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Intraoperative Imaging and Navigation for Minimally Invasive Spinal Tumor Surgery: Case Series and Literature Review

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ABSTRACT

INTRODUCTION: The prognosis for spinal tumors depends on the extent of resection and time to adjuvant therapy. Minimally invasive surgery (MIS) helps to accomplish these goals with fewer complications, and intraoperative navigation may improve the degree of resection and guide accurate placement of instrumentation. The authors aimed to analyze the utility of 3-D navigation for minimally-invasive spinal tumor surgery through a case series and literature review.

METHODS: Current literature was reviewed to identify studies utilizing MIS with intraoperative navigation for the treatment of spinal tumors. The medical records and imaging studies for 4 cases from the authors' experience were analyzed in conjunction.

RESULT: Four patients were included in our case series with an average age of 53.8yrs. Pathology included 3 metastatic tumors and 1 chordoma. Gross total resection was achieved in 3 of the 4 cases with no evidence of recurrence noted at each respective follow-up. A literature search revealed 3 studies that incorporated navigation assisted MIS for treating spinal tumors.

CONCLUSION: Image-guided navigation can serve as a useful adjunct to MIS by improving the accuracy of instrumentation and enhancing the ability to obtain gross-total resection. Further clinical trials are warranted to demonstrate its benefits in a systematic manner.

KEY WORDS: Isocentric C-arm, minimally-invasive, navigation, O-arm, stealth, spine tumor

INTRODUCTION

Computer-guided intraoperative navigation has evolved to become an integral part of spinal surgery (5,38,43). By rendering multiplanar three-dimensional (3-D) reconstruction in real-time, modern navigation techniques provide instant visualization of complex spinal anatomy and allow tracking of various surgical instruments within the operative field. Multiple studies have shown that navigation enhances the safety and accuracy of various spinal procedures in both the laboratory and clinical setting (6,9,14,25,27,56). It is especially useful for complex revision cases and minimally-invasive surgeries in which common anatomical landmarks are unrecognizable or no longer visible.

Spinal tumors often present with distorted anatomy secondary to direct osseous involvement and/or epidural compression, resulting in intractable neurologic symptoms and increased morbidity for the patient (2,35,36). It has been shown that greater extent of resection improves prognosis and neurologic function for primary and metastatic lesions, respectively (1,24,55). As such, the goal of surgical treatment involves maximal decompression without inflicting further neurovascular injury and possible reconstruction and fusion in order to minimize segmental instability and spondylotic pain (1).

The advent of minimally invasive surgery (MIS) for the spine has brought forth improved techniques that limit the extent of tissue dissection while achieving the same surgical goal (35, 44, 48). Preserving the integrity of the posterior ligamentous complex also avoids or reduces the incidence of iatrogenic instability (48). Additionally, MIS leads to reduction in intraoperative blood loss and postoperative pain, resulting in quicker recovery and shorter hospital stay (25). Lastly, MIS through smaller incisions may mitigate wound complications secondary to large tissue dissections, which can shorten the time to radiation treatment and lessen the chance for dehiscence during therapy (58).

Despite the growing evidence for MIS and intraoperative navigation, there is a paucity of articles in the literature analyzing the combined benefits of both modalities for treating spinal tumors. Many of the early experience with 3-D intraoperative navigation have focused on techniques (i.e. accuracy of pedicle screw placement) without delineating the advantages for supplementing the treatment of neoplastic pathology (13, 14, 40). As such, most of the data is embedded within these larger trials. The authors herein attempt to highlight the utility of intraoperative navigation in MIS spinal tumor surgery by presenting a case series and reviewing the most recent literature.

MATERIAL AND METHODS

Literature Review

An extensive literature review was performed in the MEDLINE PubMed and Google Scholar database for the following MeSH term: ("spinal cord neoplasms"(MeSH Terms) OR ("spinal"(All Fields) AND "cord"(All Fields) AND "neoplasms"(All Fields)) OR "spinal cord neoplasms"(All Fields) OR ("spinal"(All Fields) AND "tumor"(All Fields)) OR "spinal tumor"(All Fields)) AND navigation(All Fields) and key words: "minimally-invasive," "spine," "tumor," "intraoperative," "navigation." All studies published in the English language utilizing intraoperative navigation for MIS spine tumor surgery were included. All epidural, intradural/extramedullary, and intramedullary spinal tumors were considered.

Case Series

A retrospective review of 4 cases from the Keck Medical Center of the University of Southern California (USC) in which intraoperative navigation was used for resection of a spinal tumor was performed. All operations were performed by the senior author (PCH). Patients' chart and imaging findings were reviewed and the following data were extracted: patient age, demographics, pathology, operative report, estimated blood loss, duration of operation, duration of hospital stay, complications including reoperation rate, discharge location, and subsequent follow-up.

RESULTS

Literature search

The initial literature search in the PubMed database resulted 62 abstracts related to navigation in spinal tumor surgery. Each abstract was reviewed according to our inclusion criteria and 60 articles were excluded. The most common reason for exclusion was either incorporation of navigation without an MIS approach, or vice versa. Further search in the Google Scholar database revealed one additional study that assessed minimally invasive pedicle screw placement using navigation for various pathologies including tumors (Table 1).

Case series

Four patients were included in our case series. There were 3 males and 1 female with an average age of 53.8yrs (25-72yrs). Pathology included 3 metastatic tumors (carcinoid, cholangiocarcinoma, non-small cell lung cancer) and 1 chordoma. The mean estimated blood loss (EBL) was 312.5mL (range 50mL-800mL) and the average operative time was 6h3m (range 4h15m-6h19m). Three of the four patients underwent gross total resection and one patient (case 4) had intralesional resection with positive peripheral margins that was asymptomatic and was treated with adjuvant therapy. All patients experienced significant improvement of their pain symptoms following the procedure. There were no intraoperative complications. There were no recurrence of disease at each respective follow-up, and all instrumentation remained intact. No subsequent interventions were required. Individual cases are described below and summarized in Table 2.

Case 1

Patient is a 54-year-old gentleman with a history of carcinoid tumor. He presented with progressive back pain and evaluation with magnetic resonance imaging (MRI) demonstrated a large mass involving the neural foramina and lateral recess at the right T11-12 level leading to cord compression (Figure 1A). Given the cord compression and the patient's significant pain, surgical treatment was offered.

Operation

Patient underwent a MIS T11-T12 hemilaminectomy with complete facetectomy and partial costotransversectomy for exposure and excision of the tumor. A MIS T11-T12 posterolateral arthrodesis was performed, supplemented with MIS percutaneous instrumentation at T11-T12. Intraoperative computed tomography (CT) was utilized with the O-arm Surgical Imaging System (Medtronic Sofamor Danek, Memphis, TN) for three-dimensional navigation throughout the case. A 22mm MIS tubular retractor was used for the surgical corridor. There was a large vascularized tumor along the lateral recess and neural foramina at the right T11-12 level with cord and T11 nerve root compression. After the tumor was successfully resected, intraoperative navigation was used to confirm appropriate resection margins. Subsequently, a navigational drill guide was used

Table 1: Summary of literature reporting the use of intraoperative navigation to guide MIS spine tumor surgery.

Author (Year)	Mode of Navigation	Pathology	Study Type	Procedure	Outcome
Rajasekaran, 2008	Siremobil Iso-C 3D (Seimens), Vector Vision navigation (BrainLab)	4 osteoid osteoma: - Levels: C5, T11, L2, L3	Case Series	MIS approach, reference array attached to SP of vertebra caudal to index level	- Complete resection in all cases - Minimal bone removal without compromise of stability, no need for fusion - Mean OR time: 74min (range 60-90min) - Mean HS: 2.5d - no recurrence or complication up to 2 yr f/u
Mannion, 2009	O-Arm (Medtronic), Stealth Station navigation (Medtronic)	13 ID/EM tumors: - 9 schwannomas - 2 ependymomas - 2 meningiomas Level: - 1 cervical - 6 thoracic - 6 lumbar	Case Series	MIS approach, O-arm guided Percutaneous pedicle screw fixation using Sextant system (Medtronic)	- Mean HS: 3.1days - Mean OR time: 2.5 hr (1.4-4.2hr); - No major complications - 2 cases of wrong exposure
Houten, 2012	O-arm vs. fluoroscopy (historic)	52 pts (O-arm) - 47 stenosis w/ spondylolisthesis - **3 tumors** - 2 disc herniation Total Screws: 205 - 4 (L1) - 10 (L2) - 30 (L3) - 68 (L4) - 69 (L5) - 24 (S1)	Case series with historic control	O-arm: - 51 (98%) MIS TLIF (98%) - 1 (2%) MIS XLIF/DLIF Fluoroscopy: - 39 (93%) TLIF - 3 (7%) XLIF/ DLIF	- No separate analysis for the 3 tumor patients - Perforated screws: O-arm (3%) vs Fluoroscopy (12.8%) ($p<.01$) - OR Time: O-arm: 200 (153-241) min Fluoroscopy: 221 (178-302) min ($p<.03$)

SP: spinous process, **OR:** operating room, **HS:** hospital stay, f/u: follow-up, **TLIF:** transforaminal lumber interbody fusion, **XLIF:** extreme lateral interbody fusion, **DLIF:** direct lateral interbody fusion.

Table 2: Case Descriptions.

Case (age/sex)	Pathology	Localization Technique	Procedure	Intra-op Navigation Use	Note
Case 1 (54M)	Metastatic carcinoid tumor T11-T12	O-arm	MIS T11-T12 hemilaminectomy with complete facetectomy; partial costotransversectomy; posterolateral arthrodesis with DBX and allograft; percutaneous instrumentation at T11-T12	Localization of incision and throughout exposure Pedicle screw placement	- EBL: 50cc - OT: 5h14m - D/C: home - No reoperation - No breach
Case 2 (25F)	Chordoma L4-L5	O-arm	Left MIS L4-L5 hemilaminectomy, complete facetectomy, partial L5 corpectomy, L4-5 transforaminal discectomy	Localization of incision and throughout exposure	- EBL: 800cc - OT: 4h15m - D/C: home - Given the unexpected pathology during the case, fusion was delayed and the pt subsequently returned and underwent a L4-L5 anterior interbody fusion and instrumentation
Case 3 (64M)	Metastatic cholangiocar-cinoma L3	O-arm	MIS approach Left L2-3 laminotomy and medial facetectomy L3-4 laminectomy with complete left facetectomies L3 partial corpectomy L2-L4 posterolateral arthrodesis and instrumentation with MIS percutaneous pedicle screws	Localization of incision and throughout exposure Pedicle screw placement	- EBL: 200cc - OT: 5h24m - No pedicle breach - POD7: Given residual stenosis from bony fragments and epidural tumor, pt underwent anterior L2-L4 discectomy, L2-L4 anterior interbody arthrodesis and fusion with TSLP plate and VB screws
Case 4 (72M)	Metastatic non-small cell lung cancer T9	O-arm	Bilateral MIS T8-T9, T9-T10 laminectomy with bilateral foraminotomies T9 percutaneous kyphoplasty T8-T10 posterior arthrodesis with local autograft MIS Pedicle screws and rod construct at T7, T8, T10, T11	Localization of incision and throughout exposure Pedicle screw placement	- EBL: 200cc - OT: 6h19m - No reoperations - Pain significantly improved at 2 week f/u with intact instrumentation

MIS: Minimally-Invasive surgery, **ED:** Extra-dural, **D/C:** Discharge, **OT:** operation time, **f/u:** follow-up to drill pedicle screw tracts into the T11-T12 pedicles under navigational guidance. K-wires were then advanced through to the vertebral bodies. Navigation was used to tap each of the pedicle tracts and 6.5 x 45 mm pedicle screws were placed into T11 and T12 under navigation and K-wire guidance. Percutaneous rods were placed and segmental compression was applied to reduce the kyphosis and better approximate the joint surface for segmental arthrodesis. The EBL for the case was 50cc and the total operation time was 5h14m.

Postoperative CT scan showed no breach of the pedicles and correct placement of the instrumentation (Figure 1B). Postoperative MRI revealed gross total resection (Figure 1C). The patient did well post-op and was discharged to home after 4 days. At the 2-year follow-up, patient had no back pain and CT imaging revealed intact instrumentation and fusion at the left facet joint.

Case 2

Patient is a 23-year-old female with a history of progressive back pain. On workup, she was found to have an extradural dumbbell shaped contrast-enhancing lesion abutting the L4 nerve root. The tumor extended from the ventral epidural space, all the way out to the extraforaminal region. Preoperative imaging was interpreted to be consistent with a nerve sheath tumor (Figure 2A). Given the size of the lesion and the symptomatic nerve root compression, surgical treatment was offered.

Operation

Patient was positioned prone on a Jackson spinal table and

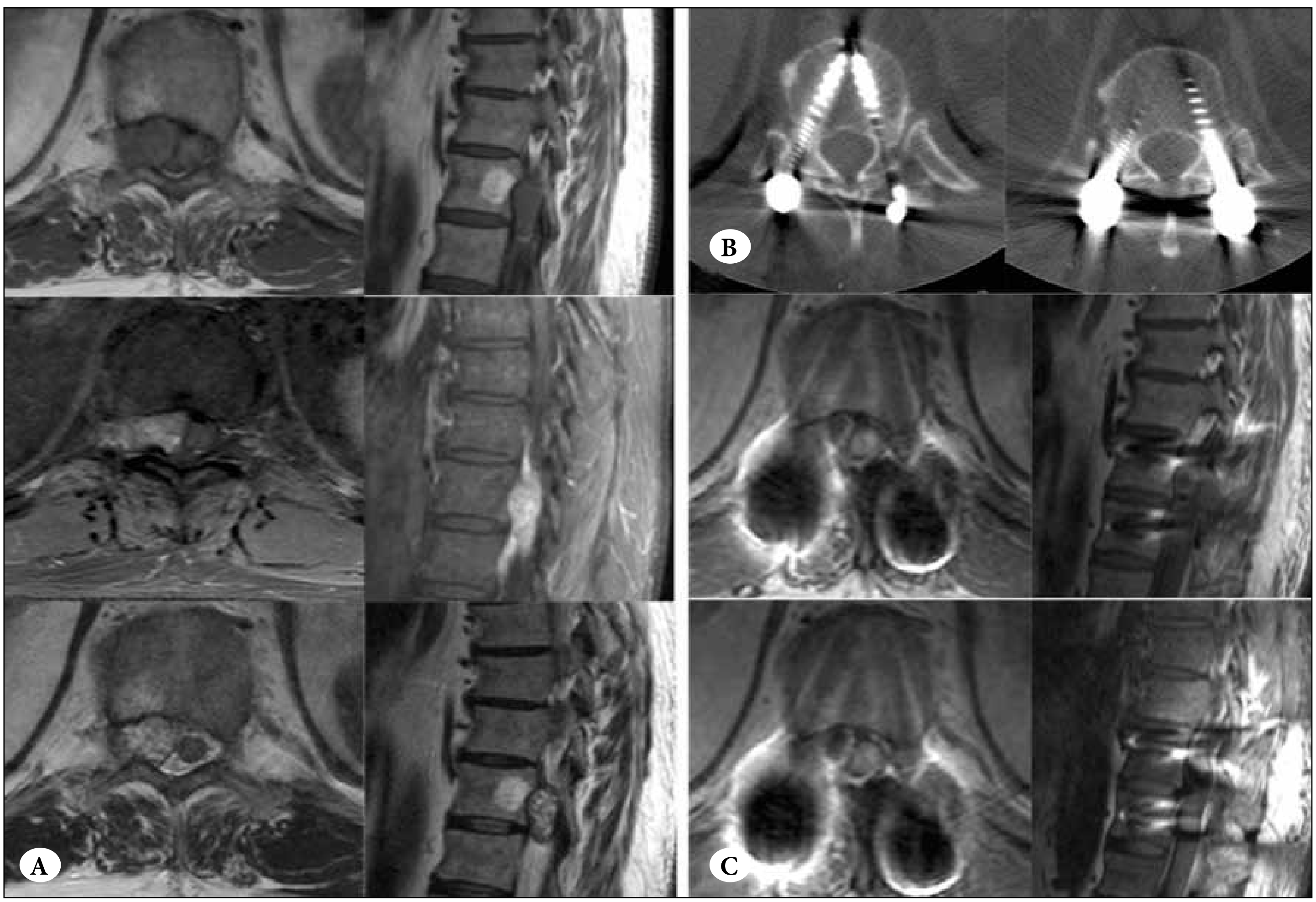

Figure 1: *Case 1 (Metastatic carcinoid tumor):* ***A)*** *Pre-operative MR imaging of the thoracic spine showing a lobulated intradural, extramedullary mass with isointense T1 signal (top panel), hyperintense T2 signal (bottom) and avid contrast enhancement (middle). The mass is causing a leftward displacement of the spinal cord and exiting the right T11-T12 neural foramen. There is an incidental benign hemangioma noted in the T11 vertebral body.* ***B)*** *Post-operative axial CT scans demonstrating good pedicle screw placement at the instrumented levels.* ***C)*** *Post-operative T1WI MR imaging demonstrating no definite residual enhancing tissues.*

preoperative neurophysiological parameters were obtained. A percutaneous pin was placed into the right posterior superior iliac spine (PSIS) for placement of a stereotactic navigational reference frame. The O-arm (Medtronic) was brought in to register the anatomy for the stereotactic navigation. Under navigational guidance, the incision site was marked out 4cm lateral to the midline centered over the left L4-L5 interspace. A 25mm incision was made and dilators were used to dilate the paraspinal muscles over the left L4-L5 facet joint and the lamina facet junction. A quadrant retractor was then placed into the field to maintain our exposure. A Left L4-5 hemilaminectomy was performed with complete facetectomy to expose the tumor. A large bluish capsulated mass was noted extending throughout the extradural neural foraminal and lateral recess with significant nerve root compression. Frozen samples were suggestive of a chordoma. Due to the malignant nature of the pathology, intraoperative navigation was used to delineate surgical tumor margins as best as possible. A radical or en bloc resection could not be performed without sacrificing the nerve root and dura, but the availability of the navigation system assisted in maximizing the extent of intralesional tumor removal. The EBL for the case was 800cc and the total operative time was 4h15m.

The patient recovered well after the operation and postoperative MRI on the first post-op day revealed gross total resection and restoration of CSF flow (Figure 2B). Patient subsequently underwent a stand-alone anterior lumbar interbody fusion to stabilize her L4-5 instability while still minimizing the potential imaging artifacts from the spinal instrumentation. She underwent adjuvant proton beam radiation after her wounds were healed. She remained neurologically intact and had an uncomplicated post-

Figure 2: *Case 2 (Chordoma).* ***A)*** *Pre-operative MR imaging of the lumbar spine showing a T2 hyperintense (bottom), T1 hypointense (top), and mildly enhancing (middle) dumbbell-shaped mass within the ventral epidural space posterior to the L4 vertebral body. The mass is causing scalloping of the posterior L4 vertebral body and extends along the ventral epidural space with extension out the left neural foramen. Moderate to severe compression of the thecal sac is present at this level with crowding of the cauda equina nerve roots.* ***B)*** *Postoperative MR images of the lumbar spine showing no evidence of residual enhancing mass.*

treatment course. At her most recent follow-up at one year, the patient experienced continued improvement of her pain and postoperative MRI showed no evidence of recurrent disease.

Case 3

Patient is a 64 year-old male smoker with a history of metastatic cholangiocarcinoma who presented with significant hip pain and progressive low back pain radiating to his anterior thighs bilaterally. On further workup, he was found to have a L3 pathologic fracture with severe central canal stenosis secondary to retropulsed bone fragments and epidural tumor (Figure 3A). He was admitted to oncology with intractable pain and radiculopathy. Despite extensive medical treatments, he was severely limited by his pain and unable to mobilize. Given the patient's intractable lumbar radiculopathy despite conservative treatment, surgical resection was offered.

Operation

Patient was positioned prone onto a Jackson table and preoperative neurophysiological parameters were

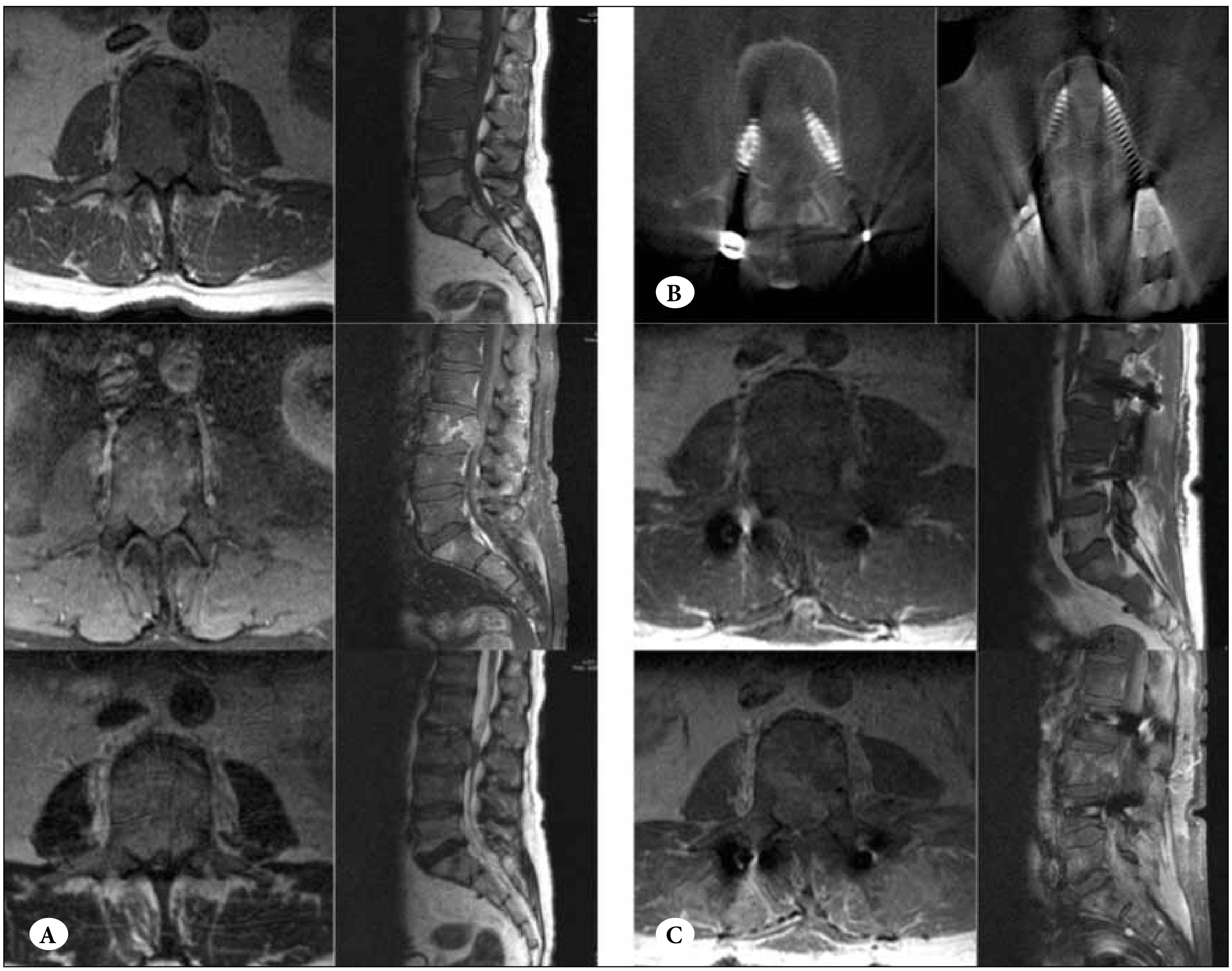

Figure 3: *Case 3 (Metastatic cholangiocarcinoma)* ***A)*** *Pre-operative MR imaging of the lumbar spine showing extensive metastatic lesions scattered throughout the visualized osseous structures. There is a homogenously enhancing lesion (middle panel) causing a pathologic fracture at the L3 vertebral body with approximately 10% loss of height and associated retropulsion. There is severe spinal canal stenosis and complete effacement of CSF at this level with cauda equina compression.* ***B)*** *Intraoperative O-arm (Metronic) axial images demonstrating good placement of pedicle screws at the instrumented levels.* ***C)****Post-operative MR imaging showing no residual enhancing mass. Noted are extensive metastatic lesions through the lumbar spine.*

obtained. A stab incision was made over the left PSIS on which a percutaneous reference frame for navigation was placed. Following navigational guidance with the O-arm (Medtronic), a 30mm incision was marked out 4 cm lateral to midline overlying the L2-L4 area, centered over the L3 pedicle. Incision and dissection was carried down to the L2-L3 and L3-L4 facet joints. Dilators were placed under navigational guidance over the L3-L4 facet joints bilaterally. The paraspinal muscles were dilated off and fixed tubular retractor system was placed to maintain exposure. The microscope was then brought in and a high-speed drill was used to perform a laminectomy and complete facetectomy at the left L3-L4 and L2-3 levels. A tumor sample was removed from the mid L3 vertebral body through an L3 transpedicular approach and sent for frozen pathology. The tumor was subsequently removed in a piecemeal fashion with the assistance of intraoperative navigation to ensure maximal tumor resection. At the completion of tumor resection, instrumentation was placed from L2-4 in a minimally invasive manner. Post-instrumentation O-arm (Medtronic) imaging confirmed good placement of the pedicle screws (Figure 3B). The patient then underwent a second stage anterior L3 corpectomy due to residual canal stenosis from vertebral body retropulsed bone fragments.

The procedure concluded without any complications and the patients' neurologic symptoms greatly improved. At last follow-up at 4 months, there was good placement of instrumentation noted on plain films and the MRI scan showed no recurrence of disease at the operated segment (figure 3c), however, there was evidence of extensive metastases noted elsewhere. Patient continued medical treatment for his extensive metastases until he succumbed to his medical disease 6 months later.

Case 4

Patient is a 72-year-old gentleman with a history of non-small cell lung cancer with known metastatic disease in the thoracic spine. He had previously undergone radiation treatment at an outside hospital. His pain started to worsen and progress to the point where he needed emergent treatment and was admitted to the oncology service. On further work-up, he was found to have a T9 pathological fracture with contrast enhancement consistent with active tumor growth involving the bilateral pedicles (Figure 4A). Mild to moderate central canal stenosis was also noted with involvement of the neural foramen. Given the patient's progressive mechanical back pain associated with the pathological fracture after failure of medical management, he was offered operative treatment.

Operation

The patient was positioned prone onto a Jackson spinal table and the O-arm (Medtronic) was used to register the anatomy. Under navigational guidance, the incision sites over the T7-T11 pedicles were identified bilaterally. An approximately 1.5-cm incisions were made at all these points to allow placement of the percutaneous tower.. A navigational drill guide was then used to drill into the pedicle tracts, and pedicle screw tracts were tapped under navigation. 6.5 x 50 mm screws were placed at T11 bilaterally, 6.5 x 45 mm screws at T10 bilaterally, and 5.5 x 45 mm screws at T7 and T8 bilaterally. Next, bilateral pedicle tracts were drilled into T9 and tapped with a 5.5 mm tap. A kyphoplasty working cannula was placed into the T9 tract under fluoroscopy guidance. Biospy specimens were obtained using a drill biopsy needle once the working channel was placed in the anterior portion of the vertebral body. Fluoroscopy was then used to help place the cement for the kyphoplasty. Approximately 7 mL of cement were injected into the vertebral body at T9.

The O-arm (Medtronic) was brought back in in to register the anatomy and confirm the screw placement. It was noted that the left T8 pedicle screw was slightly medial (approximately grade I). However, it did not violate the thecal sac or the nerve root, and given the small pedicle diameter, it was felt to be unnecessary to remove the screw and attempt a revision of the tract and repositioning of the screw.

Next, the paraspinal muscles over the T9-T10 junction were dilated under navigational guidance. MIS 22 access tubes were placed and the microscope was brought into the field to facilitate the rest of the procedure. Bilateral laminectomy at T9 was performed using a high-speed drill. The T9 nerve roots were identified bilaterally and a partial medial facetectomy was performed to allow wide central and neural foraminal decompression. There was pathological involvement of the T9 compatible with his history and navigational imaging. After extensive exploration near the nerve roots and epidural space, the epidural tumor was resected and no gross residual tumor was identified in the posterolateral gutter of the canal. The facet joints near the T8-9 and T9-10 levels were decorticated and allograft with DBX was placed into the joint space for arthrodesis.

Figure 4: *Case 4 (Metastatic non-small cell lung cancer)*
A) *Pre-operative MR images showing an avidly enhancing lesion (middle panel) involving the anterior and superior aspect of the T9 vertebral body with <25% height loss. There is a small enhancing soft tissue lesion in the T9 paraverebral space abutting the ventral spinal cord.* ***B)*** *(Left panel) Pre-operative axial CT scan demonstrating a pathologic fracture of the T9 vertebral body resulting in height loss with no associated bony retropulsion. (Right panel) Postoperative axial CT scan showing good placement of the T9 kyphoplasty and instrumentation.*

Appropriately sized rods were placed percutaneously to connect the screws from T7-T11 bilaterally. Distraction was applied to allow open reduction of his pathologic fracture. The screw caps were secured in place and the incision was closed in the standard fashion. Neurophysiologic monitoring was stable throughout the entire case. The EBL was 200mL and the total operative time was 6h19m. Patient was extubated in the operating room and transported to the post anesthesia unit in stable condition.

The post-operative course was uneventful. Patient experienced adequate pain control and was able to ambulate with physical therapy. MRI scan obtained on postoperative day 3 showed mild enhancement in the anterior epidural space at T9 concerning for tumor extension vs. post surgical changes. Since the patient's symptoms had greatly improved, no additional operation was deemed necessary. The patient was discharged after 7 days under stable condition. At his 2-week follow-up, he was reportedly doing very well overall with complete improvement of his back pain. He had some difficulty swallowing secondary to herpes simplex involvement of his throat, but denied any new neurologic symptoms. Follow-up CT scan showed stable placement of instrumentation (Figure 4B).

DISCUSSION

Through our case series, we demonstrated the feasibility of using intraoperative CT-based navigation to plan the most optimal incision and dissection for our minimally invasive exposure. More importantly, intraoperative navigation greatly assisted in ensuring gross-total resection of these tumors. Although soft-tissue visualization is often poor on CT, many of these tumors presented with bone-eroded margins that helped to guide the extent of tumor bed removal. Our average operative time and EBL were consistent with those reported in prior studies (25), adding further proof of concept to the principles of MIS.

The advancement of 3D intraoperative navigation systems offers a new paradigm for minimally invasive treatment of spinal tumors. When compared to conventional fluoroscopy, intraoperative cone-beam CT is able to image multiple spinal levels in a single sequence, thereby reducing radiation exposure to the surgeon and staff (3, 51). The portability of the scanners also improves the accuracy of navigation since the patient's anatomy is registered in the surgical position (56). Post instrumentation scans allows immediate determination of the integrity of the instrumentation in all three planes, allowing the surgeon to readjust malpositioned screws in the same setting (52). In addition, intraoperative navigation allows real time assessment of the extent of resection, enhancing the opportunity for gross total removal without the need of a reoperation (34,55).

The majority of our patients presented with intolerable pain secondary to metastatic disease and experienced significant relief following the procedure. Spinal cord involvement is common in systemic cancer (nearly 70%), with the thoracic spine most frequently affected (39). It is well known that surgery combined with radiation offers these patients the best functional and survival outcomes (1,26). Although open surgical decompression has long been viewed as the standard of care, it is been associated with large amounts of blood loss, higher wound infection rates, and longer hospital stay (7,33). MIS has been shown to minimize these adverse effects while providing improvement of pain and neurologic function despite the poor overall prognosis of metastatic cancer patient (21,22,29,37,41).

One of the greatest benefits of MIS for metatstatic tumor surgery is the ability to place posterior instrumentation without excessive tissue dissection(18). This advantage offers potential treatment for patients who would not have been eligible for open surgery under the current recommendations. In a prospective case series of 27 patients with metastatic spine tumors, Kumar et al. analyzed the feasibility of using MIS posterior percutaneous instrumentation for several indications, including decompression and stabilization with and without a corpectomy (18). For all procedures, the authors found a significant alleviation of pain with improvement in neurological and ambulatory status. They also noted an overall reduction in blood loss, operative time, postoperative complications, and hospital stay compared to a match cohort undergoing open surgery. Importantly, the time to initiate radiotherapy was less for the MIS group by a week, which can significantly benefit the response to treatment for these patients. Although this study did not incorporate intraoperative navigation, it is reasonable to deduce from our experience and that of others that 3-D guidance will only enhance the already added benefits of MIS for the treatment of metastatic cancer and this concept warrants further evidence through future systematic clinical trials.

Pedicle screw constructs are an integral component of reconstruction following spinal tumor surgery. However, neoplasms involving the spine and spinal canal often distort normal anatomical landmarks and alter the trajectory by which screws can be safely placed. Complications of inaccurate placement can lead to serious neurological injuries (28,30,50), and previous studies have shown that pedicle screws may be misplaced at a rate of 14%-55% using standard insertion techniques(15,54). Ever since spinal navigation was introduced in the mid-1990's (8,11), it has shown to improve the accuracy of pedicle screw placement and decrease the incidence of neurological injuries in multiple subsequent trials, several of which included spinal tumor patients. (40, 49, 57). Therefore, spinal navigation serves as a critical adjunct for the accurate placement of pedicle screws following spinal tumor resection.

As imaging modalities and navigation techniques advance in their complexity, it is imperative to understand the basic principles of the most commonly used systems. Frequently used modalities include 3-D Isocentric-C arms (Iso-C arm), intraoperative CT (iCT) with a sliding gantry (scanner moves in relative to the patient), the O-arm (Medtronic), and ultrasonography with or without contrast enhancement.

Three-dimensional C-arm fluoroscopy combines an isocentric C-arm flurosocope with an image-guided computer. The isocentric C-arm is able to obtain multiple successive images during a 190 degree-rotation with a specific spinal reference point in the center of the field. Specialized software then reconstructs the images into axial, sagittal, and coronal planes, producing images comparable to pre-operative CT scans. The images are acquired with reference markers on the patient and the C-arm to allow an automated registration. All standard surgical instruments may then be tracked in relation to the reconstructed images (45).

A unique advantage of the isocentric C-arm is that it acquires the images with the patient in the surgical position, decreasing the chance for navigational inaccuracy. Also, the surgeon-dependent registration step is eliminated, and navigation may begin immediately after images are received by the software system. In addition, three-dimensional fluoroscopy is well suited for minimally invasive procedures (percutaneous pedicle screw placement, minimally invasive decompression) since it renders CT-quality mulitplaner views without the need for registration (14,19). It also allows tracking of non image-guided instruments (i.e K-ware) using a single device.

CT scanners with a sliding gantry may be installed into operating rooms, allowing intraoperative scanning without the need to reposition the patient (4,23).

Compared to Iso-C arm fluoroscopy, iCT offers better image quality (essentially equivalent resolution as modern non-movable scanners) and increased length of scan volume, reducing the number of scans needed during multi-level interventions. However, the greatest limitation to iCT is its limited availability and high start-up cost, and only a few centers in the world have it installed. Thus, the evidence is promising but limited (20,23).

The O-arm (Medtronic) is a relatively new imaging modality capable of providing intraoperative 3-dimensional volumetric CT scans with automated registration for navigation. The source and detector are contained within a cylindrical bore and can rotate in a 360-degree arc. The CT-scans are acquired rapidly (~13 seconds) and cover relatively large areas (up to ~392 single images in a full rotation). The LED tracker is integrated into the system, allowing for an automated registration for intraoperative navigation simultaneously as the CT is acquired intra-op.

Although there are multiple studies demonstrating the benefit of using the O-arm (Medtronic) in guiding accurate placement of pedicle screws and assessing extent of resection in cranial tumor resection (5,13,17,31,32,52), the data is sparse regarding its use with MIS spinal tumor surgery. In a retrospective review of 13 intradural extramedullary tumors treated using MIS techniques with O-arm (Medtronic) based navigation, Mannion et al(25) demonstrated satisfactory gross total resection of 12/13 tumors confirmed by post operative MRI. No particular difficulties were encountered with regards to tumor dissection and extent of resection. The EBL, operative time, and hospital stay were comparable to other MIS studies. There were no post-operative complications including CSF leaks. In conjunction with the findings of this study, our experience found the O-arm (Medtronic) to be greatly beneficial in confirming placement of instrumentation, providing accurate platform for navigation, and assessing the extent of resection.

The advent of phased-array probes with small footprints and optimal focusing at a range of depths that allow for minimally invasive application has renewed interest of using ultrasonography (US) in guiding intraspinal surgery. Furthermore, recent studies have demonstrated the utility of 3-D ultrasonography-based navigation systems in guiding dural opening, myelotomy, and extent of resection for intra- and extramedullary spinal cord tumors (12,16). A significant benefit of this modality is its ability to account for intraoperative shifts due to manipulation of tissues and CSF leaks in a relatively easy and affordable fashion.

In one of the largest series of US-guided spine tumor surgery, Prada et al(47) evaluated 34 cases of extradural, intradural extramedullary, and intradural intramedullary tumors. In all cases, it was possible to visual the lesion as well as the surrounding neural and vascular structures (dura mater, dentate ligament, arachnoid membranes). In 9 cases, intraop US demonstrated that the surgical approach was too small, leading to enlargement of the bony opening prior to dural incision. In 8 intramedullary cases, the intraop US correctly tailored the myelotomy.

Given its low-cost and relatively safe application (i.e. lower radiation exposure) compared to conventional intraoperative imaging modalities, the use of intraop US in MIS spine surgery deserves further evaluation through well-designed clinical trials.

Despite the benefits of improving pedicle screw placement and decreasing radiation exposure, the use of intraoperative 3-D navigations is not generally accepted as the standard of care among spine surgeons in Northern America. In an international survey assessing the attitude toward spine navigation and the perceived problems, only 11% of the surgeons surveyed (orthopedic and neurosurgical) in North America and Europe used navigation despite its availability (59). Common reasons for non use were high cost of navigation systems, lack of adequate training, equipment issues, steep learning curve, and disruption of workflow with perceived increase in added OR time. These surgeons commonly sought further data before committing to the new technology.

Limitations and Future Directions

Although intraoperative navigation offers many advantages as highlighted in this article, it is not without limitations. In respect to guiding extent of resection, CT images may not clearly demonstrate the extent of the soft-tissue components of the tumor or tumor invasion within bones. In these cases, the surgeon must have a sound understanding of the pre-operative MRI regarding the soft tissue boundaries. New advancements in MRI merged navigation techniques may alleviate this shortcoming (10).

A potential disadvantage of MIS is the possibility of exposing the wrong surgical level, especially in the mid- to upper thoracic spine (25). Given the limited ability to extend the exposure compared to open procedures, intraoperative localization of the correct pathologic level is of critical importance. Whenever there is any doubt that conventional fluoroscopic guidance will be difficult, the utilization of intraoperative 3-D CT imaging and navigation may help minimize these errors. Our limited experience with pre-incisional O-arm (Medtronic) scanning followed by navigation-guided exposure have correctly identified the pathological level for all cases.

Patient-dependent factors (i.e obesity) may create challenges with positioning and maneuvering imaging devices. Furthermore, the increased soft tissue results in poorer quality images that can impact the accuracy of registration and subsequent navigation (56). Operator-dependent factors include the initial learning curve involving the registration process and the ability to direct instruments based on imaging visualized on a screen(42). Other operating room factors include the availability of specific equipment, such as the sliding gantry iCT, O-arm (Medtronic), and optimal surgical beds with minimal radiodense metal that result in less radiographic artifacts (i.e. Jackson table).

Further applications of intraoperative 3-D navigation has been shown in combination with video-assisted thoracoscopic surgery (VATS) for treating thoracic tumors and disc herniation (46). Alternatively, Prada et al. have shown the utility of combining contrast enhancement with intraoperative ultrasound, achieving better delineation of intramedullary tumors in order to guide the extent of the myelotomy and resection (53). These advancements highlight the growing interest in the use of intraoperative guidance to ensure the most optimal resection and outcome for patients suffering from spinal tumors.

Although our study was limited by a small number of patients and heterogeneous pathology, we further contribute to the growing evidence of incorporating 3-D intraoperative CT guided navigation for the purpose of treating various spinal tumors in a minimally-invasive fashion. Furthermore, our literature review reveals the paucity of evidence that exists specifically for this clinical question and highlights the need for additional systematic clinical trials.

CONCLUSION

Image guided navigation can serve as a useful adjunct in MIS spine tumor surgery. Although it is not without its limitations, it has repeatedly shown to improve the accuracy of instrumentation in complex cases and results in reduced operation time (once the learning curve is overcome), EBL, and hospital stay. We believe that intraoperative navigation can greatly assist in the ability to obtain gross-total resection of spinal tumors for the ultimate improvement in long-term outcome in this population. Combined with a MIS approach, intraoperative navigation may offer the best chance of rapid symptomatic improvement in spine tumor patients who are often debilitated by intolerable pain and/or are in need of chemoradiation treatment as soon as possible in order to prolong progression free survival. Further clinical trials are warranted to demonstrate its benefits in a systematic manner.

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