Initial Experience Using Intraoperative Magnetic Resonance Imaging During a Trans-Sulcal Tubular Retractor Approach for the Resection of Deep-Seated Brain Tumors: A Case Series

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BACKGROUND: Treatment of deep-seated subcortical intrinsic brain tumors remains challenging and may be improved with trans-sulcal tubular brain retraction techniques coupled with intraoperative magnetic resonance imaging (iMRI).

OBJECTIVE: To conduct a preliminary assessment of feasibility and efficacy of iMRI in tubular retractor-guided resections of intrinsic brain tumors.

METHODS: Assessment of this technique and impact upon outcomes were assessed in a preliminary series of brain tumor patients from 2 centers.

RESULTS: Ten patients underwent resection with a tubular retractor system and iMRI. Mean age was 53.2 ± 9.0 yr (range: 37–61 yr, 80% male). Lesions included 6 gliomas (3 glioblastomas, 1 recurrent anaplastic astrocytoma, and 2 low-grade gliomas) and 4 brain metastases (1 renal cell, 1 breast, 1 lung, and 1 melanoma). Mean maximal tumor diameter was 2.9 ± 0.95 cm (range 1.2–4.3 cm). The iMRI demonstrated subtotal resection (STR) in 6 of 10 cases (60%); additional resection was performed in 5 of 6 cases (83%), reducing STR rate to 2 of 10 cases (20%), with both having tumor encroaching on eloquent structures. Seven patients (70%) were stable or improved neurologically immediately postoperatively. Three patients (30%) had new postoperative neurological deficits, 2 of which were transient. Average hospital length of stay was 3.4 ± 2.0 d (range: 1–7 d).

CONCLUSION: Combining iMRI with tubular brain retraction techniques is feasible and may improve the extent of resection of deep-seated intrinsic brain tumors that are incompletely visualized with the smaller surgical exposure of tubular retractors.

KEY WORDS: Brain tumor, Exoscope, Intraoperative MRI, Minimally invasive tumor resection, tubular retraction

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Deep-seated brain tumors, especially in eloquent regions, remain a challenging problem. Large craniotomies can damage areas of critical brain function. Less invasive tubular retractors may minimize potential injury by maintaining uniform concentric displacement of brain tissue, rather than focal points of pressure, while providing

a clear working corridor. Recently, translucent cylindrical or speculum-like tubular brain retractors have been developed and, coupled with high-definition exoscopes, improve visualization. Because they are compatible with intraoperative magnetic resonance imaging (iMRI), they can be left in situ during image acquisition. It is unclear if the reduced exposure offered by tubular retractors limits extent of resection by decreasing visualization.

Intraoperative imaging modalities, such as iMRI, have been developed to optimize safe tumor resection.^{1–17} iMRI images can identify residual tumor, allowing for its safe resection during the same operation. iMRI can improve extent of resection for various brain lesions. Recently, pre- and intraoperative

ABBREVIATIONS: DTI, diffusion tensor imaging; GBM, Glioblastoma; GTR, gross total resection; I-MINDTM, IMRISTM Multicenter iMRI Neurosurgery Database; iMRI, intraoperative magnetic resonance imaging; REDCapTM, Research Electronic Data Capture; STR, subtotal resection; WHO, World Health Organization

diffusion tensor imaging (DTI) tractography has improved resection safety by providing a map of peritumoral neuronal networks, allowing for a safer surgical trajectory.

The current case series describes the preliminary experience using a tubular retractor system for trans-sulcal resection of deep-seated lesions with neuronavigation, an exoscope, and iMRI. To our knowledge, this is the first report of this combination of techniques that conceptually could facilitate safer tumor resections.

METHODS

Patients

The prospective institutional review board-approved IMRISTM Multi-center iMRI Neurosurgery Database (I-MiNDTM) was used to identify consecutive patients from 2013 to 2017 at 2 academic centers with tumor resections performed using iMRI and an MRI-compatible tubular retractor (BrainPathTM, NICOTM Corporation, Indianapolis, Indiana). The IRB approval was granted with waiver of consent. Three neurosurgeons trained in the use of iMRI and the tubular retractor system performed the procedures. The I-MiNDTM study used the Research Electronic Data Capture (REDCapTM, Nashville, Tennessee) electronic data capture tools.¹⁸ The study has been registered on ResearchRegistry.com, and the PROCESS Guidelines were used in the formation of this manuscript.

Surgical Procedure

Before incision, craniotomies and trajectories for the tubular retractor were designed using stereotactic navigation systems (StealthTM, Medtronic, Dublin, Ireland for 6 patients, and Stryker NavTM, Stryker Co, Kalamazoo, Michigan for 4 patients). In 7 of 10 (70%) patients, preoperative DTI tractography of white matter tracts (corticospinal fibers, optic radiations, and arcuate fasciculus) was used to avoid eloquent structures when planning surgical trajectories.¹⁹ In 5 of 10 (50%) patients, task-based and resting-state functional MRI techniques (language, motor function) were utilized to further optimize trajectories. When possible, trajectories were planned through the long axis of the tumor, and the specific approach used was dictated by the tumor location and the path of least disruption of normal cerebral tissue. A scalp flap, craniotomy, and a cruciate dural incision approximately 15 mm in diameter were made overlying a sulcus chosen during stereotactic planning. The arachnoid was incised and the tubular retractor including the internal obturator was introduced through the sulcus using continuous navigation to a depth of approximately 75% of the long axis of the tumor. The appropriate length of the tubular retractor device was selected based upon the simulated trajectory (Figure 3). The obturator was removed and the outer cannula was stabilized in the brain with the retractor system (GreenbergTM, Symmetric Surgical, Antioch, Tennessee) and the “shepherd’s hook,” a metal attachment connecting the retractor system to the tubular retractor. Visualization was achieved with a high-resolution exoscope (VITOMTM, Karl Storz GmbH & Co, Tuttlingen, Germany) attached to a pneumatic arm (UniArmTM, MitakaTM USA Incorporated, Park City, Utah; Figure 1). Bipolar cautery, suction, and the side-cutting tumor-aspiration device (MyriadTM, NICOTM Corporation) were used for lesion resection. Standard draping and safety procedures were completed prior to obtaining iMRI studies. The surgeon

determined the use of iMRI based on preference and as a procedural adjunct due to the deep-seated nature of the lesion. All cases were performed in iMRI suites (IMRIS, Inc, Minnetonka, Minnesota) with a movable ceiling-mounted EspreeTM (Siemens, Malvern, Pennsylvania) 1.5 T iMRI device. In select cases (30%), the tubular retractor was left in situ, secured by anchoring sutures. The iMRI scans, including DTI tractography when available, were loaded into the neuronavigation system. Additional resection was performed as indicated. Somatosensory and motor evoked potential monitoring was performed in 2 (20%) of the patients at the discretion of the surgeon, and subcortical mapping was not performed.

Outcomes

Patient preoperative and demographic data including age, gender, presenting symptoms, tumor size (maximum diameter), tumor location, and MRI characteristics were evaluated. Intra- and postoperative outcomes including extent of resection (on iMRI and postoperative scan), estimated blood loss, surgical time, length of hospital stay, tumor pathological diagnosis, postoperative neurologic condition, progression, and survival to date were evaluated. Illustrative cases are discussed.

RESULTS

Preoperative Data

Ten patients from 2 institutions underwent tumor resection using a tubular retraction system and iMRI (Table 1). Average patient age was 53.2 ± 9.0 yr. Eight (80%) patients were male. These predominantly deep-seated brain tumors were located in the frontal (6), temporal (3), and occipital (1) lobes, the average lesion maximal diameter was 2.9 ± 0.9 cm, and the average depth from the cortical surface to the most superficial depth of the lesion was 2.6 ± 0.7 cm (range 1.2–3.5 cm).

Intraoperative Data

Six patients (60%) had subtotal resection (STR) identified on iMRI. Five of these 6 (83%) patients underwent further resection after iMRI, and 4 (80%) of these patients achieved gross total resection (GTR). Thus, GTR rate improved from 4 (40%) based on iMRI to 8 (80%) patients based on postoperative MRI. No additional resection of residual tumor was performed after iMRI in 2 cases due to lesion proximity to corticospinal fibers. One (10%) patient received intraoperative DTI, which was integrated with stereotactic navigation to ascertain proximity of residual tumor to corticospinal fibers, and no further resection was attempted. Average operative time including iMRI (“skin-to-skin”) was 335.7 ± 63.0 min (range 230–440 min). Estimated blood loss was 220.0 ± 85.6 mL (range 100–350 mL).

Postoperative Outcomes

Pathologic diagnoses included glioblastoma (GBM) (3), low-grade glioma (2), anaplastic astrocytoma (1), and metastasis (4): renal cell, nonsmall cell lung, breast, and melanoma. Neurologic condition improved immediately after surgery (3; 30%), remained stable (4; 40%), or worsened (3; 30%). Three (30%) patients had postoperative neurological decline. One patient

FIGURE 1. Operating room setup for a tubular retractor brain tumor resection case. **A**, Patient head with overlying surgical drapes. **B**, “Shepherd’s hook” mounted on self-retaining retractor used to hold the tubular retractor in place (“Shepherd’s hook” has been rotated out of the surgical field and out of the figure). **C**, Stereotactic neuronavigation reference frame. **D**, Stereotactic neuronavigation probe. **E**, Pneumatic arm. **F**, Exoscope. **G**, Exoscope image displayed on high resolution flat-panel monitor. **H**, Stereotactic neuronavigation infrared display. **I**, Stereotactic neuronavigation infrared camera.

developed right-sided hemiplegia after left frontal tumor resection with no improvement 4 mo after surgery. Two cases had transiently worse postoperative neurologic exams with increased contralateral weakness. Both improved to baseline after 2 d. Two of the 3 patients with neurological decline occurred in cases where additional resection was performed after iMRI, while the third patient had an STR without additional resection due to the tumor’s proximity to the corticospinal tract. Average length of hospital stay was 3.4 ± 2.0 d (range 1-7 d). Average follow-up was 11.2 ± 12.4 mo (range 0-42 mo). All patients with GTR had no local tumor progression on follow-up. Both patients with STR had local progression of disease after 2 and 11 mo, respectively; however, no neurological consequences of progression were

noted. Five (50%) patients expired during follow-up (median 4.5 mo, range 4 d-11 mo) due to progression of disease (2 GBM—1 recurrent and 1 new diagnosis, 1 renal cell carcinoma, and 1 melanoma) or pulmonary embolism (4 d after surgery for GBM).

Illustrative Cases

Case 1

A 37-yr-old male presented with an incidental lesion in the right posterior temporal lobe on computed tomography scan after minor trauma. MRI revealed a nonenhancing lesion with maximum diameter of 1.2 cm (Figure 2A-2C). DTI

TABLE 1. Pre-, Intra-, and Postoperative Data From 10 Patients Undergoing Tubular Retractor Access Resection of Deep-Seated Brain Tumors with IMRI

Case	Age	Sex	Tumor location	Maximum diameter (cm)	Depth from cortical surface (cm)	EOR iMRI	Added resection	EOR post-OP	Final pathology	Post-OP adjuvant	Follow-up (MO)	Post-OP neurological deficit	Local progress	Death
1*	37	M	R temporal	1.2	3.2	GTR	N	GTR	LGG	NONE	42	N	N	N
2*	61	F	R frontal	4.3	2.7	GTR	N	GTR	MET (breast)	WBRT, pembrolizumab	16	N	N	N
3	53	M	L frontal	2.5	1.9	GTR	N	GTR	MET (RCC)	SRS to cavity	7	N	N	Y
4*	53	M	L temporal	2.4	2.8	GTR	Y	GTR	LGG	None	10	MILD diplopia, RHP, aphasia	N	N
5	64	M	L frontal	2.6	1.2	STR	Y	GTR	GBM	None	N/A	RHP, neglect	N/A	Y ³
6	53	M	L occipital	3.6	2.4	STR	Y	GTR ⁴	GBM	XRT, temozolomide	2	N	N	Y
7	48	M	R LAT VENT	2.5	3.2	STR	Y	GTR	Recurrent AA (III)	Immunotherapy	7	N	N	N
8	57	M	L frontal	2.8	3.5	STR	Y	GTR	Recurrent MET (NSCLC)	Nivolumab, Temsirolimus	4	N	N	N
9*	64	F	L frontal	4.3	2.7	STR	N ¹	STR	MET (melanoma)	SRS, WBRT, pembrolizumab	2	RHP, aphasia	Y	Y
10	42	M	R frontal	3.2	2.4	STR	N ²	STR	Recurrent GBM	XRT, temozolomide	11	N	Y	Y

*Illustrative cases described in the results section.

¹No additional resection was performed due to tumor proximity to corticospinal tract.²No additional resection was performed since the tumor involved the internal capsule.³Sudden death on postoperative day 4 likely secondary to pulmonary embolism.⁴Gross total resection of dominant of two unrelated intracranial tumors. Smaller remote tumor treated with radiotherapy.

Abbreviations: AA, Anaplastic astrocytoma; EOR, Extent of resection; GBM, Glioblastoma; GTR, Gross total resection; IMRI, Intraoperative magnetic resonance imaging; LAT VENT, Lateral ventricle; LGG, Low-grade glioma; MET, Metastatic lesion; NSCLC, Non-small cell lung cancer; RHP, Right hemiparesis; SRS, Stereotactic radiosurgery; STR, Subtotal resection; WBRT, Whole-brain radiation therapy; XRT, External beam radiotherapy.

FIGURE 2. Case 1. Preoperative axial **A** T2-weighted, coronal **B** T1-weighted contrast-enhanced, and sagittal **C** FLAIR sequence MRIs revealing a 1.2 cm nonenhancing right temporal lesion. Intraoperative magnetic resonance imaging (iMRI) axial **D** T2-weighted, coronal **E** T1-weighted contrast-enhanced, and sagittal **F** FLAIR sequences showing complete resection of the lesion. iMRI was safely performed with the tubular retractor in place without artifact. Forty-two-month follow-up imaging (not shown) was without evidence of recurrent or residual tumor. Pathology revealed angiocentric glioma, WHO grade I.

tractography was used to create a right posterior temporal lobe approach inferior to the optic radiations. The predetermined sulcus was incised after sacrificing one branch of an adjacent vein. Intraoperative pathology confirmed low-grade glioma. Visual inspection of the cavity suggested GTR. The tubular retractor was secured in place and left in situ during the iMRI, which was consistent with GTR (Figure 2D-2F). The retractor caused no safety or distortion issues during iMRI. The retractor was removed, hemostasis achieved, and closure performed. The patient recovered without complications. Forty-two-month postoperative MRI demonstrates no evidence of residual or recurrent disease. Final pathology was an angiocentric glioma (World Health Organization, (WHO), I). No further treatment was required.

Case 2

A 61-yr-old female with a history of metastatic breast cancer with known liver metastasis presented with recent facial weakness, left arm tremor, fatigue, and headache. MRI revealed a large right frontal enhancing lesion (Figure 3A and 3B). Resection was performed using a tubular retractor, and intraoperative pathology showed metastatic breast cancer. The retractor was removed. iMRI revealed GTR (Figure 3C and 3D). The patient did well postoperatively with no new neurological deficit or complications and was discharged on postoperative day 4. The patient underwent postoperative chemotherapy and whole-brain radiation therapy. At 7-mo follow-up, MRI revealed growth of a distant posterior-cingulate lesion for which stereotactic radiosurgery was performed. The patient remains stable with

FIGURE 3. Case 2. Preoperative axial **A** and coronal **B** T1-weighted contrast-enhanced MRI revealing a deep-seated large right frontal lesion consistent with breast cancer metastasis. Intraoperative axial **C** and coronal **D** T1-weighted contrast-enhanced MRI shows gross total resection (GTR) of the lesion. 16-mo postoperative axial **E** and coronal **F** T1-weighted contrast-enhanced MRI shows gross-total resection of the lesion with no progression of disease.

no new neurological deficits at 16-mo follow-up (Figure 3E and 3F).

Case 4

A 52-yr-old male presented with 1 yr of episodes of automatisms and staring spells. MRI revealed a T2 and FLAIR hyperintensity in the left mesial temporal lobe (Figure 4A). Lesion resection was performed using a tubular retractor system. Intraoperative pathology was low-grade glioma. iMRI showed apparent GTR (Figure 4B). Postoperatively, the patient had recurrent brief episodes of aphasia, right-sided weakness, and double vision

without EEG correlate. His antiepileptics were adjusted. He was discharged home on postoperative day 6. Final pathologic diagnosis was primary nonspecific low-grade neoplasm with immunohistochemistry negative for p53, IDH-1 (R132H), BRAF (V600E), and EGFR amplification, and no evidence of 1p and 19q chromosomal co-deletion. The patient recovered with no further seizure activity and no complications. MRI scans from 3-mo (Figure 4C) and 10-mo (Figure 4D) follow-up showed stable findings of FLAIR hyperintensity surrounding the resection cavity possibly related to the surgical procedure or the underlying infiltrative tumor. To date, the patient has been observed without further intervention.

FIGURE 4. Case 4. **A**, Preoperative axial FLAIR MRI shows a hyperintense lesion of the left mesial temporal lobe consistent with low-grade glioma. **B**, Intraoperative FLAIR MRI suggests GTR, which was confirmed on 3-mo postoperative FLAIR MRI **C**. **D**, Follow-up FLAIR MRI 10 mo after surgery showed stable FLAIR hyperintensity adjacent to the resection cavity.

Case 9

A 64-yr-old female with a remote history of a resected superficial arm melanoma presented with mild aphasia and hemiparesis. MRI revealed a left frontal lesion 4.3 cm in maximum diameter. Outside hospital biopsy revealed melanoma (Figure 5A-5C). Lesion resection was performed with a tubular retractor system. The tubular retractor was removed. iMRI with DTI tractography was obtained, showing residual tumor

adjacent to the corticospinal tract (Figure 5D-5F) precluding further resection. The patient's postoperative course was complicated by a right hemiparesis and worsened expressive aphasia, which improved to baseline 2 d later. She underwent postoperative fractionated stereotactic radiosurgery and treatment with pembrolizumab. She did well until 3 mo postoperatively when she developed altered mental status, word-finding difficulties, and falls. MRI revealed that the treated lesion had decreased in size;

FIGURE 5. Case 9. Patient with biopsy proven metastatic melanoma. Preoperative coronal **A**, sagittal **B**, and axial **C** T1-weighted contrast-enhanced MRI images integrated into the surgical navigation software with pre- and postoperative diffusion tensor imaging (DTI) tractography overlay. Note anatomical left is on left of the image in this software (opposite conventional radiology orientation). Preoperative studies demonstrate a 4.3 cm enhancing lesion in the deep left frontal lobe. Overlying DTI images demonstrate the left corticospinal tracts (in red from the preoperative DTI MRI acquisition, and in light blue from the iMRI acquisition). Right corticospinal tracts from the preoperative DTI MRI acquisition are shown in green. Intraoperative coronal **D**, sagittal **E**, and axial **F** T1-weighted contrast-enhanced MRI shows a subtotal resection of the lesion with residual tumor adjacent to the corticospinal tract. Further resection after iMRI was not pursued due to proximity to motor fibers.

however, there was progression at multiple other sites. Despite stereotactic radiosurgery and palliative whole-brain radiation, she had progressive decline and family elected for hospice care. The patient expired 5 mo postoperatively.

DISCUSSION

The safety and efficacy of trans-sulcal tubular retraction techniques for a variety of lesions have been previously described.²⁰⁻²⁴ To our knowledge, this is the first study to report the addition of iMRI to this approach to maximize resection safety.

In the 1930s, Walter Dandy described accessing intraventricular lesions using a cylindrical or speculum-like retractor system.²⁵ Over the years various iterations of this technique have been described including more recent development of transparent tubular retractors.^{26,27} Tubular retractors apply circumferential pressure and provide a clear working channel. This report is the first to confirm that a tubular retraction system can be safely left in situ during iMRI without causing imaging artifact and furthers

our previous understanding of the use of tubular retractors in the resection of deep-seated lesions.^{28,29}

At centers accustomed to obtaining iMRI, imaging acquisition times are approximately 45 to 70 min.⁵ For malignant gliomas, a small randomized trial demonstrated that iMRI improved tumor resection and progression-free survival.⁶ Multiple other studies have evaluated iMRI for low- and high-grade gliomas.^{7,8,10,12,13,30,31,32} At the authors' institutions, iMRI is used in the majority of glioma cases. iMRI has become a powerful adjunct in neurosurgical procedures. For resections of metastatic lesions, iMRI is used more selectively at the surgeon's discretion for deeper or more challenging tumors.

Newer tubular retractors are made of MRI-compatible materials, which can be left in situ during iMRI. Leaving the retractor in place may provide pressure-hemostasis to the walls of the trajectory, additional ease in navigating back to the resection cavity if needed, and does not cause imaging artifact.

This series describes the combination of tubular retractors with iMRI for deep-seated lesions. The relative safety of this technique is supported by the low estimated blood loss and

relatively short length of hospital stays. However, 1 patient did sustain a postoperative stroke resulting in hemiplegia. These results are a reminder of the potential risks when operating on tumors in eloquent regions. STR was noted on iMRI in 6 (60%) cases, which decreased to 2 (20%) after additional resection. There remain some challenges given the narrow working corridor of the transparent tubular retractor. In our sample, GTR was unattainable only in cases where it was precluded by proximity to the corticospinal tracts (Case 9 and 10). Thus, further resection was deemed unsafe.

Advanced imaging, such as fMRI and DTI tractography, are increasingly used to improve the safety of neurosurgical procedures.¹⁹ This is particularly helpful for deep-seated lesions, as these modalities assist in creating an optimal surgical trajectory. These sequences are now being incorporated into iMRI studies, as demonstrated in Case 9, and may further guide safe resection.

During resection, tissue-shifts can alter neuronavigation accuracy. iMRI allows the surgeon to update neuronavigation with images that reflect these changes, improving the accuracy of tumor and peritumoral tract localization. However, these advanced techniques may be more susceptible than standard anatomical sequences to artifacts in the iMRI environment including fluid and air interfaces in the resection cavity, nonstandard head positions in comparison to neutral positions for diagnostic MRI, and the MRI-compatible headholder. Continued refinement and validation of techniques such as iMRI DTI are warranted.

Limitations

This small, nonrandomized, retrospective study with short follow-up precludes higher-level statistical evaluation or comparison to a matched group. Given the small sample size, survival analysis of the use of iMRI could not be performed. Limitations related to the technique include increased operative time for obtaining an iMRI scan and the undefined learning curve for the system and iMRI. iMRI lengthens operative time but can be obtained in less than 1 h. Despite these limitations, this series demonstrates the safety and feasibility of combining tubular retractors with iMRI to maximize safe resection of deep-seated lesions.

CONCLUSION

iMRI is a useful adjunct in the safe maximal resection of deep-seated intrinsic brain tumors when combined with a tubular retractor, neuronavigation with tractography, and exoscope visualization. The grouping of these techniques appears feasible and may improve maximal safe resection of intracerebral lesions. A prospective cohort with larger sample sizes may help to further support this combination of techniques.

Disclosures

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The I-MiND™ project is a multicenter retrospective and prospective (since 2008) registry from 8 North American neurosurgical centers. At the time of this publication, the I-MiND™ project has data from over 7500 surgical procedures collected for brain tumors and other pathologies including over 3500 surgeries performed with the IMRIS™ movable intraoperative MRI device.

COMMENTS

The authors report their initial experience using intraoperative magnetic resonance imaging during a transsulcal tubular retractor approach for the resection of deep-seated brain tumors.

This is an interesting paper and I believe this should be part of any surgeon's armamentarium. Tubular retractors are here to stay, and when combined with intraoperative magnetic resonance imaging (iMRI) this becomes a powerful tool. The authors report on 10 patients who underwent resection with a tubular retractor system and iMRI. The iMRI demonstrated subtotal resection in 6 of 10 cases (60%); additional resection was performed in 5 of 6 cases (83%), reducing subtotal resection rate to 2 of 10 cases.

This technique combined with DTI will become the standard of care for subcortical cases allowing for a safer approach with less collateral damage and a more complete resection.

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In this case series of 10 patients from 2 institutions, the authors describe the use of tubular retractors with intraoperative MRI (iMRI). These lesions consisted of 6 gliomas and 4 metastases. The iMRI showed subtotal resection in 6 cases, and, of those 6 cases, 5 underwent additional resection. We routinely use tubular retractors for deep-seated lesions as it provides a protected corridor to perform these resections with minimal collateral damage. The idea of implementing this tool with iMRI shows that many different adjuncts can be combined together to maximize outcomes. The authors also show that the retractor can be kept in place during the iMRI to confirm trajectory. We prefer to use real-time imaging with ultrasound to confirm trajectory and assess for extent of resection. Nonetheless, it shows the tubular retractors can be effectively used in combination with iMRI to assess extent of resection.

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