Impact of Intraoperative Magnetic Resonance Imaging (i-MRI) on Surgeon Decision Making and Clinical Outcomes in Cranial Tumor Surgery

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Abstract

Background Although intraoperative magnetic resonance imaging (iMRI) has an established role in guiding intraoperative extent of resection (EOR) in cranial tumor surgery, the details of how iMRI data are used by the surgeon in the real-time decision-making process is lacking.

Materials and Methods The authors retrospectively reviewed 40 consecutive patients who underwent cranial tumor resection with the guidance of iMRI. The tumor volumes were measured by volumetric software. Intraoperative and postoperative EOR were calculated and compared. Surgeon preoperative EOR intention, intraoperative EOR assessment, and how iMRI data impacted surgeon decisions were analyzed.

Results The pathology consisted of 29 gliomas, 8 pituitary tumors, and 3 other tumors. Preoperative surgeon intention called for gross total resection (GTR) in 28 (70%) cases. After resection and before iMRI scanning, GTR was 20 (50.0%) cases based on the surgeon's perception. After iMRI scanning, the results helped identify 19 (47.5%) cases with unexpected results consisting of 5 (12.5%) with unexpected locations of residual tumors and 14 (35%) with unexpected EOR. Additional resection was performed in 24 (60%) cases after iMRI review, including 6 (15%) cases with expected iMRI results. Among 34 cases with postoperative MRI results, iMRI helped improve EOR in 12 (35.3%) cases.

Conclusion In cranial tumor surgery, the surgeon's preoperative and intraoperative assessment is frequently imprecise. iMRI data serve several purposes, including identifying the presence of residual tumors, providing residual tumor locations, giving spatial relation data of the tumor with nearby eloquent structures, and updating the neuro-navigation system for the final stage of tumor resection.

Keywords
- cranial tumor
- extent of resection
- glioma
- gross total resection
- intraoperative MRI

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Introduction

Since the first report in 1999 of intraoperative magnetic resonance imaging (iMRI) at Brigham and Women's hospital,[1] it has been increasingly recognized as an important tool for cranial tumor surgery.[2–7] iMRI allows the neuro-navigation system to be re-registered with intraoperative imaging data, mitigating inaccuracy issues due to brain shift. It also provides objective verification of the extent of resection (EOR) of intracranial pathology. Thus, iMRI allows surgeons to make additional resection, maximizing the EOR, and avoiding unnecessary re-operation.[8–11]

There is currently scant data on how iMRI actually assists the surgeon in real-time practice when making critical decisions and reformulating surgical plans. We studied how iMRI data impact a surgeon's intraoperative decision-making process as well as clinical outcomes.

Materials and Methods

Patient

This was a retrospective study reviewing database records from the 3 Tesla intraoperative MRI (iMRI) of patients who underwent cranial tumor resection between June 2019 and September 2021. Indications for iMRI guidance were tumors in which intraoperative EOR was difficult to determine with certainty.

Set Up of Operating Room and iMRI

Surgery took place in a dual independent operating room connected to a stationary 3T-iMRI (Ingenia; Philips Medical Systems, Best, The Netherlands) room design. The operating table was mounted with an MRI-compatible rigid head fixator with integrated MRI coil (Noras, Hoechberg, Germany). The operating rooms were equipped with an integrated ceiling mounted neuro-navigation system (Brainlab, Munich, Germany).

Workflow

All patients were anesthetized in a standard fashion. Patient heads were fixed in an MRI-compatible rigid head fixator with integrated MRI coils. Registration of the navigation system was performed by surface matching prior to the operation. Standard surgical equipment was used throughout the procedure. For pituitary tumor and clival chordoma, patients were operated by rigid endoscopic surgery (Storz, Tuttlingen, Germany). After the surgeon finished the resection and decided to perform an intraoperative scan, non-MRI compatible equipment was removed from the patient and the surgical field was covered with a sterile sheath with head coils attached to the head fixator. Anesthetic equipment was changed to an MRI compatible type. A "time out" procedure was performed to ensure all MRI safety protocols had been followed. The patient was then moved to an MRI-compatible trolly that transported the patient into the MRI scanner. After iMRI scanning was completed, the patient was returned to the operating table and re-draped. The neuro-navigation system was re-registered with the iMRI dataset. The surgeon then examined the iMRI results without a neuroradiologist involved. If additional resection was not required, the surgical field was closed in a standard fashion. If additional resection was deemed necessary, the operation was resumed until additional resection was completed after which the surgeon may opt for another iMRI scanning.

MRI Acquisition and Volumetric Analysis

Tumor volume was measured using semiautomated commercial software (iPlan element, Brainlab, Munich, Germany) by a neurosurgeon in a blinded fashion (►**Fig. 1**). MRI parameters included 5 (1) post contrast coronal and sagittal T1-weighted with fat suppression for pituitary tumor, (2) postcontrast axial T1-weighted turbo field echo for enhancing glioma and other enhancing tumors, (3) axial fluid-attenuated inversion recovery (FLAIR) for non-enhancing glioma, and (4) axial T2-weighted for chordoma.

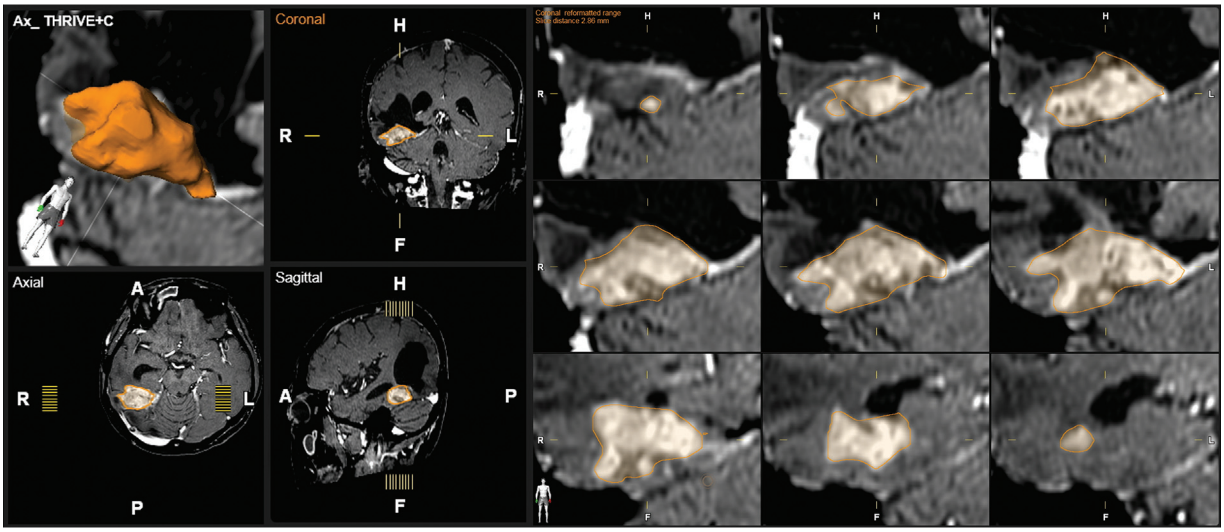

Fig. 1 Tumor volume was measured using semiautomated segmentation software on thin slice MRI.

There is different timing of postoperative MRI (pMRI) for brain tumors in the literature. It is generally common to obtain pMRI within 72 hours[7,12] or even within 24 hours[13,14] to avoid postoperative tissue reactions. However, there are also several publications using late pMRI (3 months) for low-grade glioma[3,15] and pituitary tumors,[16,17] after which postoperative reactions have subsided. The latter practice, however, may not be suitable for rapidly growing tumors. Therefore, in this study, we used early pMRI obtained within 72 hours for enhancing glioma and late pMRI between 8 and 12 weeks for non-enhancing glioma and other benign tumors with the same parameters as the preoperative MRI.

The pMRI was independently examined by a neuroradiologist to determine the presence of residual tumor. Extent of resection was expressed as a percentage and calculated by the following formula: preoperative tumor volume minus postoperative tumor volume divided by preoperative tumor volume. Percentages were graded into three levels: (1) gross total resection (GTR)—100% resection, (2) near-total resection (NTR) at 90% or greater and less than 100% resection, and (3) subtotal resection (STR) less than 90% resection.

Data Collection

Data retrieved from medical records included patient characteristics, pathological diagnosis, tumor location and volume, duration of iMRI scanning, additional resection required, preoperative surgeon intention and intraoperative perception of EOR (graded into GTR, NTR, or STR), would the surgeon continue or stop resection if iMRI is not available? (yes/no), comparison between iMRI results and the surgeon's perception (as expected or if unexpected-in what regards EOR or location of tumors), interruption duration cause by the iMRI process (time when the operation was stopped to the time when operation was resumed), and clinical outcomes (neurological complications, surgical infection, hormone remission in secreting pituitary tumors). This retrospective study involving human participants was approved by the Institutional Review Board (COA No. 1308/2021). Separate written informed consent was not required for this retrospective study.

Statistical Analysis

Patient characteristics, demographic data, and tumor volume are presented in means and standard deviation (SDs) for continuous variables and percentages and quartiles for non-continuous variables. Intraclass correlation coefficients (ICCs) were used to analyze the correlation of the tumor volume. Cohen's kappa coefficient was used to analyze the correlation of EOR. Statistical analysis was performed using the IBM SPSS version 20 software (IBM Co., Armonk, NY, USA). A p-value of less than 0.05 was considered statistically significant.

Result

Patient Characteristic and iMRI Scan

During the study period, 40 cases underwent cranial tumor surgery with iMRI guidance. Seventeen (42.5%) were males and 22 (57.5%) were females with a mean age of 31.9 ± 16.3 years (range, 2–66 years). Tumor locations included supratentorial compartment, infratentorial compartment, and in the sella turcica in 28 (70%), 4 (10%), and 8 (20%) cases, respectively. The majority of pathologies were glioma and pituitary tumor as shown in ►**Table 1**. Ten (25%) patients had undergone a previous operation for cranial tumor removal. Intraoperative neurophysiologic testing was used in 4 (10%) cases. All cases underwent iMRI once. Average iMRI scanning duration was 36.7 ± 11.1 minutes (range, 22–70 minutes). The operation interruption duration was 81.3 ± 24.3 minutes (range, 46–179 minutes). There was one case with a hardware malfunction causing a delay that resulted in an interruption of 179 minutes.

Table 1 Types of pathology

Pathology ($n = 40$)	Number of cases
Glioma ($n = 29$)	
WHO Gr I	4
WHO Gr II	15
WHO Gr III	2
WHO Gr IV	8
Pituitary tumor ($n = 8$)	
Non-secreting	3
-Knosp 0–2	2
-Knosp 3–4	1
Hormone secreting	5
-Knosp 0–2	5
-ACTH	5
Others ($n = 3$)	
Chordoma	1
Medulloblastoma	2

Clinical Outcome

There were 10 (25%) cases with new neurological deficits including 6 (15%) temporary and 4 (10%) permanent (lasted longer than 6 months). There were 4 (10%) cases with postoperative infection including 2 (5%) with meningitis, 1 (2.5%) with urinary tract infection, and 1 (2.5%) with pneumonia. There was no 30-day mortality. Hormone remission was achieved in three cases of hormone-secreting pituitary tumor.

Surgeon Plan and Decision Making

Preoperative surgeon intention called for GTR in 28 (70%) cases. After resection, GTR was 20 (50%) cases based on the surgeon's perception. iMRI result showed actual GTR in 12 (30%) cases. There were five (12.5%) cases where surgeons would continue resection if iMRI was not available. Results from the iMRI were unexpected to the surgeon in 19 (47.5%) cases, consisting of unexpected locations of residual tumors in 5 (12.5%) and unexpected EOR in 14 (35%) cases. A total of

Table 2 Surgeon's perception, iMRI results, and addition resection ($n = 40$)

	n (%)	Number of cases											
Preoperative intention	GTR 28 (70)	GTR 28						NTR 9					STR 3
	NTR 9 (22.5)												
	STR 3 (7.5)												
Intraoperative surgeon's perception	GTR 20 (50)	GTR 20			NTR 8			NTR 7			STR 2		STR 3
	NTR 15 (37.5)												
	STR 5 (12.5)												
iMRI EOR	GTR 12 (30)	GTR 12	NTR 1	STR 7	NTR 3	STR 5		NTR 1	STR 6		STR 2		STR 3
	NTR 5 (12.5)												
	STR 23 (57.5)												
Expected/ Unexpected iMRI result	E 21 (52.5)	E 12	Ueor 1	Ueor 7	Uloc 3	Ueor 3	E 2	Uloc 1	Ueor 3	E 3	Uloc 1	E 1	E 3
	Ueor 14 (35)												
	Uloc 5 (12.5)												
Additional resection	24 (60)	0	1	6	3	3	1	1	3	2	1	1	2

Abbreviations: E, expected; Ueor, unexpected EOR; Uloc, unexpected locations of residual tumors.

24 cases (60%) received additional resection after iMRI, 18 (45%) were with unexpected iMRI results, and 6 (15%) were with expected iMRI results. Full details are presented in ►**Table 2**.

Tumor Volume and Extent of Resection

Among 40 cases, pMRI data were available for evaluating the postoperative EOR in 34 cases. Meaningful additional resection, defined as resection resulting in improved EOR grade, was achieved in 12 (35.3%) cases. Details of tumor volume at each phase of operation and extent of resection of these 34 cases are shown in ►**Table 3**.

Correlation between iMRI and pMRI

Among 34 cases with results of pMRI, there were 14 (41.2%) cases that did not undergo additional resection after iMRI scanning as gross total resection had already been accomplished (10 cases) or the surgeon decided it was unsafe to continue the resection (4 cases). There were two cases with false negative for residual tumor on iMRI, both of which were Cushing's disease with residual tumor volume on pMRI of 0.5 mL and 0.1 mL. Additionally, the authors compared the result of iMRI to pMRI to analyze their correlation (►**Table 4**).

Discussion

The pathology in our study reflected the type of tumor the surgeon encountered when the intraoperative EOR was difficult to determine. This may be due to the indistinguishable appearance of a glioma or blind spot in pituitary tumors or skull base tumors. In the present study, a majority of tumors were gliomas followed by pituitary tumors, similar to previous publications studying the use of iMRI in cranial surgery.[2,18–21]

iMRI and Surgeon's Decision Making

Surgeon preoperative intention is generally a surrogate for the relation between the tumor and nearby important structures where GTR, NTR, and STR imply the tumor is clear from, is adjacent to, and involves the nearby eloquent structures, respectively. In our study, a high proportion of intention for GTR suggested most tumors were located away from the eloquent structures and could be removed safely. Thus, residual tumors were likely the result of the imprecise surgeon's perception rather than being prohibited by nearby vital structures.

Although surgeon preoperative intention for GTR was 70% of the cases, intraoperative perceptions of GTR reduced to 50%. However, when asked if the iMRI was not available, the surgeons indicated only five (12.5%) cases for continued resection. This implied that, in most cases, the surgeons believed it was unsafe to continue resection without additional information from iMRI.

After iMRI scanning, the actual cases of GTR dropped even further to 30% as compared with the surgeon's perception prior to iMRI and the iMRI result was unexpected to the surgeon in 19 (47.5%) cases. The discrepancy between surgeon assessment and the actual result of the iMRI has been well documented in previous publications. Scherer et al. studied surgeons' perceptions in supratentorial glioma and found an average negative predictive value for additional resection of 43.6%.[22] Even in a center with a high case volume, Lau et al reported an overall accuracy of the surgeons' perceptions of EOR in glioma surgery to be 79.6%.[23] Khunt et al reported 293 cases of glioma undergoing iMRI-guided craniotomy with residual tumor remaining unresected in 17.7% among the cases intended for GTR.[9]

In our series, iMRI not only identified an unexpected EOR but also revealed unexpected locations of residual tumors.

Table 3 Tumor volume, extent of resection, and additional resection ($n = 34$)

	All ($n = 34$)	Glioma ($n = 23$)	Pituitary ($n = 8$)	Others ($n = 3$)
Preoperative volume (mL)				
Median (range)	11.7 (0.1–113.0)	13.0 (1.3–113.0)	1.5 (0.1–18.6)	26.2 (13.1–46.2)
Intraoperative				
Residual tumor vol. (mL), median (range)	1.7 (0–54.9)	3.5 (0–54.9)	0 (0–5.5)	1.7 (0.9–3.9)
Extent of resection				
%, Median (range)	85.8 (14.9–100)	69.1 (14.9–100)	100 (70.4–100)	91.6 (87.0–96.6)
GTR, *n* (%)	10 (29.4)	4 (17.4)	6 (75.0)	0 (0)
NTR, *n* (%)	5 (14.7)	3 (13.0)	0 (0)	2 (66.7)
STR, *n* (%)	19 (55.9)	16 (69.6)	2 (25.0)	1 (33.3)
Postoperative				
Residual tumor vol. (mL), median (range)	0 (0–30.4)	0 (0–30.4)	0.1 (0–4.1)	0 (0–1.6)
Extent of resection				
%, Median (range)	100 (19.4–100)	100 (19.4–100)	94.7 (64.3–100)	100 (87.8–100)
GTR, *n* (%)	19 (55.9)	13 (56.5)	4 (50)	2 (66.7)
NTR, *n* (%)	2 (5.9)	2 (8.7)	0 (0)	0 (0)
STR, *n* (%)	13 (38.2)	8 (34.8)	4 (50)	1 (33.3)
Additional resection, *n* (%)				
All	20 (58.8)	17 (73.9)	1 (12.5)	2 (66.7)
Meaningful	12 (35.3)	10 (43.5)	0 (0)	2 (66.7)
NTR→GTR	4 (11.8)	2 (8.7)	0 (0)	2 (66.7)
STR→GTR	7 (20.6)	7 (30.4)	0 (0)	0 (0)
STR→NTR	1 (2.9)	1 (4.3)	0 (0)	0 (0)

These unexpected locations could have potentially led to unnecessary re-operation if not caught by the iMRI. After iMRI scanning in our study, additional resection was performed in 24 (60%) patients. This demonstrated that iMRI delivers useful information allowing the surgeon to revise planning and perform additional resection during the same scheduled operation.

There were six cases where the surgeon chose to continue resection despite an expected iMRI result. This suggested that surgeons may initially take a more conservative approach and use iMRI findings along with re-registration of the neuro-navigation system to guide the final part of the resection. This practice offers a certain advantage because after the majority of the “laborious” part of the tumor is removed, the iMRI gives updated images of the remnant of the tumor. With a reduced volume of the tumor, the surgeon has a better orientation of the tumor to the surrounding eloquent structures. Along with the more accurate neuro-navigation system following re-registration, the surgeon can focus on fine-tuning the final resection. However, this practice may produce low initial EOR rates and overestimate the rate of EOR increase, which has been established in the literature.[5,8,9] Leroy et al has advocated exactly this staged approach in hemispheric glioma surgery, where the more definitive resection took place after iMRI scanning and neuro-navigation update.[24]

iMRI and EOR

Among 34 cases with pMRI results, when the surgeon decided to stop resection, the overall rate of GTR had reached 29.4%. With iMRI results, the surgeon opted to continue resection in 58.8% of the cases that resulted in meaningful additional resection of 35.3% and an increase in the overall GTR to 55.9%. This benefit was not equally distributed across all tumor types. In glioma, the additional resection was performed in 73.9% of cases and the rate of GTR increased from 17.4% to 56.5%. This underscores the infiltrative nature of glioma, which makes it indistinguishable from surrounding brain tissue even with the neuro-navigation technology. This is similar to other hemispheric glioma series where high-field iMRI-guided additional resection ranged from 25.9% to 68.4%.[8,9,13] The “others” group consisting of three cases of mixed tumor types also benefited from the iMRI with additional resection in two of the cases increasing GTR from 0% to 66.7%. The benefit was clearly lower for pituitary tumors where additional resection was performed in only one case without improvement of EOR. Our result in the pituitary group was in contrast to the published data where

Table 4 Correlation between iMRI and pMRI in cases without additional resection

Case	Diagnosis	Preop. intention	Preop. tumor volume (mL)	iMRI tumor volume (mL)	pMRI tumor volume (mL)	iMRI EOR	pMRI EOR
1	Parietotemporal astrocytoma	GTR	10.9	0	0	GTR	GTR
2	Lateral ventricle ependymoma	GTR	1.5	0	0	GTR	GTR
3	Temporal astrocytoma	GTR	11.5	0	0	GTR	GTR
4	Insular anaplastic oligodendroglioma	NTR	76.4	54.9	24.2	STR	STR
5	Frontal anaplastic oligodendroglioma	GTR	20	0	0	GTR	GTR
6	Pontocerebellar DMG*	STR	38.5	15.7	15.2	STR	STR
7	Cushing's disease	GTR	0.1	0	0	GTR	GTR
8	Cushing's disease	GTR	0.2	0	0	GTR	GTR
9	Cushing's disease	GTR	1.4	0	0.5	GTR	STR
10	Cushing's disease	GTR	1.5	0	0	GTR	GTR
11	Cushing's disease	GTR	0.8	0	0.1	GTR	STR
12	Non-secreting adenoma	GTR	9.4	1.9	1	STR	STR
13	Non-secreting adenoma	GTR	11.8	0	0	GTR	GTR
14	Clival chordoma	GTR	13.1	1.7	1.6	STR	STR
2				ICC = 0.861 (95% CI 0.566–0.955)†		Kappa's coefficient = 0.696‡	

Abbreviations: DMG, diffuse midline glioma; preop., preoperative.
†$p < 0.001$.
‡$p = 0.006$.

iMRI-guided additional resection occurred in 30% to 62% of cases with increase GTR of 3% to 20%.[17,25,26]

iMRI versus pMRI

The ability of iMRI to provide accurate data are important because there are several factors that can impact the correct interpretation of iMRI. Disturbance factors that can impact accuracy may include residual blood product, hemostatic materials, brain shift, intracranial air, and brain swelling.[27–29] As a result, the authors analyzed the correlation between iMRI and pMRI in the cases where additional resection was not performed. Among 14 cases with no additional resection, despite overall strong agreement of residual tumor volume[30] and substantial correlation of EOR,[31] there were two cases with false-negative results, both of which were Cushing's disease with residual tumor volume of 0.5 and 0.1 mL. This further explained the low additional resection rate in the pituitary group. The inaccuracy of high-field iMRI has previously been reported in the series of pituitary tumor surgery showing variation rates ranging from 16.4% to 28.1%.[16,32,33] The study comparing high-field iMRI to pMRI in other types of tumor is limited. Jankovski et al reported discrepancy of 21% between 3T iMRI and pMRI in their 23 cranial tumor cases.[34] Further investigations with a larger number of patients are warranted for a more definitive conclusion.

iMRI and Drawbacks

Despite the aforementioned benefits, iMRI also poses certain drawbacks and concerns. First, iMRI causes a major interruption to the operation due to the temporary closure and covering of the surgical field, removal of surgical instruments and retractors, and transportation of the patient into the bore of an iMRI. After iMRI scanning, the surgical field has to be re-draped and re-opened, surgical instruments, and retractor system are re-assembled before the operation is resumed. In our study, although the average scanning time was approximately 36 minutes, the average duration of the entire interruption was over 80 minutes. This interruption remained constant even with more experienced operating room personnel. This can lead to the issues of operating room utilization, increased anesthetic time, and concerns of surgical infection. Moreover, it causes major inconveniences to repeat iMRI several times per operation, which is why all cases in our study had only one iMRI scan. This duration of interruption is considerably longer as compared with other assisting technologies such as intraoperative ultrasound or intraoperative fluorescence, which pose very minimal or no interruption. Future studies to improve case selection may help maximize the benefit of iMRI utilization.

Second, the risk of increased neurological deficit due to more aggressive resection-guided by iMRI is also a concern. However, as long as the surgeon remains cognizant of the eloquent areas or utilizes neurophysiological monitoring when indicated, the incidence of neurological decline has been found no different from conventional operations.[7,12,35] The overall rate of neurological deterioration in the present study was 25% with permanent deficit of 10% which is similar to conventional surgery in our institute.[36,37]

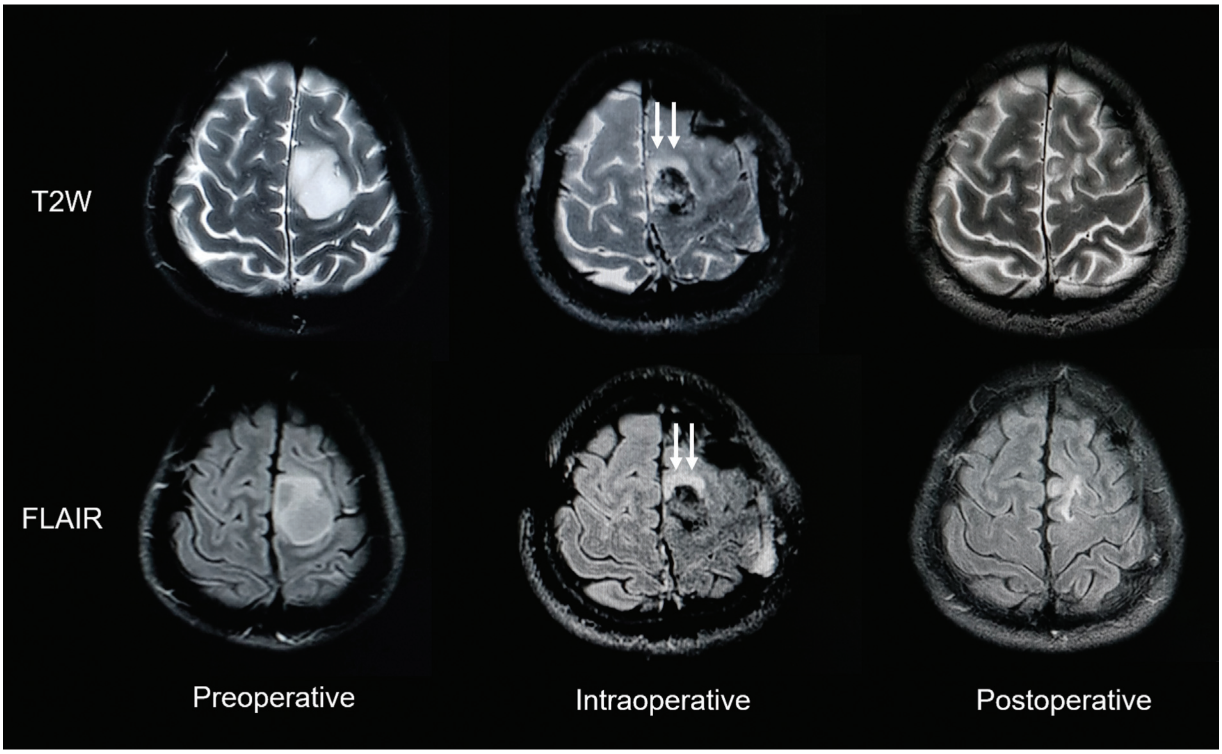

Fig. 2 Case 1: Left medial frontal low-grade astrocytoma located anteriorly to the precentral gyrus. After initial resection, iMRI shows residual tumor at the anterior border of the cavity (*double arrow*). Following additional resection, postoperative MRI shows no residual tumor.

Third, although there is a concern for sterility breach during preparatory process and around the time of iMRI scanning, the rate of postoperative surgical infection and neurological complications in the present study was not different from conventional cranial surgery.[38,39]

Illustrative cases

Case 1: A 27-year-old male patient with left medial frontal low-grade astrocytoma presented with 2-month history of epilepsy. After initial resection, iMRI showed residual tumor at the anterior border of the resection cavity. Additional tumor removal resulted in gross total resection. There was no postoperative neurological deficit (►**Fig. 2**).

Case 2: A 52-year-old female patient with recurrent right temporal glioblastoma. After initial resection, iMRI showed residual tumor located anteriorly. The patient underwent additional tumor removal and postoperative MRI showed no residual tumor. There was no postoperative neurological deficit (►**Fig. 3**).

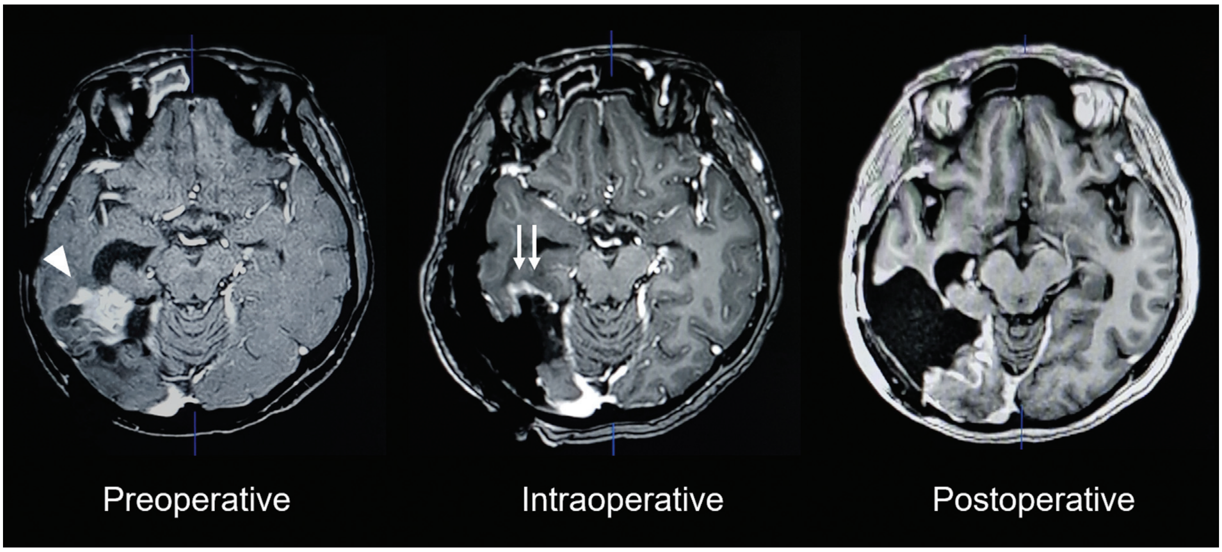

Fig. 3 Case 2: Recurrent right temporal glioblastoma (*arrow head*). After initial resection, iMRI shows residual tumor at the anterior border of the cavity (*double arrow*). Following additional resection, postoperative MRI shows no residual tumor.

The present study has demonstrated iMRI data can help the surgeon make more informed decisions and improve planning in several ways: (1) iMRI provides objective EOR as the surgeon's perception is not always reliable and surgeons frequently overestimate the EOR, (2) iMRI gives the location of residual tumors which may be overlooked, (3) iMRI allows the surgeon to initially perform a conservative resection and approach the final or critical part of the resection after reviewing an updated anatomy from iMRI scanning, and (4) iMRI provides an updated image set to the neuro-navigation system to account for the altered anatomy.

There are limitations to the study worth mentioning. The retrospective nature of this study incurs many patient selection biases. A small number of cases, an uncontrolled design, and heterogeneity of the tumors in this study prevented a stronger conclusion of the impact of iMRI. The authors also did not take into account the financial aspect of iMRI, which is a well-known barrier to implementation of this intraoperative technology.[40]

Conclusion

In cranial tumor surgery, the surgeon's assessment of EOR is frequently imprecise. iMRI data can improve this precision by identifying the presence of residual tumors, providing tumor locations, giving spatial relations data of the tumor to nearby eloquent structures, and updating the neuro-navigation system for the final stage of tumor resection.

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Conflicts of Interest
None declared.

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References

1 Black PM, Alexander E III, Martin C, et al. Craniotomy for tumor treatment in an intraoperative magnetic resonance imaging unit. Neurosurgery 1999;45(03):423–431, discussion 431–433
2 Bisdas S, Roder C, Ernemann U, Tatagiba MS. Intraoperative MR iaging in neurosurgery. Clin Neuroradiol 2015;25 (Suppl 2):237–244
3 Coburger J, Merkel A, Scherer M, et al. Low-grade glioma surgery in intraoperative magnetic resonance imaging: results of a multicenter retrospective assessment of the German Study Group for Intraoperative Magnetic Resonance Imaging. Neurosurgery 2016; 78(06):775–786
4 Fountain DM, Bryant A, Barone DG, et al. Intraoperative imaging technology to maximise extent of resection for glioma: a network meta-analysis. Cochrane Database Syst Rev 2021;1:CD013630
5 Kubben PL, ter Meulen KJ, Schijns OE, ter Laak-Poort MP, van Overbeeke JJ, van Santbrink H. Intraoperative MRI-guided resection of glioblastoma multiforme: a systematic review. Lancet Oncol 2011;12(11):1062–1070
6 Rao G. Intraoperative MRI and maximizing extent of resection. Neurosurg Clin N Am 2017;28(04):477–485
7 Senft C, Bink A, Franz K, Vatter H, Gasser T, Seifert V. Intraoperative MRI guidance and extent of resection in glioma surgery: a randomised, controlled trial. Lancet Oncol 2011;12(11): 997–1003
8 Hatiboglu MA, Weinberg JS, Suki D, et al. Impact of intraoperative high-field magnetic resonance imaging guidance on glioma surgery: a prospective volumetric analysis. Neurosurgery 2009;64 (06):1073–1081, discussion 1081
9 Kuhnt D, Ganslandt O, Schlaffer SM, Buchfelder M, Nimsky C. Quantification of glioma removal by intraoperative high-field magnetic resonance imaging: an update. Neurosurgery 2011;69 (04):852–862, discussion 862–863
10 Lewin JS, Nour SG, Meyers ML, et al. Intraoperative MRI with a rotating, tiltable surgical table: a time use study and clinical results in 122 patients. Am J Roentgenol 2007;189(05): 1096–1103
11 Nimsky C, Fujita A, Ganslandt O, Von Keller B, Fahlbusch R. Volumetric assessment of glioma removal by intraoperative high-field magnetic resonance imaging. Neurosurgery 2004;55 (02):358–370, discussion 370–371
12 Olubiyi OI, Ozdemir A, Incekara F, et al. Intraoperative magnetic resonance imaging in intracranial glioma resection: a single-center, retrospective blinded volumetric study. World Neurosurg 2015;84(02):528–536
13 Mohammadi AM, Sullivan TB, Barnett GH, et al. Use of high-field intraoperative magnetic resonance imaging to enhance the extent of resection of enhancing and nonenhancing gliomas. Neurosurgery 2014;74(04):339–348, discussion 349, quiz 349–350
14 Alhilali LM, Little AS, Yuen KCJ, et al. Early postoperative MRI and detection of residual adenoma after transsphenoidal pituitary surgery. J Neurosurg 2020;134(03):761–770
15 Pala A, Durner G, Braun M, Schmitz B, Wirtz CR, Coburger J. The impact of an ultra-early postoperative MRI on treatment of lower grade glioma. Cancers (Basel) 2021;13(12):13
16 Fahlbusch R, Keller Bv, Ganslandt O, Kreutzer J, Nimsky C. Transsphenoidal surgery in acromegaly investigated by intraoperative high-field magnetic resonance imaging. Eur J Endocrinol 2005; 153(02):239–248
17 Hlaváč M, Knoll A, Mayer B, et al. Ten years' experience with intraoperative MRI-assisted transsphenoidal pituitary surgery. Neurosurg Focus 2020;48(06):E14
18 Ginat DT, Swearingen B, Curry W, Cahill D, Madsen J, Schaefer PW. 3 Tesla intraoperative MRI for brain tumor surgery. J Magn Reson Imaging 2014;39(06):1357–1365
19 Giordano M, Samii A, Lawson McLean AC, et al. Intraoperative magnetic resonance imaging in pediatric neurosurgery: safety and utility. J Neurosurg Pediatr 2017;19(01):77–84
20 Rogers CM, Jones PS, Weinberg JS. Intraoperative MRI for brain tumors. J Neurooncol 2021;151(03):479–490
21 Schulder M, Carmel PW. Intraoperative magnetic resonance imaging: impact on brain tumor surgery. Cancer Contr 2003;10 (02):115–124
22 Scherer M, Jungk C, Younsi A, Kickingereder P, Müller S, Unterberg A. Factors triggering an additional resection and determining residual tumor volume on intraoperative MRI: analysis from a prospective single-center registry of supratentorial gliomas. Neurosurg Focus 2016;40(03):E4
23 Lau D, Hervey-Jumper SL, Han SJ, Berger MS. Intraoperative perception and estimates on extent of resection during awake glioma surgery: overcoming the learning curve. J Neurosurg 2018;128(05):1410–1418
24 Leroy HA, Delmaire C, Le Rhun E, Drumez E, Lejeune JP, Reyns N. High-field intraoperative MRI in glioma surgery: a prospective study with volumetric analysis of extent of resection and functional outcome. Neurochirurgie 2018;64(03):155–160
25 Juthani RG, Reiner AS, Patel AR, et al. Radiographic and clinical outcomes using intraoperative magnetic resonance imaging for

transsphenoidal resection of pituitary adenomas. J Neurosurg 2020;134(06):1824–1835

26 Zaidi HA, De Los Reyes K, Barkhoudarian G, et al. The utility of high-resolution intraoperative MRI in endoscopic transsphenoidal surgery for pituitary macroadenomas: early experience in the advanced multimodality image guided operating suite. Neurosurg Focus 2016;40(03):E18

27 Edjlali M, Ploton L, Maurage CA, et al. Intraoperative MRI and FLAIR analysis: implications for low-grade glioma surgery. J Neuroradiol 2021;48(01):61–64

28 Hirschl RA, Wilson J, Miller B, Bergese S, Chiocca E. The predictive value of low-field strength magnetic resonance imaging for intraoperative residual tumor detection. Clinical article. J Neurosurg 2009;111(02):252–257

29 Knauth M, Aras N, Wirtz CR, Dörfler A, Engelhorn T, Sartor K. Surgically induced intracranial contrast enhancement: potential source of diagnostic error in intraoperative MR imaging. Am J Neuroradiol 1999;20(08):1547–1553

30 Koo TK, Li MY. A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. J Chiropr Med 2016;15(02):155–163

31 Landis JR, Koch GG. The measurement of observer agreement for categorical data. Biometrics 1977;33(01):159–174

32 Fomekong E, Duprez T, Docquier MA, Ntsambi G, Maiter D, Raftopoulos C. Intraoperative 3T MRI for pituitary macroadenoma resection: Initial experience in 73 consecutive patients. Clin Neurol Neurosurg 2014;126:143–149

33 Hannan CJ, Daousi C, Radon M, Gilkes CE. 3 Tesla intra-operative MRI as an adjunct to endoscopic pituitary surgery: an early assessment of clinical utility. Br J Neurosurg 2021. Doi: 10.1080/02688697.2021.1981237

34 Jankovski A, Francotte F, Vaz G, et al. Intraoperative magnetic resonance imaging at 3-T using a dual independent operating room-magnetic resonance imaging suite: development, feasibility, safety, and preliminary experience. Neurosurgery 2008;63 (03):412–424, discussion 424–426

35 Patel KS, Yao Y, Wang R, Carter BS, Chen CC. Intraoperative magnetic resonance imaging assessment of non-functioning pituitary adenomas during transsphenoidal surgery. Pituitary 2016;19(02):222–231

36 Bunyaratavej K, Sangtongjaraskul S, Lerdsirisopon S, Tuchinda L. Continuous physical examination during subcortical resection in awake craniotomy patients: its usefulness and surgical outcome. Clin Neurol Neurosurg 2016;147:34–38

37 Bunyaratavej K, Wangsawatwong P. Catheter guided cerebral glioma resection combined with awake craniotomy: its usefulness and surgical outcome. Br J Neurosurg 2019;33(05): 528–535

38 Ahmadi R, Campos B, Haux D, Rieke J, Beigel B, Unterberg A. Assessing perioperative complications associated with use of intraoperative magnetic resonance imaging during glioma surgery - a single centre experience with 516 cases. Br J Neurosurg 2016;30(04):397–400

39 Lu CY, Chen XL, Chen XL, Fang XJ, Zhao YL. Clinical application of 3.0 T intraoperative magnetic resonance combined with multimodal neuronavigation in resection of cerebral eloquent area glioma. Medicine (Baltimore) 2018;97(34):e11702

40 Eljamel MS, Mahboob SO. The effectiveness and cost-effectiveness of intraoperative imaging in high-grade glioma resection; a comparative review of intraoperative ALA, fluorescein, ultrasound and MRI. Photodiagn Photodyn Ther 2016;16:35–43