation data (Fig. 4). Bilateral pedicle screws from the T11 to L3 levels, excluding L1 and L2, were subsequently placed with AR computer navigation assistance by use of, in sequence, a tracked pedicle probe (Medtronic), a pedicle tap, and a screwdriver (DePuy). Screws (7.0-mm diameter; Expedium, DePuy Synthes) were inserted. A lateral extracavitary dissection was then performed to expose the full body of L1, the rostral body of L2, and the caudal body of T12. The extraspinal T12, L1, and L2 roots were then identified, dissected, and isolated. We next proceeded to perform bone cuts using a BoneScalpel (Misonix). For each bone cut (i.e., osteotomies and laminectomies) and discectomy, the AR-HMD was used to ensure the cuts did not breach the tumor capsule. Specifically, we first performed laminectomies of T12, L1, and L2 to get access to the epidural tumor. Facetectomies and pedicle cuts were then performed to just above where the tumor began (Fig. 4). T12 and L1 nerve roots were then sacrificed proximal to the dorsal root ganglion. The epidural tumor extension was then dissected off the thecal sac. Total discectomies were then performed at T12–L1 and L1–2 discs. Temporary rods...
were placed for intraoperative stabilization and distraction to facilitate ventral dissection of the L1 vertebral body. Following ventral mobilization of the segmental arteries, aorta, and inferior vena cava, the L1 vertebral body was rotated and removed en bloc (Fig. 5). The defect was replaced with a titanium cage filled with structural allograft bone. An additional intraoperative CT scan confirmed appropriate hardware positioning. Vertebroplasties with 1.5 mL of cement (DePuy) were subsequently performed at each cannulated pedicle screw. Temporary rods were then exchanged for a quad-rod construct with a cabled fibular strut allograft (Fig. 5). The case was then completed in standard fashion with irrigation, bony surface decortication, laying of morselized bone allograft, hemostasis, vancomycin powder, and plastics closure.

Execution of AR-Guided Osteotomies and Discectomies

As referenced above, bone cuts (i.e., osteotomies and laminectomies) and discectomies were performed with AR-HMD guidance to avoid a tumor capsule breach. The present AR-HMD platform enables both surgeons to simultaneously wear an HMD, intuitively displaying the 2D

FIG. 3. **Left:** An initial registration clamp is used for calibration. **Center:** The registration clamp is then switched for a working clamp, based on the spinous process. **Right:** Spinous process reference clamp (A) and registration marker placement over the L3 spinous process (B). Exchange of registration marker for reflective navigation marker (C) that can be flipped from left to right for minimizing LOS interruption. Figure is available in color online only.

FIG. 4. AR-HMD provides simultaneous in-field navigation to both surgeons. The left-sided surgeon is using a tracked tool (A) to plan an osteotomy (B) that avoids the tumor capsule (red asterisk) extending into the left-sided pedicle and canal (C, red asterisk). The right-sided surgeon aligns the working tool in parallel to the tracked tool to execute the cut. Figure is available in color online only.
and 3D navigational guidance from their respective point of view (i.e., the left-sided operator sees the left-sided anatomical overlay and vice versa). To perform the bone cuts, one surgeon held the tracked pointer in the ideal (tumor avoiding) osteotomy trajectory while the other surgeon aligned the BoneScalpel in the same angle and performed the osteotomy (Fig. 4). The AR-HMD allowed the surgeon performing the osteotomy to simultaneously visualize the navigational guidance provided by the contralateral surgeon’s tracked pointer and the progress of the BoneScalpel aligned in parallel with the tracked instrument. This was then repeated when performing the contralateral osteotomies. Tumor capsule–avoiding discectomies were executed in the same sequential fashion. This serial process permitted execution of disc and bone cuts that avoided the tumor capsule but minimized exposure and collateral tissue damage, ultimately enabling a less invasive successful en bloc resection of this lesion.

Peri- and Postoperative Course

The operative procedure took approximately 6 hours, which was less time than we expected. The patient tolerated the procedure well and woke up at his neurological baseline with the exception of mild bilateral inguinal and upper thigh anesthesia. Pedicle screws inserted with AR-HMD guidance demonstrated the desired navigational trajectories without any pedicle breach. Intraoperatively, there were minute chyle and pleural leaks detected following completion of the resection. Both were repaired intraoperatively. No chest tube was required. The patient was given nothing by mouth postoperatively for 72 hours and progressively transitioned to a regular diet. No chyle was detected in the drain output. An ileus developed on postoperative day (POD) 3 and resolved by POD 7. The patient was discharged to inpatient rehabilitation on POD 9 and subsequently discharged to home from inpatient rehabilitation on POD 16. Pathology confirmed no neoplastic involvement of the resection margins. The patient recently had his 6-week follow-up, at which he remained neurologically intact. His incision was well healed, and he had discontinued the use of narcotic pain medications. He began proton beam radiation shortly afterward. At this point it was too early to assess arthrodesis.

Discussion

ARMS through an ITC HMD is a novel stereotactic navigation platform for spine surgery. The technology has been validated in both cadaveric and live applications and recently received FDA approval. The proposed technological benefit of this platform is the replacement of the traditional navigation system RTC/remote display for an ITC/direct retinal display. A headset ITC is inherently positioned directly over the working field of interest, thereby eliminating external LOS obstruction sources and permitting uninterrupted instrument tracking in the most obtuse of tracked tool angles. The direct retinal lens translucently displays navigational data on the surgical field. The 2D data provide axial and sagittal projections of the tracked tool trajectory (Fig. 4). The 3D data for 3D segmentation of the bony spine anatomy are overlaid over the real spine in an anatomically matching orientation, location, and size so that the computer spine projection matches the position and size of the real spine (Fig. 1C). The mixed-reality 2D and 3D navigational data permit simultaneous visualization of the navigated tool, navigation data, and surgical field—eliminating the distraction and inefficiency of cyclical attention shift and a remote 2D display. Our group has experienced high workflow efficiency, precision, and accuracy results with the insertion of pedicle instrumentation employing this AR-HMD system. Consequently, we hypothesized that

FIG. 5. Final spine reconstruction following resection. A: 3D reconstruction demonstrating cage placement. B and C: Sagittal and axial reconstruction demonstrating correct AR-HMD–guided pedicle screw placement. D: En bloc vertebrectomy sample. Intracanalicular tumor component seen on MRI is visualized (white asterisk). E: Posterior view of final quad-rod and canned fibular structural allograft construct. Figure is available in color online only.
we could employ this platform on highly technical surgical applications. Specifically, we aimed to use the AR-HMD to provide AR guidance in unique osteotomy execution to achieve an en bloc wide marginal resection of an L1 chordoma through a posterior-only approach.

Chordomas are rare malignant primary neuraxis tumors with a 5-year life expectancy of 50%. Localized disease warrants consideration for potential curative en bloc resection in combination with neoadjuvant and adjuvant radiation therapy. En bloc spinal tumor resections are technically demanding procedures and have complication rates ranging from 36% to 83%. Factors contributing to the high morbidity of these procedures are the conventionally large exposure and resection goals required to achieve en bloc resections. Stereotactic surgical navigation presents an opportunity to perform the smallest possible resection plan while still achieving an en bloc resection. In essence, computer navigation can be used to plan and execute bone and soft tissue cuts that are just at the en bloc resection margin on all planes. We performed bone cuts with a BoneScalpel, which requires one surgeon to hold a tracked pointer at an ideal angle of attack while another surgeon executes the bone or soft tissue cut in parallel to the tracked pointer. Although this concept is sound in theory, we have had difficulty with execution when using conventional RTC/remote display navigation systems such as the StealthStation (Medtronic). The required simultaneous attention to the angle of the tracked pointer, the working tool, and a remote display is impractical. We often had the experience that either surgeon was predisposed to changing the tracked pointer or working tool trajectory when distracted by the remote display. Frequent LOS obstruction of the RTC is also problematic and does not permit efficient execution of these maneuvers. Specifically, execution of these bone and soft tissue cuts occurs at a relatively deep position in the surgical field in relation to the skin, and the RTC does not allow adequate visualization of the tracked pointer in relation to the fixed reference frame. In addition, the presence of the tracked pointer and working tool in combination with the surgeons’ hands adds multiple sources of LOS obstruction for the RTC.

With regard to efficiency, we believe that the xvision system is an asset, although this belief is difficult to objectively demonstrate at this point with so few cases completed. As with any complex case, the time to complete a spondylectomy varies greatly and depends on the pathology and anatomy, but a review of the literature reveals that en bloc spondylectomy procedure durations can average 11–14 hours, while this case took 6 hours. Therefore, it may be that in our case the system did increase efficiency. As our experience grows with this device, we will be able to further study this feature.

From the standpoint of precision, surgeon LOS is not a variable that is known to affect navigational precision. Navigation technical precision, which differs from navigation clinical accuracy, is subject to many variables, including registration fidelity, mechanical stability of the registration frame, number of tracked fiducials, rigidity of the tracked instrument, stability of the articulations and modular attachments to tracked instruments, and importantly, the distance of the tracking camera from the tracked instrument and tracked registration frame. Navigation technical precision is inversely related to the distance of the tracking camera to the tracked objects. One substantial difference of the present platform from conventional remote camera–based tracking systems is the close proximity of the head-mounted tracking camera to the tracked instrument and registration frame, resulting in high benchmark precision data. The technical precision of the 3D-plane data of the present platform compares favorably with that in an analogous analysis using conventional navigation solutions. From a cost-effectiveness standpoint, at the time of this writing there had been no formal study yet of the xvision system, but it should be noted that initial capital acquisition cost and per case disposables are priced lower than currently available navigation workstations and robots. The current manufacturer’s suggested retail price for two headsets, workstation, and instrument sets is US $159,000. As a comparison, the Medtronic StealthStation S7 retails for around US $245,000, and a spine robot is estimated to be US $1.5 million for the Globus ExcelsiusGPS and US $850,000 for the Medtronic Mazor X.

Despite the successful execution of the operation we describe here using this novel technology, the present AR-HMD is not yet ideally tailored for this procedure. Limitations include the absence of a true tracked pointer. In this case, we had to use a tracked gearshift as our tracked pointer. Ideally, the system should fully integrate tracking of the working tool (e.g., drill, osteotome, BoneScalpel, etc.) obviating the need for a tracked pointer altogether. Additional potential user experience drawbacks when employing AR-mediated navigation include mechanical discomfort, visual discomfort, and visual obstruction. The AR-HMD platform is lightweight (800 g) and is meant to be worn only during instrumentation insertion. Although we did not experience mechanical discomfort or fatigue while wearing the device for an extended period, this remains a possibility and will be a surgeon-dependent experience. Visual discomfort may occur as users must adapt to having visual data directly projected to the retina and mixed with real visual objects. The AR-HMDs are matched to users’ interpupillary distance (IPD). It is critical to individually calibrate and match the operator’s IPD to avoid this experience. Visual obstruction may also occur. Although the projected visual data are translucent, they can still obstruct visualization of key anatomical structures. A learning curve is involved in avoiding this issue, which can be done by adjusting the position of the retinal display lenses in such a way that both the surgical field and navigational data are unobstructed. Additionally, visual difficulties can be mitigated by toggling the projected images on and off with a foot pedal or adjusting one’s gaze to view the area of interest outside the retinal projection of the navigation data. Last, it should be emphasized that this platform is approved only for navigation assistance in the insertion of thoraco lumber pedicle instrumentation and does not have a specific FDA clearance for additional navigation applications such as the one described in this article.

Conclusions

We found that the present AR-HMD platform enabled
improved integration of surgical navigation for en bloc spinal tumor resections. Primarily, due to the close proximity of the HMD ITC directly over the surgical field, we experienced minimal LOS interruptions. This permitted tool navigation at the greatest depths of the surgical field even when multiple tools and working hands were in the field. Second, we found the ability by both operators to visualize the tracked pointer, working tool, and navigational data simultaneously over the surgical field to be critical in performing the osteotomies while staying parallel to the tracked tool.

References

Disclosures
Dr. Molina reports being a consultant for Augmedics and DePuy Synthes. Dr. Witham reports direct stock ownership in Augmedics and Additive Orthopedics, membership on the medical advisory board of Augmedics, and receiving support of a non–study-related clinical research effort that he oversees in a grant from Eli Lilly and Co. and from the Gordon and Marilyn Macklin Foundation. Dr. Sciubba reports being a consultant for Medtronic, K2M, Misonix, DePuy Synthes, Stryker, NuVasive, and Baxter and having direct stock ownership in Augmedics.

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