The anaesthetist's role in the setting up of an intraoperative MR imaging facility

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ABSTRACT
The clinical and economic advantages of intraoperative magnetic resonance (MR) imaging for neurosurgery are apparent. Hence, more medical institutions are setting up such services. Establishing such a service can be daunting because of the cost and specifications, its highly technical nature and many safety considerations. The anaesthetists have an integral part to play during this process because of their stake as key users and their vital role in conducting anaesthesia for complex neurosurgery within this hostile, and sometimes remote, environment. Moreover, their experiences with efficient workflows, patient screening and concern about safety make them eminently qualified members of the planning and building process. They are also no strangers to budgets and equipment appraisals. The complex interactions between conducting anaesthesia in a hostile environment and in a remote site conspire to make this a challenging undertaking. This article describes the role, the practical considerations and the difficulties experienced by the neurosurgical anaesthetists in setting up an intraoperative MR imaging operating theatre at Singapore General Hospital, from planning to equipment procurement and streamlining the workflow. Safety concerns and training are vital aspects of this article. It is hoped that our experiences will be of help to others who will be called upon at some point in a similar undertaking.

Keywords: anaesthesia, imaging-guided surgery, intraoperative magnetic resonance imaging, magnetic resonance imaging, neurosurgery

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INTRODUCTION
Neurosurgical techniques have made advancements, especially with the progress in computer software technology that marries imaging and stereotaxy. There is a trend towards intraoperative imaging, ideally without having to physically move the patient from the operating area to an imaging facility, a process that is fraught with their attendant problems. The intraoperative magnetic resonance imaging (iMRI) and intraoperative CT scan (iCT) operating theatres are examples of such facilities. Their development marks a significant advance in neurosurgery.[1,2] iMRI is safe and has minimal negative influence on anaesthetic measures of perioperative anaesthetic outcome, even though iMRI may prolong the duration of surgical procedures.[3]

Our institution, Singapore General Hospital (SGH), has completed the building of the iMRI and iCT facility. These have been in use for the past months. The involvement by the neurosurgical anaesthetists in SGH with the planning and implementation of the iMRI was paramount in setting up a safe, effective and successful iMRI service. It is therefore timely to share our experiences. This article focuses on issues of interest to anaesthetists who are called upon to assist with the setting up of an iMRI service.

WHY INTRAOPERATIVE IMAGING?
Intraoperative MR imaging allows for high resolution, three-dimentional anatomical imaging of the brain. It also provides information of function (functional imaging with fMRI), which is useful in functional neurosurgery, for example, epilepsy surgery. It can also provide information on metabolism with MR spectroscopy. There are low-, middle- and high-field MR imaging systems, ranging from 0.12 to 1.5T, and each can focus on different aspects of neurosurgery.[4] Intraoperative imaging facilitates access to difficult tumours and helps with determining the extent and adequacy of tumour excision,[5] especially those with ill-defined demarcations. iMRI allows for swift acquisition of images and formulation of a surgical plan with minimal coordination efforts. This reduces repeat surgery and risk of tumour recurrence. Moreover, iMRI usage provides immediate quality control during surgery. Cost savings are achieved since early postoperative follow-up scanning may not necessary.[4]

During standard stereotactic craniotomies, brain shifts may result in errors in targeting and localisation. This is avoided with iMRI. Complications such as haemorrhage can also be recognised immediately.[5] iMRI has been credited with the development of new neurosurgical techniques and approaches, and the development of new MR sequences. Its research potential has been touted as an advantage. Finally, improved medical outcomes, shorter hospitalisation, and faster procedures with fewer complications are advantages.[6] Singapore is the first country in Southeast Asia to have such a facility. In this current competitive climate of attracting foreign patients as well as skilled clinicans and researchers, having an iMRI facility would help improve the strategic position of the hospital, as well as potentially improve operating revenue from the application of this service.

THE IMPORTANT ROLE OF ANAESTHETISTS IN THIS PROJECT

The anaesthetists have an integral part to play during this process. They will ultimately have to work in this facility as key users. They need to conduct anaesthesia for complex neurosurgery in this hostile and sometimes remote environment. Moreover, their experiences with efficient workflows, patient screening and concern about safety make them eminently qualified members of the planning and building process. They are also no strangers to budgets and their constraints. Their experience with equipment appraisal is crucial in choosing equipment for use in an MR imaging environment which possesses strict safety criteria.

Anaesthetists are familiar with setting up new services, as illustrated historically by the setting up of acute and chronic pain services, perioperative units and critical care services. As important members in the hospital steering committee created to oversee the setting up of the iMRI facility, our presence was required to highlight to others the clinical priorities, especially when most planners, technical and administrative staff have little idea of the expected workflow in this facility.

FEATURES OF AN iMRI SYSTEM

Intraoperative anatomic imaging must be guided by intraoperative guidance via a navigation system, allowing instant real time updating of navigation which compensates for brain shift. The images should be acquired swiftly and be of superior image quality.[4,6] There are different concepts with respect to scanner and operating theatre design. The simplest set-up involves surgery in an operating room. When scanning is required, the patient is transported to an MR imaging scanner which could be in another location in the hospital or in an adjoining scan room.

Some iMRI involves a portable magnet while others require operating in the scanner with limited surgical space. Newer iMRI systems such as BrainSUITE allow for surgery in the vicinity of the MR imaging machine but outside of the crucial 5-Gauss line. When scanning is required, a rotating operating table mechanism brings the patient into the magnetic core for scanning. The field strength of the magnet should be sufficiently high. Other features to be taken into consideration include flexibility in patient positioning but yet ensuring good positioning of the head. The surgeon's mobility and the ability to use surgical microscopes are important considerations.[6] iMRI should ideally be installed by a vendor who would be responsible for implementation and management of the project and be able to achieve fast installation at a predictable cost. MR safety, code compliance, compatibility of various components of the iMRI are also assured. Finally, staff training, documentation of authority approval, and most importantly, clinical case support must be ensured.

Our hospital acquired the BrainSUITE (BrainLAB AG) iMRI, which has been touted as a state-of-the-art operating room in a self-contained environment.[2] This set-up included a Siemens MAGNETOM Symphony 1.5T, which is capable of standard MR imaging, MR angiography and spectroscopy, fMRI and diffusion tensor imaging, all of which are considered standard aspects of neurosurgical planning.[7] There is a navigation and data management system, a radiofrequency-shielded operating room cabin (an area of 86 m^2), operating lights, a ceiling-mounted microscope and basic anesthethesia equipment. Room control system for control of major electrical components was included.

An MR-compatible operating table with a surgical head clamp and radiofrequency coil is a vital part of the system. BrainSUITE uses a rotating operating table which also serves as an MR tray. The patient's head is fixed in an MR-compatible head clamp with a head coil. During surgery, the head of the patient is positioned outside the 5-Gauss line, hence allowing for the use of standard surgical instruments. During MR imaging scanning, the table is rotated 160° and the patient's head positioned in the centre of the scanner.[8] At the end of scanning, the operating table swings back in place, with the patient's head outside the 5-Gauss line. This set-up is safe, involves minimal movement of anaesthetic equipment and incurs only a short transit time to and from the MR imaging scanner. The monitoring cables and ventilation circuits have to be of sufficient length to allow for this rotational movement and care must be taken during this movement to avoid disconnections.

FUNDING FOR iMRI

In December 2006, the concept of building an iMRI facility was brought forth by neurosurgeons at Singapore National Neurosciences Institute. Funding was obtained from a philanthropic foundation for the iMRI facility to be built in the SGH campus, with SGH contributing space, infrastructure support, staffing and medical equipment. This sum of money was matched by an equal sum by the Health Ministry, Singapore.

Table I. Summary of events during surgery in the iMRI operating theatre.

Neurosurgical patient, suitable for iMRI, is listed for surgery.
The patient is screened at the ward level and in the operating theatre: no contraindications, no ferromagnetic material on the patient.
MR imaging technician prepares the MR imaging equipment.
Anaesthesia staff prepares the anaesthetic equipment.
Staff leave wallets and personal belongings in lockers.
Induction of anaesthesia, placement of invasive lines in the anaesthetic induction room.
Earplugs are provided for the patient.
The patient is positioned on the operating table.
The patient's head is pinned to the operating table.
The patient is kept warm with layers of blanket.
Precaution: ensure contact of monitoring cables with the skin is avoided.
Limbs are wrapped with wool, avoiding skin to skin contact, especially the axilla and groin folds.
The patient is moved from the induction room onto the operating table in the iMRI operating theatre.
Entry into the MR imaging scanner.
The anaesthetist maintains anaesthesia, prevents dislodgement of endotracheal tubes, fluid lines and monitors during movement.
MR imaging scanning takes place.
The patient is monitored from the MR imaging control room during scanning.
The patient is moved out of the MR imaging scanner and swung into position at the edge of the 5-Gauss line.
The anaesthetist monitors the anaesthetic machine, infusion pumps and intravenous lines near the foot of the operating table.
Surgery proceeds.
At appropriate points, the patient is moved into scanner to assess the extent of surgery.
Multiple episodes of scanning may be needed.
At the end of surgery, the patient is moved back to the induction room for reversal of anaesthesia.
The patient returns to the intensive care unit.

PROCUREMENT OF BrainSUITE iMRI

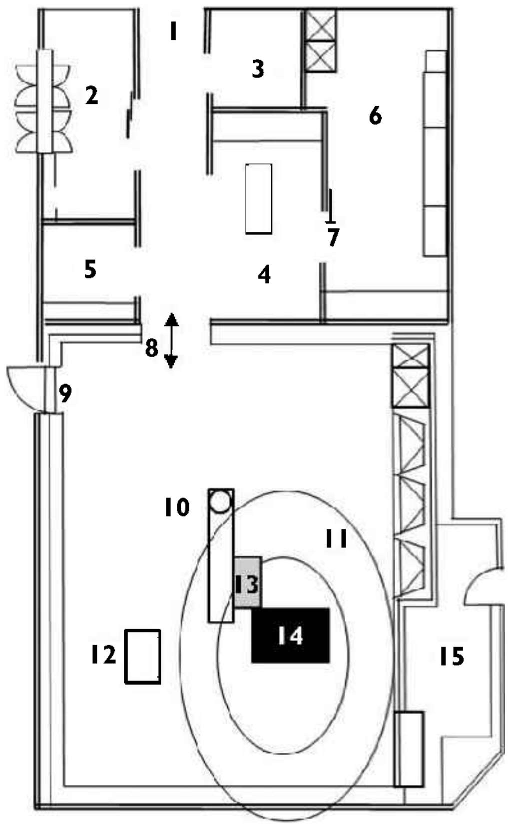
The neurosurgical team, neuroradiologists, MR imaging technologists, hospital architects and administrators made several trips to visit centres with different models of iMRI before deciding upon BrainSUITE in May 2006. There was a timeframe of 18 months for it to be built, installed and made operational. It was after these fact-finding trips that neurosurgical anaesthetists were involved, primarily for our input on the workflow and on the choice of anaesthetic equipment for the iMRI facility. The fact-finding trips were of a rather technical nature and was of most relevance to the radiologists and the neurosurgeons. Although the anaesthetists could have been involved at the fact-finding stage, it is likely that the technical considerations of a particular iMRI system would override the anaesthetic, safety and resuscitation considerations. Hence, the challenge was to understand the system that was decided upon and adapt the anaesthetic considerations, with the help of other existing centres, to the iMRI system.

A hospital steering committee was set up, comprising representatives from the surgical, administrative, finance, building and biomedical departments. As members of the work teams had differing objectives, a chief coordinator was essential. There were frequent meetings and briefings at each stage of the project, together with email updates; this was an important forum to highlight to the other committee members who may not be aware of how certain decisions may impact on one another. Each time a major project milestone was achieved, we were required to make inspections or amendments, and sign to acknowledge our approval.

SITE PLANS

Although BrainSUITE iMRI is of a standard configuration, there is flexibility in designing the adjacent rooms for the iMRI control room, anaesthetic induction room, surgical scrubbing area, instrument preparation and disposal areas. The hospital architects had decided on a location in the main operating theatre section previously used by operating theatre managers. This location gave the advantage of being within the main operating complex, and at the same time, allowing easy access for patient movement from outside the main operating complex, so that the MR imaging scanner could also be used for diagnostic scans, thus optimising the use of the scanner when the iMRI operating theatre was not being used for surgery.

Before finalising the site plans with the hospital architects and BrainSUITE staff, a neurosurgical anaesthetist made a visit to the University of Erlangen-Nuremberg Hospital, which probably has the most experience of working with BrainSUITE. Upon her return, the anaesthetist's experience was instrumental in



1. Entrance to iMRI complex
2. Preparation room with two-way cabinets
3. Disposal room
4. Anaesthesia induction room
5. Scrub room
6. Control room
7. Viewing window between control and anaesthesia rooms
8. Entrance to iMRI operating theatre
9. Emergency exit
10. Head end of operating table
11. 5-Gauss line
12. Anaesthesia equipment and work area
13. Pivot between MR imaging scanner and operating table
14. MR imaging scanner
15. Computer systems

Fig. 1 Schematic plan of the iMRI facility.

formulating our workflow. This workflow (Table I) took into account inclusion and exclusion criteria for patients, staff and patients' screening processes, the conduct of anaesthesia and the types of appropriate anaesthetic equipment.

LAYOUT OF THE ANAESTHETIC INDUCTION ROOM

Having an anaesthetic induction room (Fig. 1) with its own set of anaesthetic equipment and monitors to anaesthetise patients give the advantages of privacy, less patient anxiety and eliminates the stress of conducting an anaesthetic and insertion of invasive lines in the vicinity of the MR imaging scanner (although once outside the 5-Gauss line, one was relatively safe from drawing ferromagnetic equipment into the magnet). This was also planned as a "safe room", because when patient complications occur, they can be moved here for resuscitation, as it is fully equipped. In additon, some equipment, such as defibrillators, are not safe in the vicinity of the MR imaging scanner. Also, additional staff needed to assist with resuscitation would be safe here especially when there may not be time to screen them for safe entry to the iMRI room.

Finally, reversal after anaesthesia and transfer to a post-anaesthetic care bed, with its oxygen source, is safer and easier in this anaesthetic induction room. We chose to have a second MR-compatible anaesthetic machine situated here as this would be useful if the machine inside the iMRI room breaks down or is being serviced. We opted to install an operating lamp that is adequate for simple procedures, such as tracheostomy, insertion of external ventricular drains or ventriculoperitoneal shunts. This allows the anaesthetic induction room to function as an extra operating room.

The input of the operating theatre nurses, the infection control team, neurosurgeons and anaesthetists were vital for planning the flow of human traffic as well as location of the surgical scrub, preparation and disposal areas in relation to the anaesthetic induction room. All users' competing demands and considerations were considered, such as privacy and tranquility needed for induction of anaesthesia and placement of aseptic invasive lines, and the infection control team's specifications about the physical distance between the disposal area for equipment / instrument preparation and scrub areas.

The surgical nurses needed adequate space to prepare their array of neurosurgical instruments and the building of two-way cupboards allowed instruments to be stocked without having to enter the iMRI facility. As a result of this "design and build", details such as door sizes, turning angles and radii had to be appropriate for the 1.9 m long ward or post-anaesthetic care bed in the induction room. As space was a constraint in the induction room, shelvings for storage of anaesthetic items and positioning of gas pendants and power points had to be carefully thought out.

CONTROL OF ACCESS INTO THE iMRI FACILITY

As the iMRI is potentially hazardous to the uninitiated, access had to be restricted to accredited staff who are fingerprint-enabled.

SCREENING OF PATIENTS AND STAFF

Screening of people entering the iMRI operating theatre helps prevent injuries from projectile effects of ferromagnetic items brought into the iMRI operating theatre accidentally, since there have been reports of injury and lethal outcomes.[9,10] Although MR imaging scanning is a relatively safe procedure, certain groups of people must be excluded from working or treated in the presence of strong magnetic fields.[11] Patients with implanted ferromagnetic devices or objects including pacemakers,[12] intracranial aneurysm clips,[13] tissue expanders with metallic ports, implantable defibrillators/cardioverters, implantable infusion pumps, cochlear implants, intraorbital metallic bodies and shrapnel, are generally contraindicated.[14]

The hospital had to adapt their policy on working in an MR imaging environment to the iMRI facility and these documents are unambiguously drafted by the hospital legal department. Staff need to declare their suitablility to being in the iMRI operating theatre and that they had undergone safety lectures on working in the iMRI environment. Patients have to be screened for specific contraindications to high field magnetic exposure[15] with the aid of a screening form and checklist,[16] and this is to be conducted in the clinic so that patients who are unsuitable for iMRI surgery are excluded from being listed for surgery in the iMRI operating theatre. As part of the patient assessment, patients having surgery in the iMRI operating theatre should be informed of any additional costs involved.

POSITIONING OF GAS OUTLETS AND ELECTRICAL POWER POINTS

Within the iMRI facility, we specified the quantity and location of electrical points and medical gas outlets, even though in practice, BrainSUITE has standard locations for the medical gas pendants and their electrical outlets. It was enlightening to know about which sockets had to have UPS (uninterrupted power supply) and how during MR imaging scanning, electrical circuitry to iMRI had to be interrupted to avoid interference with image quality, hence leaving UPS sockets to power the critical anesthetic equipment and monitors. We opted for extra electrical and gas outlets on the side wall close to where the anaesthetic machine would be sited and on the back wall (in relation to the magnetic bore) to allow manoeuvring of anaesthetic equipment, if required. Once built, it would be impossible to acquire more of these outlets.

DECIDING ON ANAESTHETIC EQUIPMENT FOR USE IN THE iMRI OPERATING THEATRE

There are several considerations regarding the use of anaesthetic equipment in the iMRI operating theatre. Firstly, the hazardous effects of the strong magnetic field on the equipment could cause malfunction. Secondly, there is risk of thermal injury to the patient. All monitoring modes using long cables (ECG, evoked potentials, bispectral array, EEG, temperature probes) can potentially cause currents to be induced by the magnetic fields of the MR imaging unit. EEG and evoked potential monitoring which use long conducting wires, will require technological advances before these can be used in magnetic fields. Finally, degradation of scanned image quality can result from using non-MR-compatible monitoring devices.[17]

Special anaesthesia equipment made of nonferrous material designed for use in the vicinity of strong magnetic fields is available.[8] There is a good reference of MR imaging-compatible equipment available.[11] An MR imaging-compatible anaesthetic machine, physiological monitoring system and three syringe pumps were included (limited to a specified maximum sum) with the BrainSUITE contract. The decision on the choice of the model of these items were left to the anaesthetists. The process of evaluating the appropriate models of choice was guided by: (a) preference for procuring familiar models, similar to those currently used in our operating rooms;[17] (b) safety and reliability of the models in the presence of a magnetic field; and (c) all monitors had to provide visual alarms since auditory alarms are not useful during scanning.[8]

Anaesthetic machine

The Aestiva / 5 MR imaging anaesthesia machine (GE Healthcare, Madison, WI, USA) was deemed appropriate for our purpose. It has been validated for use in an MR imaging environment of up to 300 Gauss and has a magnetic field strength monitor (Gauss alarm). The machine accepts TEC 5 and 7 vaporisers (TEC 6 vaporisers cannot be used in the MR imaging environment).

Physiological monitor

The physiological monitor of choice was the InVivo Precess (Research Parkway, Orlando, FL, USA) and was chosen for the following features. It allowed monitoring of several channels including central venous pressure, intra-arterial and intracranial pressures. The Precess system includes two monitor screens (a master and a slave), one of which could be left in the iMRI operating theatre and the other in the induction or iMRI control room, useful for remote monitoring during scanning. Most importantly, Precess uses wireless ECG and pulse oximetry monitoring. This removes the hazard of potential thermal burns and avoids lengthy electrode cables getting in the way during rotation of the MR imaging table into the MR core during scanning. Other features of the InVivo Precess include compatibility to 3.0T, 5,000 Gauss, audible and visual alarms, 5 anaesthetic agent identification, eight-hour battery and offers a fibreoptic surface temperature sensor.

Syringe pumps

These pumps were important to acquire since total intravenous anaesthesia is widely used during neurosurgical anaesthesia at our centre. The syringe pump selected was a Medfusion 3500 Syringe Pump (Smiths Medical, Carlsbad, CA, USA), which has been MR imaging tested up to 150 Gauss. It weighs 1.7 kg and is compact, offering flow rates of 0.01–1,130 ml/hr. They provide several delivery modes including flow rates, body weight, mass, volume over time and custom dilution. The pumps have a ten-hour battery life using a 60 ml syringe at 5 ml/hr.

Other anaesthetic equipment

By virtue of the relatively isolated site (since access was to be controlled during surgery), the objective was to have a self-contained work environment without staff moving in and out each time an item was required. E gas cylinders, non-ferromagnetic regulator yokes and self-inflating bags with an oxygen source are available in the event of central gas failure. Other items considered essential included equipment for difficult intubation, a defibrillator, MR imaging-compatible anaesthesia drug trolley, laryngoscope, stethoscope,(17) ultrasonography for difficult line placements, and miscellaneous items such as a refrigerator and warm air blowers. Long breathing circuits (length of patient's airway to the ventilator is about 2–3 m), extension tubings for invasive line transducer systems and infusion lines have to be acquired.

FUNDING FOR OTHER ANAESTHETIC EQUIPMENT

Philanthropy had only provided for setting up of BrainSUITE, while SGH provided the premises. Manpower, training and equipment funding had to be borne by SGH. To their credit, the hospital administration approved our request for additional neuroanaesthetists and dedicated anaesthetic nurses to manage the iMRI facility and also provided training funds. Funding for anaesthetic equipment initially caused the finance department some confusion. This was because the BrainSUITE contract included provision of an anaesthetic machine, monitor and syringe pumps. The setting up of the anaesthetic induction room required additional items which SGH had to fund. Lengthy discussions, letters of justification and patience were required in order to obtain the required equipment.

OTHER CONSIDERATIONS

During scanning, noise levels may average 95 db in a 1.5 T scanner. Protective earplugs are required for staff and patients. This noise also limits auditory sense as a monitoring tool and interferes with communication.(17) The low temperatures set in the iMRI operating theatre to accommodate the sophisticated computer systems make the maintenance of the patients' body temperature during surgery difficult,(16) since warming devices may not be suitable in the iMRI machine. Therefore, an MR imaging-compatible axillary temperature probe is available. Good padding and blankets are essential for keeping the patient warm.

Unlike diagnostic MR imaging scanning, iMRI surgical procedures are prolonged and the patient is unable to communicate. Hence, measures to prevent thermal injuries are needed. As mentioned earlier, thermal injuries from sensors and cables placed on the patients may arise from pulsed magnetic-gradient field and pulsed radiofrequency field.(18) Preventative measures include paddings to prevent direct skin to skin contact, placing sensors and cables away from the magnetic coil, keeping cables off the patients and running them on blankets,(19) avoiding formation of loops of patient limbs, monitor cables, infusion lines and preventing contact of cables with the scanner.(8,19) As with standard practice before the commissioning of all operating theatres, bacterial and particulate counts were obtained from various areas of the operating room.

POSTOPERATIVE CARE

There were no changes to our usual practice of sending patients to the post-anaesthetic care unit or intensive care unit after surgery.

TRAINING AND DEVELOPMENT OF WORKFLOW

Training visits by neurosurgical anaesthetists and neurosurgical theatre nurses were made to centres with functioning BrainSUITE iMRI (Erlangen-Nuremberg and Nagoya University Hospitals). MR imaging technicians were trained by BrainLAB in the use of the BrainSUITE's complex computer software and programmes.

MR imaging safety lectures were conducted by BrainLAB for the staff. Part of the workflow developed included training any new anaesthetic or surgical doctor on the considerations of working in the iMRI facility.(17) This ongoing education is important because of the high turnover of staff and visiting specialists to our hospital. When BrainSUITE was almost operational, doctors and nurses had hands-on sessions on using the patient trolley, transfer of patients onto the MR imaging operating and scanning table, with staff simulating an anaesthetised patient who had the relevant fluid and monitoring lines.

Scenarios of problems, such as unanticipated difficult airway, a patient jammed in the scanner, a patient whose head was pinned and while within the 5-Gauss line suffering an arrhythmia requiring immediate resuscitation, were rehearsed. Workflow for fetching of equipment, drugs and blood in urgent situations were also rehearsed. Emergency exits/routes, fire drills and the role of the quench button were highlighted.

CONCLUSION

iMRI usage is becoming more common. Anaesthetists are commonly involved in the setting up of clinical services. Because an iMRI service has many considerations that involve anaesthesia,[17] the anaesthetist is an integral part of the team during the planning and setting up of this specialised service. They need to work closely with different teams of non-medical personnel, all with quite differing objectives. Safety of staff and patients using the iMRI facility is of utmost importance. Issues anaesthetists have to consider for iMRI have been discussed.[20] Over and above these concerns, the considerations of conducting anaesthesia for neurosurgery in a somewhat hostile environment requiring its own precautions, make it a challenging undertaking. There is much literature about the considerations, precautions and case reports of near misses, usually from human error and miscommunication,[21] while working in such an environment.

It is important that all teams, under an effective chief coordinator and a lead person from the vendor, communicate effectively during the planning and building process. Anaesthesists have clinical commitments in addition to this project. Hence, much of the planning has to be done in the midst of or in between cases or after office hours. With the advent of the World Wide Web, much literature and information can be obtained to help with the many questions and concerns that arose during the planning and building. The importance of sharing experiences from those who have gone through that path cannot be emphasised enough. A site visit to an existing and similar facility is very important. One gains friendship, and emails allow almost instant advice. Beyond that, one has to adapt what was learnt to the local environment. Workflows must be established, as they are important to prevent omissions in a service that require constant vigilance with no let-up in safety and clinical standards.

Apart from the altruistic ideals of furthering our subspecialty and a sense of accomplishment, there are few rewards, explaining why there are few takers to be involved in such a task. As iMRI becomes more affordable and more commonly used, many hospitals will start setting up such a service, and we hope this article will be of some help to those who are considering acquiring this facility.

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