Chapter

Intraoperative MRI in Brain Tumor Surgeries

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Abstract

Intraoperative MRI (ioMRI) has evolved since it used in 1991. ioMRI has been effective tool not only in glioma surgeries but also in other neurosurgical procedures. It provides real time information with high quality resolution and it is not affected by brain shift. ioMRI images can be uploaded in the navigation which helps in further resection of residual tumors. ioMRI can be used for confirmation of complete excision of tumor or location of microelectrode catheter tip DBS/sterotatic biopsy. It provides valuable information like location and amount of residue which guides surgeon for further resection safely as possible. ioMRI requires specialized operation theater with MRI compatible instruments which makes this setup expensive and it is available in only few centers across the globe.

Keywords: Intraop MRI, glioma surgery, MRI guided resection

1. Introduction

In 1991 at the Brigham and Women's hospital first intraoperative MRI (ioMRI) was used. Since then, its use and techniques have evolved. It is the most accurate imaging in intraoperative setting as it provides the real time information of tumor residue and guides further resections even if anatomy is distorted by brain shift [1]. The extent of resection is a prognostic factor in most tumor surgeries, like surgery for gliomas. These patients will benefit from ioMRI. The role of ioMRI is not only restricted to gliomas but other tumors/procedures as well. Designated operation theaters, operative instruments and MRI-compatible monitoring devices were required for ioMRI which has made this an expensive modality, with only few centers in the world able to afford such a facility. In this chapter we will discuss about types of ioMRI, anesthesia considerations and its role in different types of neurosurgical procedures.

2. Evolution and types of ioMRI

The first intraoperative MRI for neurosurgical operations, was developed in 1991 by the combined efforts of the Departments of Neurosurgery and Radiology of the Brigham & Woman's Hospital of the Harvard Medical School in Boston and the General Electric Medical Systems [2]. It was 0.5 T open type. Low field open type with Horizantal gap MRI was used for interventional procedures by Gronemeyer and colleagues [2, 3] which provided access to patients. Later Vertical gap MRI was developed which increased patient access and was used for various interventional, endoscopic and open surgeries. Many MRI compatible equipment had been developed since then along with ioMRI, with all ferromagnetic instruments replaced with titanium. The main drawback for open type configuration has been low field strength of magnet which does not yield good image resolution. Both vertical and horizontal systems had double doughnut magnets. The IMRIS system was developed later by a neurosurgeon, Dr. Garnette Sutherland of Calgary, Alberta, Canada. This system offered a uniquerail-mounted MRI system in which the scanner could be mobilized to the patient. It was closed type 1.5 T ceiling mounted rail system, which was moved between two rooms [4].

ioMRI scanner can be open or closed type. Open type (with horizontal gap or vertical gap) has better access to patient while compromising on image quality. Closed type (small bore or long bore) has better quality of images with no access to the patient.

Based on field strength ioMRI are classified as low field (0.2 T), mid field (0.5 T) and high field (1.5 T & 3 T). Low-field systems are the GE Signa, the Hitachi 0.3 tesla system, and the Polestar0.15 tesla system. SIGNA SP 0.5 T is a midfield ioMRI system. High-field systems are Siemens Brain Suite, IMRIS system, and the Philips systems. High field ioMRI provides good quality of images with better spatial and contrast resolution with precision and some of the studies like perfusion, DTI and fMRI are possible compared to low or mid field ioMRI [5, 6].

The imaging in ioMRI can be truly intraoperative or interoperative in nature. Intraoperative imaging is done while surgery is ongoing in the scanner without any interruption of procedure. Horizontal and vertical donut models were used for it. These are mid field ioMRIs. These are the actual real time imaging which were performed during the surgery similar to fluoroscopy. The draw backs of this system were poor image quality, need of MRI compatible instruments including microscope, navigation which were very expensive and space constrains for movement. In interoperative imaging, surgery is stopped temporarily and either patient or gantry mobilized to acquire images. This type has been developed more commercially as there is no need for continuous intraoperative imaging and imaging is required only for certain periods like, to confirm extent of resection, location of residue or guiding further resection. This type allows installation of high field strength MRI in the area near the operating room or within the same room with operating table outside of the 5 gauss line. This allows surgeon to use non-MRI compatible instruments during surgery. Patient transportation is the main drawback which takes 20–40 minutes and requires proper trained staff [4].

High field ioMRI operative rooms (OR) are of different types. First type was IMRIS. In this type MRI was rail mounted and placed between two operating rooms and mobilized into the OR when required. During imaging instruments moved beyond the 5 gauss line. The operating rooms had to be RF shielded to acquire good images. Second type was RF shielded OR in which MRI and operating table are in the same room, when imaging is required, patient is moved into gantry to require images. This type has a rotating table, during surgery head end of the table is beyond 5 gauss line. When imaging is planned table is rotated so that head goes into the gantry. This was developed by Siemens and BrainLab companies combined. BRAIN SUITE is an integrated operative area away from the magnet in which interventional procedures can be done. MRI compatible instruments are not required.

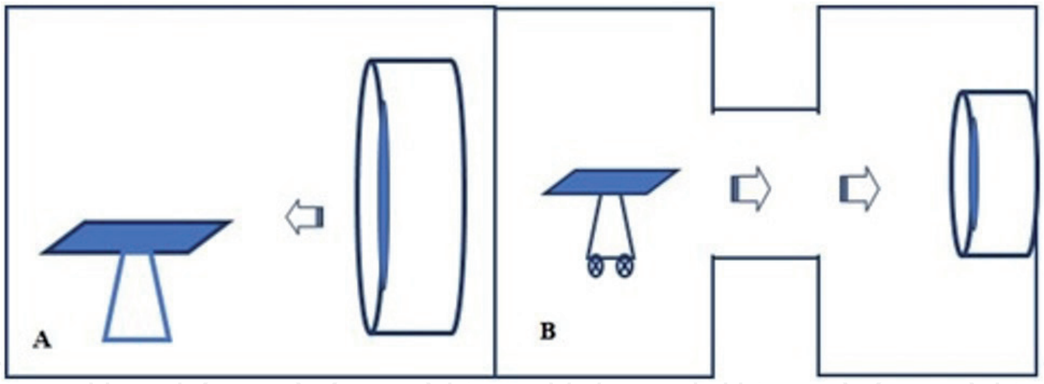

Figure 1.
Representational images. A. RF shielded ioMRI OT in which MRI moved towards operating table B. Nearby OT model, in this model patient shifted on mobile MRI compatible table top.

It also has incorporated Neuronavigation with auto registration. All of these systems are possible in high volume centers or in institutes with research interest, as the cost is prohibitive [4]. Other more commercially viable concept is "nearby OT type" –in which MRI machine is fixed in separate room adjacent to OR and operating table is transferred into MRI suite. In nearby OT type, the MRI can be used for imaging other patients through separate entry to access the MRI which can be cost effective. Whenever ioMRI is planned the MRI is room is cleaned and sterilized, the outside entry is closed and OR entry is opened to receive the patient in operative position draped, under anesthesia. All these require special protocols, trained staff, and proper communication between MRI technician, surgeon, anesthesiologist and OT staff.

Authors are using "Nearby OT model" – Siemens 3 T ioMRI and have found to be cost effective. Initially it took around 85.6 minutes for shifting in and out ioMRI and restart surgery which latter reduced to 37.4 minutes by multiple mock drills and continuous training of involved staffs [7, 8] (**Figure 1**).

3. Anesthesia considerations

The main challenge during ioMRI anesthesia is to have uninterrupted access to the patient while allowing high-quality real-time MRI images with minimal electrical noise interference. All standard monitors, equipment and anesthesia workstation should have minimal electrical noise interference and MRI compatible. Monitors can be classified as MRI unsafe (prohibited inside suite), MRI conditional (permitted not beyond 5 Gauss line inside the MRI suite), MRI safe (can be allowed freely inside the suite) [9].

Anesthetist should be aware of ECG changes like ST segment changes, P wave abnormalities, AF, Ventricular fibrillation can happen due to static magnetic field, pulse gradient and high frequency field. If these changes occur along with hemodynamic instability then it should be managed accordingly.

All patients should be screened for any metallic objects, piercings, tattoos (lead), metallic implants, pacemakers, deep brain stimulators, implantable defibrillator, vagal stimulator, aneurysmal clips during pre-operative assessment to know the MRI compatibility.

During ioMRI patient access is limited and so all IV lines and tubings should be long, tightly fixed and secured. Proper checklist has to be followed to avoid mishaps and accidents. Anesthesia depth has to be maintained throughout the procedure either with intravenous or inhalational anesthesia. Nitin et al. [10] reported thermal injuries due to radio frequency energy. It can be avoided with skin to skin packing, avoiding looping of wires, lines and tubing. Noncompatible equipment (Temperature probe and depth monitors and flexometallic tubes) are removed. Nitin Manohar et al. [11] also reported that IONM electrodes can interfere with the signals and produce artifacts affecting the image quality. Patient positioning for ioMRI requires additional attention. Position should be tailored so that head fixed to the head clamp moves freely within the ioMRI bore. ioMRI compatible Mayfield clamps are used for positioning and final position should be confirmed with bore gauge that is provided along with ioMRI compatible operative table, to avoid possible collision with the gantry. During awake procedure or surgery, preoperative counseling regarding the MRI sound, use of ear plugs and sedation should be done.

Emergency drugs should be ready in case of contrast induced reactions or hemodynamic instability during the scan. Mock drills to cope up with emergency situations for all OT and MR staff should be done with everyone knowing all steps and well versed in their roles with even quenching of MRIif needed (**Figures 2** and **3**) (Box 1).

Figure 2.
MRI compatible instruments A. Laryngoscopes, B. Monitor, C. Ventilator, D. Infusion pump and E. ECG electrodes.

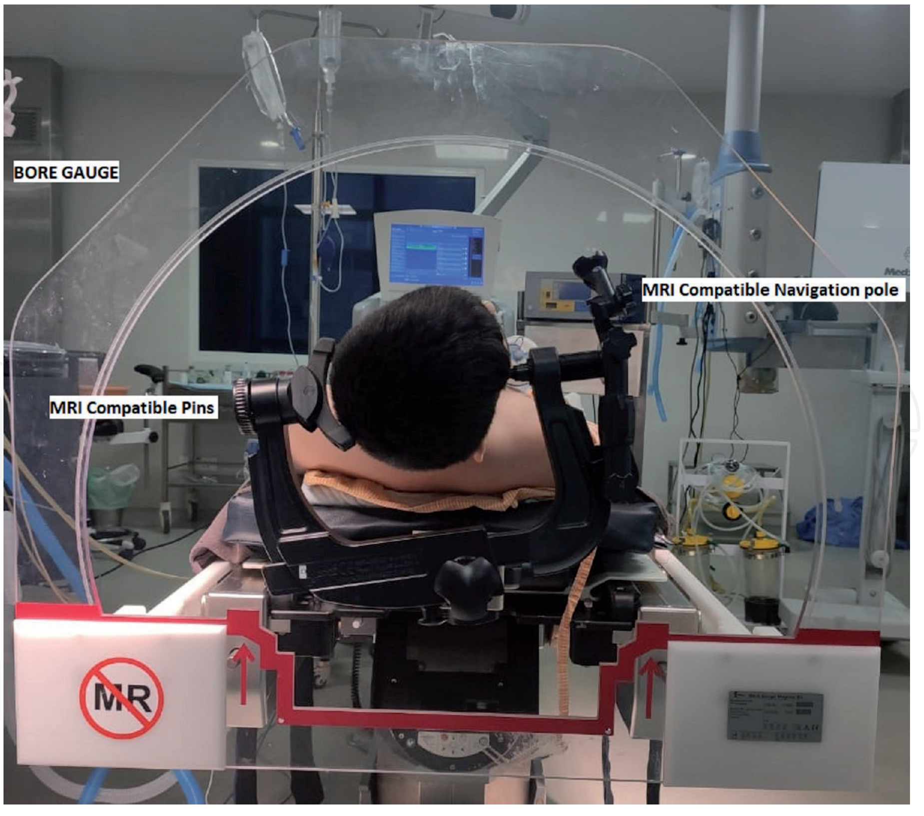

Figure 3.
Positioning of patient in operative table with MRI compatible Mayfield clamps and navigation probe. Final position is confirmed using bore gauge so that patient moves in and out of MRI machine freely.

CHECKLIST FOR INTRA-OP MRI:

(To be Completed mandatorily prior to Wheeling-1a; Please Tick on the boxes on checklist completion)

- MRI Compatible ECG electrodes: ☐
- No metallic ornaments: ☐
- No metallic Implants, Heart valves, Pacemakers in patient: ☐
- Arms insulated from body: ☐
- Padding from skin to skin: ☐
- No staplers, sand bags, metal objects in sheets, sisters check done: ☐
- OT table sheets tucked under to help sliding: ☐
- Temp probe removed: ☐
- Bag free: ☐
- Warmer disconnected: ☐
- Antibiotic repeated: ☐
- Inform MRI Technician: ☐
- Cautery pad removed: ☐
- Emergency drugs box sent in: ☐
- OT personnel moving into the MRI Suite screened for metallic objects: ☐
- MRI Compatible Monitor Ready: ☐
- MRI Anaesthesia Machine SWITCHED "ON" CHECKED: ☐
- OT Table & MRI Table ALIGNED & LEVELLED ☐
- Infusion pump casing: ☐
- Long breathing circuit (Double): ☐
- Long IV line extension (200 ml): ☐
- Long infusion extension (200 ml): ☐
- AMBU, Bains circuit ready ☐
- Compatible Laryngoscope Ready: ☐
- Relaxant bolus ☐

Box 1.
ioMRI checklist.

4. Role of ioMRI in neurosurgery

It is useful in both intra and extra axial tumors. Depending upon the situation ioMRI can be used as completion study, residue seeking or guidance for further resection. It is also used in epilepsy surgery, deep brain stimulation (DBS), sterotactic biopsies. Apart from extent of resection and location of residue, ioMRI also gives us information like hematoma in and around operative cavity, ischemia (diffusion restriction), hydrocephalus, location of electrode tips in DBS, proximity to neurovascular bundles which guides surgeon for further planning and proceeding in the same sitting of surgery.

4.1 Intraaxial tumors

Gliomas are the most common primary brain tumors. These are infiltrating tumors along the subcortical white fibers. In low grade gliomas it is difficult to differentiate from adjacent normal tissue. During surgery extended resection can cause neurological deficits or inadequate resection may leave significant residue which can progress, decreasing overall survival of the patient. Preoperatively MRI is usually done in patients with glioma which gives us valuable information about the nature of the lesion. Important sequences being FLAIR, contrast study, perfusion study, DTI, functional MRI (fMRI)and spectroscopy. Information from these sequences are compared with the ioMRI providing the valuable information for improving the safety and efficacy of the resection [12–14].

ioMRI is an ideal tool for the resection of low grade gliomas (LGGs) because of their superior resolution in differentiating tumor from the surrounding brain, it allows accurate localization of residual tumor. It allows near-real-time assessment of extent of resection and also allows correcting for the brain shift, a disadvantage for Neuronavigation, which happens as surgery progresses. In LGGs, ioMRI flair sequence compared with preoperative image shows the residual tumor. Perfusion study will demonstrate the hyperperfusing area around the surgical cavity and thereby increase the extent of resection. In high grade gliomas (HGGs) usually the lesions are contrast enhancing, post-contrast study in ioMRI will show us the extent of resection of contrast enhancing tumor. Perfusion study helps us to identify the hyperperfusing areas in the non-enhancing part of HGGs which can be resected. Resecting hyperperfusing areas in HGGs will definitively increase the extent of resection and thereby increasing progression free survival [12–14] (**Figures 4** and **5**).

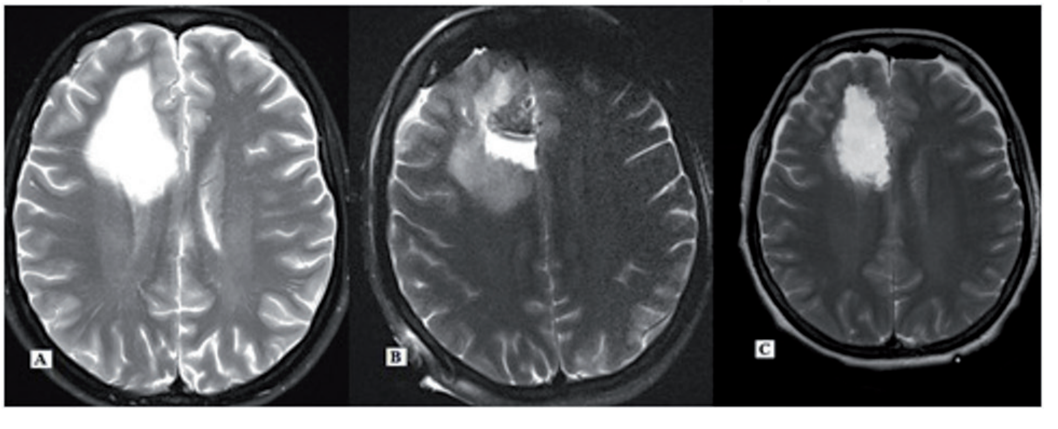

Figure 4.
A. Preoperative MRI of a patient showing T2 hyperintense LGG involving right medial frontal lobe B. ioMRI showing residue around the surgical cavity which was excised in the same sitting. C. Post-op MRI showing.

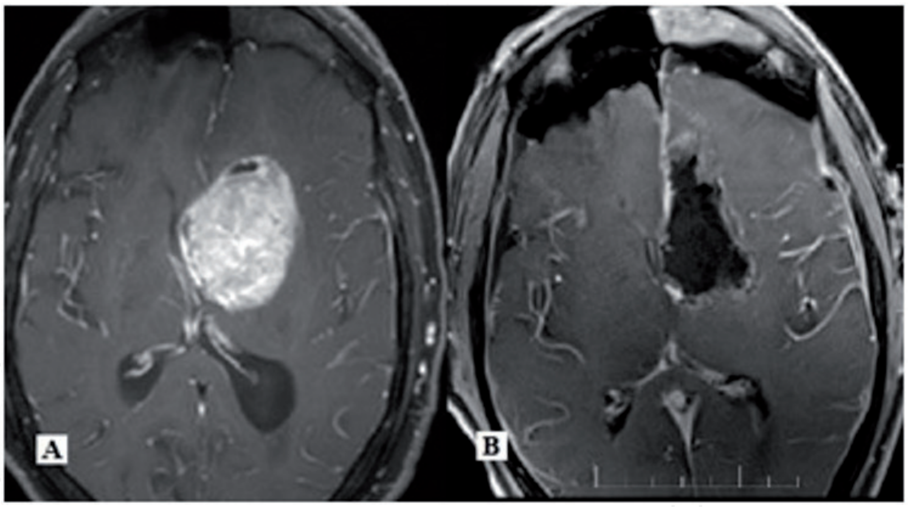

Figure 5.
A. Preoperative MRI of patient with high grade lesion which was contrast enhancing, involving left caudate and periventricular region. B. ioMRI shows no residue of the contrast enhancing lesion.

ioMRI is a valuable tool in awake craniotomy. ioMRI shows the location of residual tumor and one can perform fMRI to correlate its position with eloquent areas. If the residue is in the region of BOLD signals of fMRI then one can leave behind the residue without causing any permanent neurological deficits. Intraoperative neuromonitoring will guide us the intactness of long fiber tracts. ioMRI in intra-axial tumors involving or in proximity with these tracts will tell us the extent of residue as well as the intactness of tract using DTI imaging. During resection of the intraaxial tumors, sometimes the wall of cavity collapses and blinds a part of tumor. Deep seated tumor or tumorat difficult angles/corners may be left behind. These tumor residues can be located and resected with ioMRI guidance with additional navigation support from the newly acquired images [12–14].

In the prospective studies done by Senft and colleagues [15] and Hatiboglu and colleagues [16] with ioMRI guidance, it was established that the MRI group had a complete resection of their enhancing tumor compared with the control group [4, 16]. Also in nonenhancing tumors Hatiboglu and colleagues showed increased complete resection from 63–80% with the help of ioMRI [16]. Pamir MN et al. studied 56 patients of LGG who underwent resection with ioMRI. They found that the use of ioMRI increased the number gross total resection of from 31 to 41, up by 32.3% [17]. Coburger and colleagues in their multicenter retrospective assessment of LGGs surgery under ioMRI guidance showed that high-field ioMRI was significantly associated with gross total resection (GTR). WithGTR in 85% of cases compared with 57% with a low-field ioMRI [18]. Similarly ioMRI also used in other intraaxialtumorsandintraventicular tumors, which guides the extent of resection and location of residue.

With ioMRI we had achieved significant reduction in residual tumor volume. The mean residual tumor volume improved from 22.5 cm^3 to 11.7 cm^3 after ioMRI in 29 patients of LGGs. Also the overall extent of resection improved from 72.9% to 88.4% with ioMRI.

4.2 Extraaxial tumors

4.2.1 Sella-suprasellar tumors

ioMRI role is well established in the pituitary tumors. It is important for both functional and nonfunctional pituitary adenomas. With the advent of endoscopic

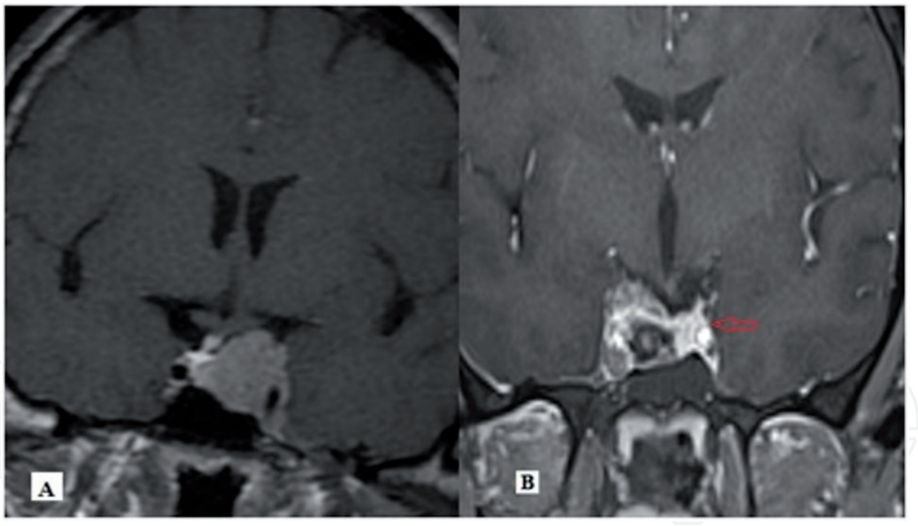

Figure 6.
A. Pre-operative MRI showing pituitary macroadenoma B. ioMRI showing residue (arrow) in left side which was removed in the same sitting after ioMRI.

pituitary excision the extent of resection has significantly increased compared to that of the microscopic approach, though the complete excision is still around 50–60%. The residual disease is strongly associated with complications like postoperative hemorrhage, need for adjuvant radiotherapy or hormonal therapy, significant higher risk of adenoma regrowth and possibly reduced life expectancy. Thus Gross total resection is recommended for both NFPAs and FPAs. With ioMRI one can locate the residue and chase it. In functional adenomas complete resection is mandatory to achieve cure, with ioMRI it is achievable. With ioMRI normal pituitary can be identified and preserved so that we can avoid post-operative hypopituitarism [19–21].

In various large series involving non-iMRI-guided transsphenoidal endoscopic resection of pituitary tumors, Dehdashti AR et al. [22] reported gross total resection of 79% and Serra C et al. [23] reported between 44–88%, while on analysis of studies that involved iMRI guided eTSS for PAs, average initial gross total resection rates at iMRI was only 51% which was increased to 73% help of ioMRI guided resection [24]. Berkmann et al. [25] observed new onset hypopituitarism of any one of the axes in 29% patients in iMRI guided resection group versus 45% in control group operated without iMRI guidance. They also observed that post-operatively RT was required in 3 patients in group without ioMRI compared to that none of the patients in ioMRI group.

ioMRI also used in craniopharyngiomas, one can assess whether adequate decompression has been achieved like decompression of optic chiasm. It also gives us information about contrast enhancing residue if any that is accessable for resection.

In our centre with ioMRI, we achieved gross total resection rate from 52–80% (p value <0.05) in 57 patients of pituitary macroadenoma (**Figure 6**).

4.2.2 Other extra axial lesions

Large extra axial lesions in the CP angle and skull base are difficult to excise completely due to its relations with cranial nerves, blood vessels and vital neural structures like brainstem. Due to its complexitysometimes surgeons lose the direction or leave behind large residues. In such cases ioMRI gives valuable information about volume and location of the residual lesion. When gross total resection of skull base lesions is not feasible then ioMRI can be a used for tailored tumor resection.

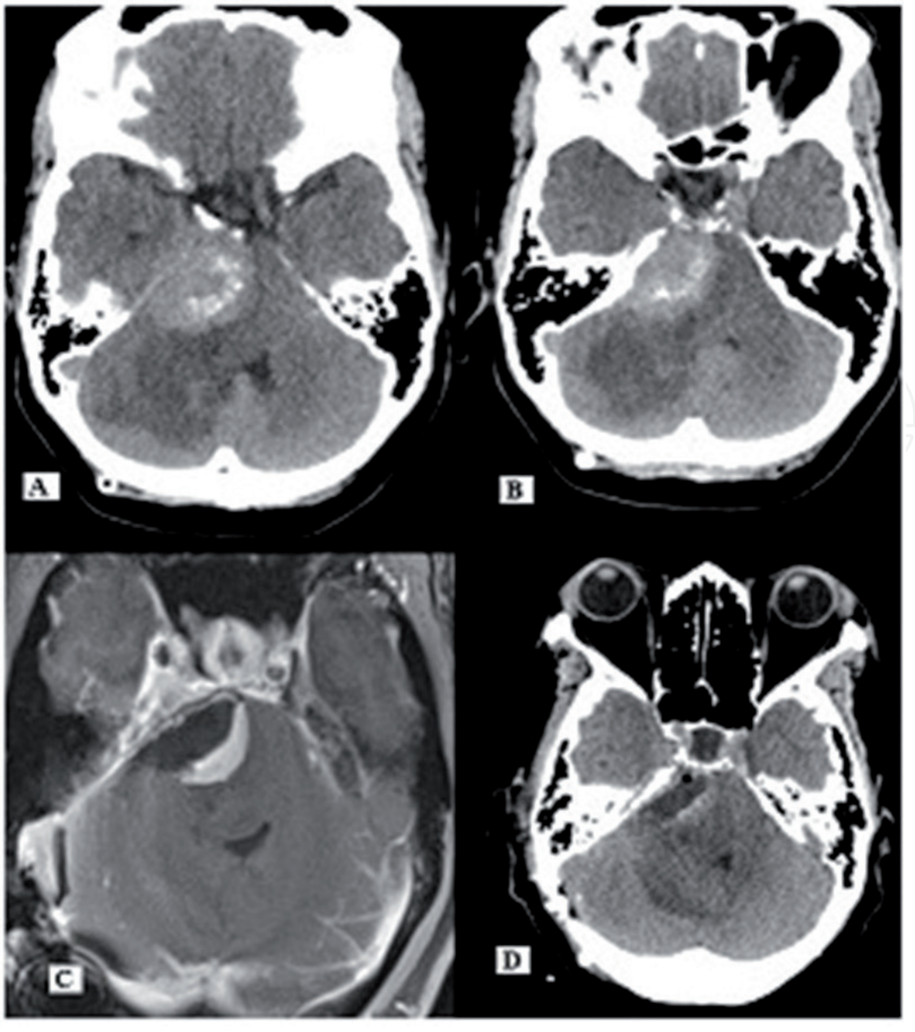

Figure 7.
A&B preoperative CT image showing CP angle meningioma, C. ioMRI showing the residue along the brainstem which was difficult to mobilize hence it was left behind and size was less than 2 cm which was subjected for SRT, D post-operative CT showing residue without any operative site hematoma. In this patient ioMRI helped to guide the surgeon to stop further resection and safely subjected for SRT without causing any neurological deficits.*

With ioMRI one can achieve maximum safe resection and decrease the size of residue so that it can become suitable for sterotactic radiosurgery [26] (**Figure 7**).

Mario Giordano et al. [27] recruited 19 patients of para-sellar meningiomas includes clinoidal, tuberculum sellae, and cavernous sinus who underwent surgical resection using intraoperative MRI. In 7(37%) of 19 patients, further tumor resection was performed based on information from the ioMRI. 56% of patients with cavernous sinus meningioma benefited by ioMRI by further safe resection of tumor. Dr. Chakraborty et al. [28] conducted a retrospective review of 70 operations performed on 66 patients with intracranial meningiomas. Among them 30 were skull base meningiomas. 9(12.8%) patients required additional tumor resection based on ioMRI findings, and in 4 patients (6%), ioMRI imaging allowed for the avoidance of further dissection near-critical neurovascular structures (**Figure 8**).

Hussam Metwali et al. [29] performed a retrospective analysis of 15 patients with skull base chordomas with ioMRI. 8 patients had complete resection confirmed by ioMRI. Out of 7 patients 3 hadtumor residual requiring further resection was located in the clivus and in 4 patients in the intradural space. All the intradural residue patients had significant improvement in preoperative deficits which was possible with ioMRI guidance for locating the residue. Joseph C. Dort et al. [30] did a prospective, non-randomized, cohort study on 31 patients with skull base lesions.

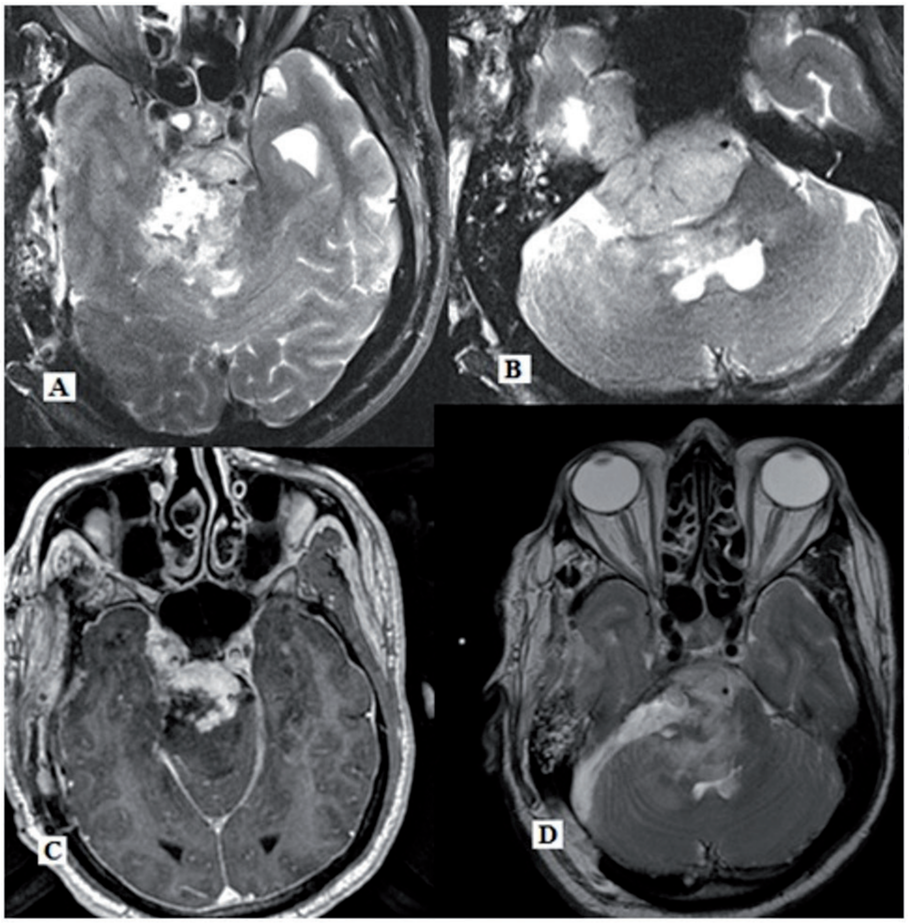

Figure 8.
A&B ioMRI images of sphenopetroclival meningioma, initially tumor was decompressed by subtemporal approach but due to intra operative bleeding and hard calcified which was unable to mobilize. In this case ioMRI helped surgeon to approach by retromastoid craniotomy and achieve further resection of tumor as safely as possible in the same sitting. C&D. post-operative MRI images showing residual tumor. Volume of the residue is significantly reduced compared to that of in ioMRI.

All these patients underwent surgery in a 1.5-Tesla ioMRI suite. 11 out of 31 patients surgical course altered with the help of ioMRI and maximum safe resection was achieved. ioMRI is a valuable adjunct to skull base surgery.

In our center we did ioMRI in 30 skull base meningiomas. 16 patients had residual lesion, of which 12 patients had subjected for further resection in same sitting. They had significant reduction in volume of residual lesion. we achieved Simpson grade 2 excision in 6 out of 12 patients. Other 4 patients, residual lesion was not chased due to its proximity to neurovascular structures.

5. Other neurosurgical procedures

Epilepsy surgery has evolved over the past few decades. ioMRIisalso a valuable tool to achieve complete resection of abnormal areas especially those with lesions. Nilesh S. Kurwale et al. [31] studied on role of ioMRI in achieving seizure control in 39 pharmacoresistant epilepsy patients. This study included tumor (31%), focal cortical dysplasia (28%), mesial temporal lobe surgeries (18%), and disconnectionsurgeries (23%). In lesionalgroupioMRI helped infurtherresections about 21% (5/23) patients. Complete resection was achieved in 87% of patients. ioMRI increases the extent of resection especially in lesionalepilepsy surgeries and thereby good seizure outcomes. Kaibara et al. [32] reported about50% patients had residual hippocampus in ioMRI aiding further resection resulting in 93% seizure freedom at 17 months. Michael Buchfelderet al. [33] assessed 61 patients with pharmacoresistant epilepsy. In this study 32 nonlesional cases underwent surgery using ioMRI, the extent of the tailored 28 temporal resection and 4 callosotomy was well documented. Out of 29 lesional cases the complete resection was done in 23 patients. In three patients lesion was extending into eloquent areas and further resection was not done. In other 3 patients ioMRI enabled to achieve complete resection. ioMRI evaluates the extent of resection or disconnection in epilepsy surgery.

ioMRI during DBS surgery provides real time confirmation of lead placement and other complications. Commonly the microelectrode placement in DBS is done with intraoperative microelectrode recording (MER) in awake conditions. With evolution of ioMRI now a days DBS is being done with ioMRI alone or along with MER. Zhiqiang Cui et al. [34] have done microelectrode placement for movement disorder patients under local anesthesia with MER and ioMRI. 56 (27%) of 206 DBS electrodes were adjusted after initial ioMRI. Another 6 times repositioned after 2 and 3 ioMRI in the same sitting. ioMRI revealed intraparenchymal hemorrhages in 2 patients. Martin Jakobs et al. [35] performed 86 surgeries in 81 patients with Parkinson's disease, essential tremor and dystonia with intraoperative stereotactic MRI-only DBS electrode implantation. A total of 167 electrodes were implanted. In 96.5% of cases the surgeries could be finished as planned. Both length of surgery and the time spent in the stereotactic frame could be significantly reduced. Caio M. Matias et al. [34, 36] evaluated placement accuracy and clinical outcomes in patients with frame-based stereotaxy and ioMRI without MER after induction under general anesthesia in DBS patients. 33 patients underwent implantation, 64 leads in total. MR images were acquired immediately after the procedure and fused to the preoperative plan to verify accuracy. At the last follow-up there was significant improvement ($p < 0.001$) in symptoms compared to preoperative state. Placement of microelectrodes in DBS with ioMRI reduces the operative time as well as the time in frame. Microelectrode tip location can be confirmed and also any intraoperative complications can be diagnosed. ioMRI is not affected by brain shift due to csf leak or intracranial air, but one has to be aware of the artifacts created by these electrodes. Role ioMRI in DBS is certainly promising and needs further validation in future.

6. Future directions in ioMRI

AMIGO (Advanced Multimodality Image Guided Operating Suite) is a three-room configuration involving the PET-CT room, operating room, and MRI room. It involves multidisciplinary teams to guide treatment before, during, and after surgery in the operating room. PET provides functional and metabolic information with molecular biomarkers. The combination of MRI and CT with PET gives anatomical, functional, and metabolic combined information to surgeons intraoperatively for further decision-making [37].

MRI-guided focused ultrasound (MRgFUS) is a noninvasive thermal ablation method.IT uses MRI for target identification, planning, and energy deposition. It allows to ablate targeted tissue without damaging normal structures. MRgFUS has been approved for the treatment of uterine fibroids. It is also evaluated for targeted drug delivery and gene therapy, which can temporarily change vascular or cell membrane permeability and release or activate various compounds. High field strength of MRI (3 T) aids better quality of images it helps both diagnosis and surgical ablation. 3 T MRI also has improved sensitivity to temperature measurements which enables multi-slice or three-dimensional thermometry. Trails are being conducted for its use in brain tumors [38].

The Smart Cyber Operating Theater (SCOT), the next generation operating room has been developed by Japan Agency for Medical Research and Development with AMED. It has a treatment room communication interface called "OPeLiNK" which projects all the information like patient data, navigation, IONM, anesthesia monitoring, operative field, ioMRI, etc. in a 70 inch screen. Approximately 20 types of equipment are connected to the system. Surgical information from these sources are sent through an application and displayed to the surgeon and it enables precision in surgery with low risk and high therapeutic effect [39].

7. Conclusion

ioMRI is a valuable tool which not only locates the residue but also guides further resections with enhanced safety. Its importance has been well documented in pituitary surgeries and gliomas. The drawbacks of ioMRI are the cost and time involved. But it is certainly beneficial for the patients in terms of improved functional outcomes and survivals.

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References

[1] Mislow JM, Golby AJ, Black PMJMRIC. Origins of intraoperative MRI. 2010;18(1):1-10.

[2] Grönemeyer D, Seibel R, Erbel R, Schmidt A, Melzer A, et al. Equipment configuration and procedures: preferences for interventional micro therapy. 1996;9(2):81.

[3] Grönemeyer D, Seibel R, Schmidt A, Melzer A, Dell MJSiHT, et al. Two- and three-dimensional imaging for interventional MRI and CT guidance. 1996;29:62-76.

[4] Seifert VJNI. Intraoperative MRI in neurosurgery: technical overkill or the future of brain surgery? 2003;51(3):329.

[5] Zhuang D-X, Wu J-S, Yao C-J, Qiu T-M, Lu J-F, et al. Intraoperative multi-information-guided resection of dominant-sided insular gliomas in a 3-T intraoperative magnetic resonance imaging integrated neurosurgical suite. 2016;89:84-92.

[6] Ginat DT, Swearingen B, Curry W, Cahill D, Madsen J, et al. 3 Tesla intraoperative MRI for brain tumor surgery. 2014;39(6):1357-65.

[7] Manohar N, Mohapatra D, Balasubramaniam A, Rao K, Srinivas D, et al. Setting Up Workflow of an Intraoperative MRI Unit: A Single-Centre Experience of First 53 Cases. Journal of Neuroanaesthesiology and Critical Care. 2018;5(03):177-183.

[8] Multani KM, Balasubramaniam A, Rajesh BJ, Kumar MS, Manohara N, et al. Utility and pitfalls of high field 3 tesla intraoperative MRI in neurosurgery: A single centre experience of 100 cases. Neurology India. 2020;68(2):413.

[9] Gandhe RU, Bhave CPJIJoA. Intraoperative magnetic resonance imaging for neurosurgery–An anaesthesiologist's challenge. 2018;62(6):411.

[10] Manohar N, Palan A, Deora H, Rajesh BJ, Balasubramanium A, et al. Thermal injuries during intraoperative magnetic resonance imaging: Mechanisms and prevention. Journal of Neuroanaesthesiology and Critical Care. 2019.

[11] Manohar N, Palan A, Mohapatra D, Rao K, Srinivas D, et al. Intraoperative Magnetic Resonance Imaging with Evoked Potential Monitoring: Tailored Method of Scalp Corkscrew Electrode Placement to Reduce Image Artifacts. Journal of Neuroanaesthesiology and Critical Care. 2019;6(1).

[12] Yrjänä S, Tuominen J, KoivukangasJJAR.Intraoperativemagnetic resonance imaging in neurosurgery. 2007;48(5):540-549.

[13] Mohammadi AM, Sullivan TB, Barnett GH, Recinos V, Angelov L, et al. Use of high-field intraoperative magnetic resonance imaging to enhance the extent of resection of enhancing and nonenhancing gliomas. 2014;74(4):339-350.

[14] Brown TJ, Brennan MC, Li M, Church EW, Brandmeir NJ, et al. Association of the extent of resection with survival in glioblastoma: a systematic review and meta-analysis. 2016;2(11):1460-1469.

[15] Senft C, Bink A, Franz K, Vatter H, Gasser T, et al. Intraoperative MRI guidance and extent of resection in glioma surgery: a randomised, controlled trial. 2011;12(11):997-1003.

[16] Hatiboglu MA, Weinberg JS, Suki D, Rao G, Prabhu SS, et al. Impact of intraoperative high-field magnetic resonance imaging guidance on glioma surgery: A prospective volumetric analysis. 2009;64(6):1073-1081.

[17] Pamir MN, Özduman K, Dinçer A, Yildiz E, Peker S, et al. First intraoperative, shared-resource, ultrahigh-field 3-Tesla magnetic resonance imaging system and its application in low-grade glioma resection. 2010;112(1):57-69.

[18] Coburger J, Merkel A, Scherer M, Schwartz F, Gessler F, 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. 2016;78(6):775-786.

[19] Bodhinayake I, Ottenhausen M, Mooney MA, Kesavabhotla K, Christos P, et al. Results and risk factors for recurrence following endoscopic endonasal transsphenoidal surgery for pituitary adenoma. 2014;119:75-79.

[20] Raverot G, Vasiljevic A, Jouanneau EJP. Prognostic factors of regrowth in nonfunctioning pituitary tumors. 2018;21(2):176-182.

[21] Brochier S, Galland F, Kujas M, Parker F, Gaillard S, et al. Factors predicting relapse of nonfunctioning pituitary macroadenomas after neurosurgery: a study of 142 patients. 2010;163(2):193.

[22] DeKlotz TR, Chia SH, Lu W, Makambi KH, Aulisi E, et al. Meta-analysis of endoscopic versus sublabial pituitary surgery. 2012;122(3):511-518.

[23] Dehdashti AR, Ganna A, Karabatsou K, Gentili FJN. Pure endoscopic endonasal approach for pituitary adenomas: early surgical results in 200 patients and comparison with previous microsurgical series. 2008;62(5):1006-17.

[24] Serra C, Burkhardt J-K, Esposito G, Bozinov O, Pangalu A, et al. Pituitary surgery and volumetric assessment of extent of resection: a paradigm shift in the use of intraoperative magnetic resonance imaging. 2016;40(3):E17.

[25] Berkmann S, Fandino J, Muller B, Remonda L, Landolt H. Intraoperative MRI and endocrinological outcome of transsphenoidal surgery for non-functioning pituitary adenoma. Acta Neurochir (Wien). 2012;154(4):639-647.

[26] Adeolu A, Sutherland GJWAjom. Intraoperative magnetic resonance imaging and meningioma surgery. 2006;25(3):174-178.

[27] Giordano M, Gallieni M, Metwali H, Fahlbusch R, Samii M, et al. Can Intraoperative Magnetic Resonance Imaging Be Helpful in the Surgical Resection of Parasellar Meningiomas? A Case Series. 2019;132:e577-ee84.

[28] Chakraborty S, Zavarella S, Salas S, Schulder MJJoET, Oncology. Intraoperative MRI for resection of intracranial meningiomas. 2017;12(2).

[29] Metwali H, Samii A, Gerganov V, Giordano M, Fahlbusch R, et al. The Significance of Intraoperative Magnetic Resonance Imaging in Resection of Skull Base Chordomas. 2019;128:e185-ee94.

[30] Dort JC, Sutherland GRJTL. Intraoperative magnetic resonance imaging for skull base surgery. 2001;111(9):1570-1575.

[31] Kurwale NS, Chandra SP, Chouksey P, Arora A, Garg A, et al. Impact of intraoperative MRI on outcomes in epilepsy surgery: preliminary experience of two years. 2015;29(3):380-385.

[32] Kaibara T, Myles ST, Lee MA, Sutherland GRJE. Optimizing epilepsy surgery with intraoperative MR imaging. 2002;43(4):425-429.

[33] Buchfelder M, Fahlbusch R, Ganslandt O, Stefan H, Nimsky CJE. Use of intraoperative magnetic resonance

imaging in tailored temporal lobe surgeries for epilepsy. 2002;43(8):864-873.

[34] Cui Z, Pan L, Song H, Xu X, Xu B, et al. Intraoperative MRI for optimizing electrode placement for deep brain stimulation of the subthalamic nucleus in Parkinson disease. 2016;124(1):62-69.

[35] Jakobs M, Krasniqi E, Kloß M, Neumann J-O, Campos B, et al. Intraoperative Stereotactic magnetic resonance imaging for deep brain stimulation electrode planning in patients with movement disorders. 2018;119:e801-e8e8.

[36] Matias CM, Frizon LA, Nagel SJ, Lobel DA, Machado AGJJoN. Deep brain stimulation outcomes in patients implanted under general anesthesia with frame-based stereotaxy and intraoperative MRI. 2018;129(6):1572-1578.

[37] Wang G, Zhang J, Gao H, Weir V, Yu H, et al. Towards omni-tomography—Grand fusion of multiple modalities for simultaneous interior tomography. 2012;7(6):e39700.

[38] Jung NY, Chang JWJJoKms. Magnetic resonance-guided focused ultrasound in neurosurgery: taking lessons from the past to inform the future. 2018;33(44).

[39] Iseki H, Muragaki Y, Tamura M, Suzuki T, Yoshimitsu K, et al., editors. SCOT (Smart Cyber Operating Theater) project: advanced medical information analyzer for guidance of the surgical procedures. Proceedings of the international display workshops; 2012.