Review Article

Intraoperative magnetic resonance imaging for neurosurgery - An anaesthesiologist's challenge

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ABSTRACT

Intraoperative magnetic resonance imaging (MRI)-guided neurosurgery has gained popularity over the years globally. These surgeries require a dedicated operating room and MRI-compatible anaesthesia equipment. The anaesthesiologist providing care in this setup needs to be experienced and vigilant to ensure patient safety. Strict adherence to MRI safety checklists and regular personnel training would avoid potential accidents and life-threatening emergencies. Teamwork, good communication, preprocedure planning, and familiarity with the surroundings are very important for safe care and good outcomes. We performed a literature search in Google Scholar, PubMed and Cochrane databases for original and reviewed articles for the origins, development and applications of intraoperative MRI in neurosurgical procedures. Much of the research has emphasised on the surgical indications than the anaesthetic challenges faced during intraoperative MRI guided surgery. The purpose of this review is to discuss the anaesthetic concerns specific to this unique environment.

Key words: Anaesthesia, awake craniotomy, challenge, electrical noise, IMRIS, intraoperative MRI, MRI safe anaesthesia equipment, MRI safety checklist, neurosurgery

INTRODUCTION

Magnetic resonance imaging (MRI) is based on the phenomenon of magnetic resonance and has been used in medical diagnostics since 1977.[1] Improved soft tissue details combined with the need for intraoperative guidance for achieving precision and accuracy as well as technological advances led to the development of the first intraoperative MRI in 1991 at the Brigham and Women's hospital.[2] Intraoperative MRI provides near-real-time imaging guidance and unlike other navigation devices used is more accurate in intraoperative setting. It can be used to assess the integrity and dynamic changes in the lesion and surrounding tissues when microscopic visualization proves to be inadequate. Intraoperative MRI requires designated operation theaters and use of MRI-compatible monitoring devices.

Anaesthesiologists are responsible for maintenance of stable patient physiology during surgery. The modern anaesthesia techniques and practices evolve as the surgeries and patient complexities increase. Introducing MRI technology into the operating room setting presents new challenges for anaesthesiologists as they have to adapt to the demands of the new technology while ensuring safe anaesthesia during surgical procedure.

Literature search and selection

We performed an electronic search in Google Scholar, PubMed and Cochrane Databases for original and review articles on anaesthetic challenges in intraoperative MRI for neurosurgery until December 2017. The search terms included intraoperative MRI, anaesthesia, IMRIS, neurosurgery, MRI safety. Only full text articles were included.

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DESIGN OF THE INTRAOPERATIVE MRI SUITE

The ideal intraoperative MRI scanner should allow uninterrupted patient access throughout the scanning while providing high-quality images in real time. The MRI scanners used in intraoperative setting are broadly classified into open and closed systems. The open scanners have either a horizontal gap [low-field 0.2–0.5 T (Hitachi 0.3 T™) and mid-field 0.5–1.0 T] or a vertical gap [midfield-0.5 T (GE 0.5 T Signa SP™)]. The advantages of the open system are that it allows uninterrupted patient access during scanning while providing near-real-time images with average image quality and no ionizing radiation. The disadvantages are the limited field strength, poor availability, and setup cost including the need for MRI-compatible surgical equipments. The closed system of scanners has either a long bore (high-field 1.5 T) or a short bore (high-field 1.5 T) design. The main advantage of long bore closed system of MRI is that it provides highest quality of images. However, there is no access to the patient during scanning. Short bore scanners have limited access to patients with image quality inferior to long bore scanners. Closed system of MRI is also expensive and needs an operating room setup specific to its needs.[3-5]

The intraoperative MR imaging system (IMRIS™) that is used in our institute was developed by a neurosurgeon, Dr. Garnette Sutherland of Calgary, Alberta, Canada [Figure 1].[3] This system is based on an actively shielded 1.5-T mobile ceiling mounted magnet that can be moved into and out of the operating room. This is an example of a high-field system that is an advancement from the previously used mid-field open configuration system which used 0.2–0.5 T magnet placed in the operating room.[3] IMRIS offers a unique rail mounted system in which a scanner is brought intraoperatively to the patient. By enabling the MR imaging system to move to the patient, the system allows improved surgical workflow and enhanced patient safety in the surgical environment. The 70-cm bore 1.5-T magnet is able to move between the two operating rooms. A magnet room is separated from the operating rooms by sliding radiofrequency and sound shielded doors. The suite is designed around the magnet and features an MR-compatible operating room table which is fixed at the base and cannot be moved out of the operating room.

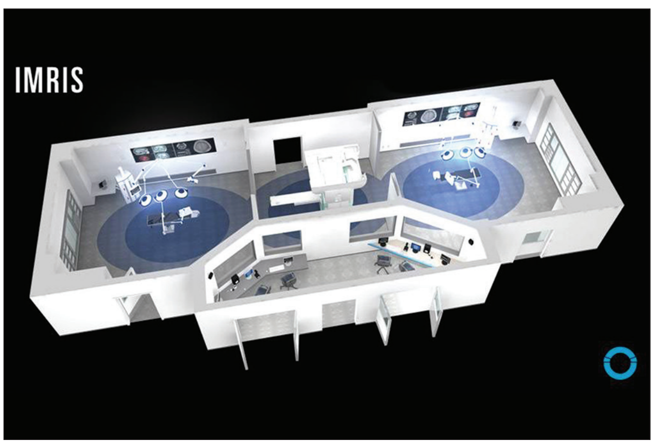

Figure 1: Design of the IMRIS suite with inner 50G line (dark blue circle) and outer 5G line (light blue circle). {Reproduced from IMRIS™ brochure}

There are specific zones in the suite depending on the strength of the magnetic field [Table 1].[6] Zone I is farthest away from the active magnet that allows free movement without screening and zone IV is the area in the vicinity of the magnet which has restricted access and non-MRI-compatible objects are prohibited.[6]

ANAESTHETIC CONSIDERATIONS

Monitoring concerns

It is crucial to maintain compliance with ASA monitoring guidelines during intraoperative MRI by ensuring adequate ventilation, delivery of inhalational and intravenous anaesthetics to achieve adequate depth of anaesthesia. The introduction of intraoperative magnetic field requires modification in monitoring standards. Anaesthesia and patient monitoring system that do not emit any electrical noise (EN) and which function during a scan were installed within MRI suite. EN distorts the physiological waveforms appearing on the monitor which could lead to inaccurate assessment of patients' vital parameters.[1] Any electronic medical device intended for use in MRI suite requires special design considerations to ensure MRI compatibility [Figures 2 and 3]. Equipments and monitors that are to be used in intraoperative MRI setting have to be labelled as MR-safe, MR-conditional, and MR-unsafe. MR-safe

Table 1: MRI zones
I. No magnetic field. Accessible to patients and staff. MRI-specific training not necessary.
II. Patients to be screened and their movements monitored by MRI personnel. MRI-specific training necessary for care providers. Acts as a transition zone. Ferromagnetic objects not to be taken beyond this zone.
III. Restricted area where the magnetic field is in close proximity. Training necessary. Screening mandatory. No ferromagnetic objects.
IV. Area within MRI magnetic field. Highest risk area. Moves with the movement of magnet.

Figure 2: MRI compatible monitor with patient positioned for Intraoperative MRI

Figure 3: MRI compatible syringe pump holder

equipments are those that do not pose any harm when exposed to any magnetic field (GE Aestiva/5MRI™ anaesthesia machine, Draeger Fabius™ anaesthesia machine, Philips-Expression MR200™ patient monitors, B-Braun SpaceStation MR™ syringe pump holder). MR-conditional equipments are those with demonstrated safety in the MR environment within defined conditions (I Tru Truphatek™ MRI conditional Laryngoscopes). These conditions include static magnetic field strength, spatial gradient magnetic field, dB/dt (time rate of change in magnetic field), radiofrequency fields, and specific absorption ratio (SAR). MR-unsafe equipments are those that pose unacceptable risk to the patient, medical personnel, or other staff in the MR environment. Only MR-safe and MR-conditional equipments are allowed inside the MRI zone IV, whereas MR-unsafe equipments have to be moved to zone II.[6]

Physical safety concerns

Anaesthesiologists need to be vigilant to prevent accidental injuries while managing patients for intraoperative MRI-guided surgeries. There is a risk of thermal injury in anaesthetized patients in intraoperative MRI settings. It should be ensured that electrocardiography (ECG) cables do not form partially or completely closed loop. Looped cables can pick up radiofrequency energy resulting in induced currents, heating of the material, and as a result, severe burn injury can occur.[7,8] Cables should not come in contact with patients' skin and are laid out without forming loops. MRI-safe ECG leads are placed on the patient and all the cables should be wrapped with cotton gauze roll to avoid their direct contact with patient. Skin-to-skin contact is avoided by placing cotton gauze pads in between finger webbings and cotton or foam pads between the upper limb and body. Implanted MRI-unsafe monitors (temperature, depth of anaesthesia) are avoided. All electronic devices must have the ability to be shut down immediately by staff if necessary and emergency manoeuvres must be known including emergency "Quenching" of the MRI.

Preoperative assessment

In addition to routine preoperative assessment, the anaesthesiologist has to be well-informed about patient factors that would interfere with MRI. MRI has the ability to induce voltages in implanted devices. Hence, all patients scheduled to undergo surgeries under intraoperative MRI guidance have to be asked regarding implanted medical devices (pacemakers, implanted cardiovertor defibrillators, deep brain stimulation pulse generators, vagal nerve stimulators, Baclofen pumps etc). It should be checked whether the devices are MRI-safe/conditional. A plan for managing these patients including the need for intraoperative MRI should be formulated in consultation with the consultant cardiologist, neurosurgical team, radiology team, and device manufacturers.[9,10] History should also be taken regarding tattoos and lead containing cosmetic use as lead can cause artefacts in MRI. Patients should be asked regarding any kidney-related ailments, contrast dye allergies, previous surgeries with placement of metallic implants, aneurysm clips, and metallic dental caps.

Intraoperative considerations

Surgical indications

Black *et al*.[2] in their pioneering work on intraoperative MRI successfully used this technique for stereotactic biopsy of intracranial lesions; craniotomy for excision of intracranial space-occupying lesions and arteriovenous malformation excision; drainage of intracranial cyst; cervical spine surgeries; and interstitial hyperthermia for tumor ablation.

Further research and development in imaging, neurosurgical, and anaesthetic technologies as well as increased awareness about beneficial effects of intraoperative MRI has increased its overall applications. Intraoperative MRI-guided neurosurgery has been successfully performed in intracranial space-occupying lesions,[2,11-13] endoscopic transsphenoidal pituitary surgery,[14,15] pediatric neurosurgery,[16] epilepsy surgery,[7,17] transoral resection of cervical spine pathologies,[18] and electrode placement in deep brain stimulation patients.[7] Sim and Tan[11] and Peruzzi *et al*.[12] have reported successful management of gliomas in eloquent cortex done under awake craniotomy in intraoperative MRI setting. The authors have successfully performed all the above-mentioned surgeries and awake epilepsy surgery under intraoperative MRI guidance.

Operation theater setup

Organization of the operating room and setup of the patient must be meticulous because of the difficulties encountered with patient manipulation once the procedure has begun. Challenges are encountered during patient positioning on the operating table due to space constraints. MR safety checklist [Table 2] should be followed strictly before initiating MRI scanning. Dangerous amount of static magnetic field is assumed to be within 5G line [Figure 4]. Static magnetic fields cause ferromagnetic objects and equipments to become projectiles leading to accidental physical harm to the patient and care givers.

Anaesthesia management

Surgeries in intraoperative MRI setting can be safely done both in supine and prone positions [Figure 5]. Surgeries in prone position along with intraoperative MRI pose more challenges to the attending anaesthesiologist such as abdominal compression, ventilatory circuit disconnections/kinking during fixation of intraoperative MRI coil, and ECG interferences. Extra care needs to be taken while securing the endotracheal tube. A combination of inhalational and intravenous anaesthetics is preferred considering the longer dead space-related delay in delivery of anaesthetics to the patients. Incorrect reading of the end tidal carbon dioxide ($ETCO_2$) and anaesthetic gases is encountered due to increased dead space. The patients are intubated with routine, appropriately sized cuffed endotracheal tubes as flexometallic tubes are not MRI-compatible. The pilot balloon of the endotracheal tube cuff is secured away from the tube as it may cause artefacts during scanning. The patients' head is fixed with MRI-compatible three-pin head holder. In a study by Barua *et al*.,[19] the time needed for setup of intraoperative MRI ranges from 30 min to 3 h with lesser time required as expertise improved.

Intraoperative MRI is asked for by the neurosurgeon either immediately after dural opening to see the extent of brain shift or after microscopic resection of the lesion is deemed to be complete. All MR-unsafe equipments are to be kept outside the magnetic field as advised [Table 2][16] and sterile drapes are placed over the patient [Figure 6]. Only MR-safe or MR-conditional equipments are to be kept in zone IV. Blood pressure monitoring during scanning process can be done by both invasive and noninvasive methods. For invasive blood pressure monitoring, the pressure bags have to be MRI-compatible (InfuseAid™ MRI Pressure Infusor). A thorough checklist [Table 2] is to be followed before exposing the patient to MRI to avoid any mishaps. The attending anaesthesiologist has to ensure adequate access

Table 2: Intraoperative MRI checklist

Items to be moved outside 5G line
Operation theater lights, operating microscope, cameras, navigation systems, cautery machine
Surgical trolleys, anaesthesia induction trolleys, drug trolleys
Intravenous stand, suction bottles, chairs, buckets
Items to be removed from the patient field
Patient warmer, temperature monitor, depth of anaesthesia monitor
Cautery pad and cords
Surgical instruments, retractors, navigation instruments and their holders after confirming counts
Radioopaque sponges

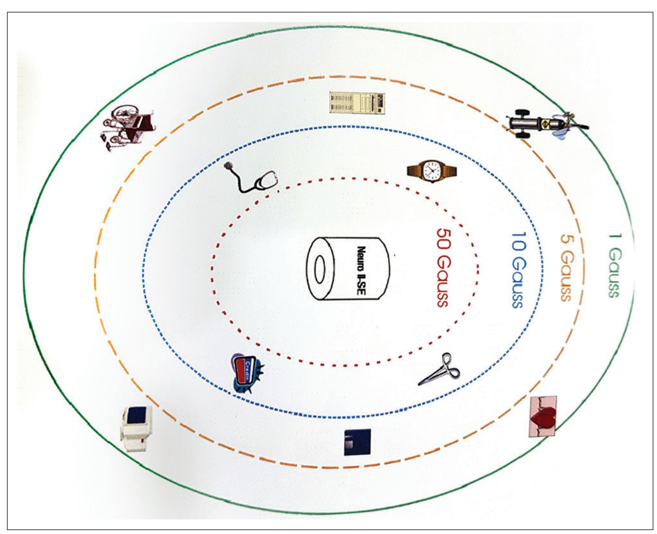

Figure 4: Gauss lines {Reproduced from IMRIS™ brochure}

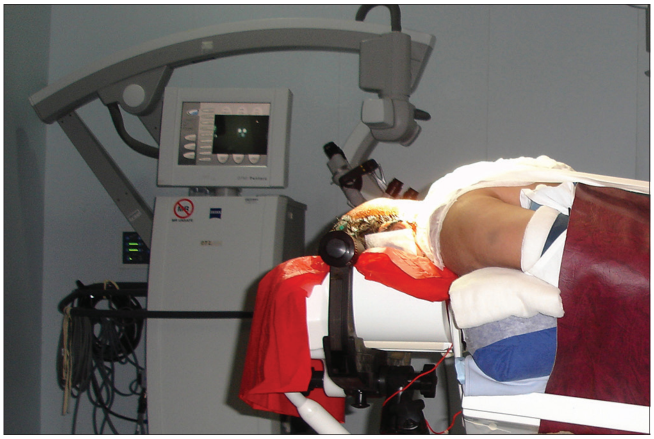

Figure 5: Patient positioned prone for Intraoperative MRI. Note the MRI compatible Head holder (black colour) and the MRI coil (white) under the patients' head

Figure 6: Patient prepared for intraoperative MRI and 5G line

for intravenous drug delivery, check the ventilatory connections, and removal of MR-incompatible monitoring devices before intraoperative scan.

The personnel who remain in MR suite during scanning process should undergo a thorough check with a hand-held magnet before MRI scanning to avoid mishaps. There should be effective communication drills between the personnel as electronic gadgets are not allowed during MRI scanning process. The personnel are protected from MRI noise by use of ear plugs. Anaesthesia should be reversed only after MRI scanning is complete and the patient is out of the bore of the magnet. Simulated drills help train care givers in managing emergency situations in the setting of intraoperative MRI.

ECG CHANGES IN MRI SETTING

MRI environment has an effect on ECG recording. ECG changes are observed not only in the presence of static magnetic field but also during scanning process as a result of pulsed gradients and high-frequency fields. ECG changes occurring in the presence of static magnetic field include ST segment changes and abnormal P-wave morphology. The changes occurring during scanning sequences range from high-frequency artefacts, continuous spikes resembling atrial fibrillation (DTI sequence), and QRS complex suppression resembling ventricular fibrillation (T2 HASTE, EPI sequences).[20]

STATIONARY MAGNET AND MOBILE PATIENT

In the scenario where the patient is to be brought to MRI scanner for intraoperative MRI, sterile drapes are placed over the patient after confirming removal of MRI-unsafe surgical instruments and anaesthesia equipments from the patient field in zone II. A thorough MRI checklist is performed, ventilator and intravenous infusion connections are rechecked, and the patient is transferred on an MRI-compatible trolley in zone II. This trolley along with the MRI-compatible anaesthesia machine and patient monitor are wheeled into zone IV and MRI scanning is performed. Once scanning is completed, the patient is wheeled back into zone II and the procedure is resumed. In the unlikely event of an emergency during scanning process, the patient should be taken back into zone II where MRI-unsafe resuscitation equipments are kept ready. While shifting the patient back to zone II, the patient should be ventilated with 100% oxygen and chest compressions given if there is a cardiac arrest.

EMERGENCY MANAGEMENT IN THE INTRAOPERATIVE MRI SETTING

Anaesthesiologists should be aware and vigilant about the potential emergencies that may arise in intraoperative MRI environment. Emergency situations are mainly due to airway compromise or haemodynamic instability. In any emergency during scanning process, non-ferromagnetic emergency equipments (crash cart, defibrillator) should be brought inside the operating room only after MRI scanner is moved back in parking position away from the patient which takes about 2 min duration. The anaesthesiologist, in the meantime, should check for ventilator connections, kinking, or compression of ventilator circuit while ventilating the patient with 100% oxygen. Intravenous fluids along with inotropic support and chest compressions are given if situation demands. Routine simulated drills, role play, and effective communication between team members will minimize incidence of emergencies and reduce response time to a minimum.

AWAKE CRANIOTOMY IN THE INTRAOPERATIVE MRI SETTING

Patients with lesions in eloquent areas of the brain need to be monitored intraoperatively for any new deficits. Awake craniotomy offers advantages when compared with craniotomy done under general anaesthesia. It helps map functional areas of the brain. In addition, it allows for continuous intraoperative neurophysiologic monitoring of the patient. Preoperatively, an anaesthesiologist should inform the patient about anaesthetic plan and ensure patient's cooperation. If intraoperative MRI is planned, the patients have to be explained regarding the noise associated with MRI and the steps taken to ensure patient comfort during screening procedure. During scanning process, the patients should be lightly draped to avoid suffocation and oxygen should be administered continuously by face mask. Conscious sedation can be achieved by intravenous dexmedetomidine and propofol infusions. Target controlled infusions based on pharmacokinetic models can be used for effective delivery of sedative medications. Airway management devices including oropharyngeal or nasopharyngeal airways, MRI-compatible laryngoscopes, and routine endotracheal tubes should be readily available.

LIMITATIONS OF INTRAOPERATIVE MRI

Intraoperative MRI, despite providing real-time guidance to the surgeon, has its disadvantages. The earlier versions of MRI systems (GE 0.5 T Signa SP™) provided average quality of images and required MRI-compatible surgical instruments. The newer high-field MRI systems offer excellent quality of images and do not require MRI-compatible surgical equipments. MRI-compatible anaesthesia machine, patient monitoring devices, and infusion pumps are required for both the systems. MRI-unsafe monitoring devices and equipments (temperature probes, neuromuscular monitor, needle electrodes for evoked potential monitoring and patient warming devices) need to be moved outside the 5G line before scanning.

Access to the patient is very difficult in high-field MRI systems when compared with low and mid-field systems. Anaesthesia connections and patient ventilatory circuit connections must be rechecked before scanning the patient. Long length of ventilatory tubings and intravenous infusion lines are required to maintain anaesthesia which may result in delayed delivery of anaesthetics to the patient. As MRI environment requires low temperature to optimize magnetic field, patients, especially children, may develop hypothermia which may lead to delayed recovery from anaesthesia. Morbidly obese patients and patients undergoing surgeries in positions other than supine may have pressure ulcers and compression-induced peripheral nerve injuries due to direct skin contact with operating table or MRI coils. This can be avoided by ensuring adequate padding and careful patient selection.

Setting up an intraoperative MRI facility requires financial investment. Intraoperative MRI includes patient preparation for the scan and performing the scan, both of which have an effect on the total duration of the surgery and eventual cost.[8]

CONTRAST MEDIA

Contrast media are used to improve the quality of imaging. They are not free of any side effects. These side effects may be immediate or delayed. Immediate side effects range from mild (allergic-urticaria, cutaneous edema, physiologic-hypertension, tachycardia, nausea, and vomiting) to life-threatening (allergic-layngospasm, bronchospasm, physiologic-hypertensive emergencies, arrhythmias, seizures). Delayed side effects are due to the effect of injected contrast media on kidneys (contrast-induced nephropathy, nephrogenic systemic fibrosis). Patients undergoing intraoperative MRI need to be preoperatively asked about previous exposure to contrast media, allergic reactions, kidney ailments, diabetes mellitus, and hypertension. Drug history should include use of metformin in patients with diabetes with kidney disease. Preoperative serum creatinine should be advised.

During intraoperative MRI, contrast media should be administered through an intravenous cannula and flushed properly due to long length of infusion tubings. The recognition of side effects under anaesthesia in intraoperative MRI setting is by observing a change in vital parameters (hypertension, hypotension, arrhythmias, and desaturation) or by a change in ventilation parameters (increased airway pressure, inadequate tidal volume). It is difficult to visualize allergic reactions in these patients as they would be under drapes and the environment would be dimly lit. Treatment includes administering 100%

oxygen, intravenous fluids (0.9% saline), intravenous epinephrine (if hypotension), intravenous atropine (if bradycardia), intravenous hydrocortisone 5 mg/kg, intravenous diphenhydramine 25–50 mg (minimize allergic reaction), beta agonists (bronchospasm), and intravenous furosemide (pulmonary edema).[21]

SUMMARY

Intraoperative MRI has added a new dimension in management of neurosurgical patients. It has resulted in increased precision and accuracy of surgical techniques leading to improved patient outcomes while presenting new challenges to anaesthesiologist specific to patient safety, monitoring, and equipment requirements. Proper preoperative planning, personnel training regarding matters unique to intraoperative MRI, effective communication, teamwork, and strict adherence to preprocedural checklist will help in achieving patient and personnel safety with favorable outcomes.

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Conflicts of interest

There are no conflicts of interest.

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