Don’t Get Sucked in: Anaesthesia for Magnetic Resonance Imaging

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Introduction
Magnetic resonance imaging (MRI) had its origins in the 1940s, when nuclear magnetic resonance (NMR) was first described by Bloch and Purcell, work for which they were awarded a Nobel Prize for Physics. Initially, NMR was primarily a biochemical tool; however, in 1973 Lauterbur and Mansfield elucidated imaging applications. These seminal discoveries gained them the Nobel Prize for Physiology or Medicine in 2003. NMR for imaging became known as MRI, while the biochemical applications are called magnetic resonance spectroscopy (MRS). Despite MRI very much concerning the nuclei of atoms, the word “nuclear” was dropped to remove connotations of ionising radiation exposure. Since anaesthesia in the MRI suite was first described in 1984, MRI has become increasingly common, and the demand for anaesthetic services in this challenging environment has climbed. Some hospitals, especially paediatric centres, will have a large number of MRI cases requiring anaesthesia. Anaesthetists in these hospitals may therefore be familiar with the principles involved and have equipment that is mostly MRI-compatible, requiring only minor changes in their anaesthetic techniques. Other hospitals may only occasionally require an anaesthetist for MRI, resulting in anaesthetists being thrust infrequently into an unfamiliar and potentially hazardous workplace. This review aims to give some background and suggestions primarily to those occasional MRI anaesthetists.

Background and basic physics
Understanding MRI requires some discussion of nuclear physics. Atomic nuclei contain a positive charge due to their protons. Some of these nuclei spin on their own axis, like the earth rotating. A spinning charged particle creates a magnetic field, with the field orientation aligned with the axis of spin (Figure 1). With some elements, the axis of rotation itself can rotate, like a spinning top, a process called “precession” (Figure 2). Elements displaying precession are termed “NMR sensitive” and include $^1$H, $^{19}$F, $^{31}$P, $^{13}$C and $^{23}$Na. MRI scanners generally use hydrogen nuclei (i.e. protons) to generate images.

When NMR sensitive nuclei are exposed to a static magnetic field, the orientation of their spinning axes will be aligned with that of the static field. For a given element, the frequency of precession is dependent on the strength of the magnetic field. Exposure to a second, transient magnetic field at right angles to the static field will cause the nuclei to “flip” orientation and rotate in alignment with the second magnetic field. This is an energy consuming process. When the second magnetic field is
removed, the nuclei will resume their original alignment, releasing energy in the process. The characteristics of this energy release can be captured and analysed to create an image. The frequency of the energy wave released will be the proton’s precession frequency. Other important characteristics of the energy wave are the time constants of the return of longitudinal magnetisation ($T_1$) and of the decay of transverse magnetisation ($T_2$).

When electricity is passed through a coil of wire, a magnetic field orientated along the alignment of the coil is generated, creating an “electromagnet”. This is how the magnetic fields used in MRI scanners are generated. The most powerful magnet in an MRI scanner creates the static ($B_0$) magnetic field. By convention, the orientation of this magnetic field is called the z-axis. The axes perpendicular to this are called the x- and y-axes. The wire in the coil creating the $B_0$ field is typically several kilometres long, and the field strength is approximately 1.5 Tesla (1 Tesla [T] = 10,000 Gauss). The earth’s magnetic field, not to be confused with its gravitational field, is approximately 0.5 Gauss, while the magnetic field generated by a typical domestic bar magnet might be 100 Gauss. The magnets used to pick up car wrecks in scrap metal yards are about 1.5T. “Open MRI” scanners (i.e. those in which the patient lies between two flat plates

**Figure 1.** A charged nucleus spins, creating a magnetic field orientated along the axis of spin.
rather than within a tunnel) operate at lower magnetic fields (approximately 0.2-0.5 T), while scanners for experimental use operate at up to 7 T.

If the coil’s wire is cooled to almost absolute zero, the wire’s resistance becomes negligible. Under these conditions, current generated in the coil will continue to flow indefinitely with no energy input. The coil is then called a “superconductor”. In an MRI scanner, this is achieved by bathing the wire (copper embedded with a niobium/titanium alloy) in liquid helium at 4.22K (−269°C). Therefore the electromagnet created by this superconductor is always “on”, day or night, regardless of whether a patient is being scanned or not. To turn the magnet off requires the helium to be allowed to evaporate, called a “quench”. The helium is vented to the atmosphere via a “quench pipe”. This is only done to allow maintenance, as to reinstate the magnet requires several days and costs tens of thousands of dollars. An uncontrolled release of helium can create an hypoxic environment, an emergency discussed below.

The primary coil creates a tunnel in which the patient lies (Figure 3). This tunnel is approximately 2m long, with an inner core diameter of approximately 0.6m. An MRI scanner also contains radiofrequency (RF) coils, which provide “RF pulses” to produce the intermittent fields at right angles to B₀. (An RF pulse is a short burst of an electromagnetic wave that is in the frequency range of the waves received on a radio.) The scanner also contains receiving coils, which receive the energy released by

Figure 2. As well as “spin”, nuclear magnetic resonance sensitive nuclei display precession, whereby the axis of spin also rotates about the “vertical” axis. The frequency of precession for a given element is dependent on the strength of the static magnetic field.
nuclei returning to their original alignment. In some scanners, a single coil doubles as the RF and receiving coil. Finally, there are “gradient coils”, which modify the $B_0$ magnetic field, creating field gradients in the x, y and z planes. As the precession frequency depends on the magnetic field strength, the gradient coils ensure that protons in different places precess at different frequencies. Therefore, the resulting NMR signal from different locations also has a different frequency, allowing spatial localisation of returning signals. Signals from hydrogen ions in different tissues can be distinguished by the variable concentration of protons in those tissues and by the effect of atoms surrounding the protons — the so-called “lattice” which receives the energy released by the hydrogen ions.

The magnetic field strength does not decay linearly as one moves away from the scanner. Scanners are “shielded” — a design resulting in the field strength falling away rapidly so that, beyond a relatively short distance (say, at the door to the scanning suite), the fringe fields are negligible. Conversely, the field strength rises rapidly as one nears the scanner and care must be taken not to inadvertently bring ferromagnetic objects dangerously close to the magnet. Some suites have “Gauss lines” (e.g. 30 Gauss and 5 Gauss lines) drawn on the floor to act as a warning.

External radiofrequency waves from television or radio transmission or from electronic equipment in adjacent offices must be excluded from the scanning suite to

![Figure 3. The patient lies inside the magnet core.](http://nobelprize.org/medicine/laureates/2003/press.html)
prevent interference. This is done by enclosing the scanner in a “Faraday cage”, a copper sheet in the walls of the suite. Cables and tubing can be passed through filtered ports in the cage.

A typical MRI scan might take 30-40 minutes, and unless the part being scanned is a leg, the patient’s head and torso will be within the magnet’s core for this time. The rapidly changing currents in the gradient coils cause a loud banging noise. These may be issues of concern for claustrophobic patients.

**Issues for anaesthetists**

1. **Remote location**

   A modern MRI scanner weighs several tonnes, presenting structural limitations on the location of the suite. Also, the need to isolate the scanner from extraneous radiofrequency waves, and the fact that it is a relatively new technology that was not incorporated into the design of older hospitals, can result in the MRI suite being situated in a far-flung basement corner of the hospital. Even if not quite as dire as this, the scanner will be outside the operating theatres, so all the issues of anaesthesia in the remote location apply. These include the necessity to take adequate drugs, equipment and assistance.

2. **Specific patient characteristics**

   Patients requiring anaesthesia for MRI tend to fall into one of a small number of categories, each with their own anaesthetic requirements. It is not the intention of this review to address each of these issues. As mentioned previously, a substantial proportion of these patients will be children. Other groups include: patients with intellectual impairment or other neurological disease that prevents them lying still for the requisite time, claustrophobic patients and critically ill intensive care patients who are sedated while on ventilators. This latter group presents a high-risk population, especially those on vasoactive infusions, and serious consideration should be given to the risk-benefit ratio of the MRI.

3. **Limited access to the patient**

   For most scans, the anaesthetist will scarcely be able to see, let alone access the patient’s airway. Furthermore, the patient’s arms may be inaccessible, necessitating long IV tubing.

4. **Ferromagnetism**

   “Ferromagnetic” refers to an element that can become magnetised when exposed to an external magnetic field. The term can cause confusion, as not all ferromagnetic objects contain iron, and not all iron-containing (or ferrous) objects are ferromagnetic. Iron is the most common example of ferromagnetism, hence the name, but other ferromagnetic elements include nickel, cobalt and some of the rare earth metals (e.g. gadolinium). Conversely, stainless steel is mostly iron, but the chromium, nickel and carbon in the alloy alter its magnetic properties. The most common form of stainless steel is called “austenitic” and is non-ferromagnetic.

   Ferromagnetic objects will be drawn to the magnet, and can become dangerous missiles for staff and patients (Figure 4). At least one death has been reported, that of a six-year-old boy struck by a flying oxygen cylinder.\(^3\) The literature is littered with reports of near misses.\(^4\) Ferromagnetic items must be kept outside the 30-50 Gauss
lines\textsuperscript{4} or, ideally, excluded from the MRI suite. Only aluminium gas cylinders are acceptable. Standard patient trolleys and IV poles contain iron, so are unsuitable. Smaller problem items include metal stethoscopes, keys, pens, scissors and paperclips. Most jewellery is safe (at least if it’s real gold!). If unsure, remove it or test it with a magnet.

Non-ferromagnetic metals will not be drawn to the magnet, but, when exposed to the magnetic fields, can have electric currents generated in them, causing heating or malfunctioning of electronic equipment. They can also cause image artefact.

5. The effect of the MRI on anaesthesia equipment

It is easiest to consider our equipment in the order in which one might encounter it when giving an anaesthetic. A comprehensive list is available at http://www.mrisafety.com.

a) Intravenous cannulae needles: These are made from stainless steel and are safe.\textsuperscript{5}
b) Monitors: MRI compatible monitors are commercially available. These may include a master monitor and a slave monitor. The slave monitor can sit in the MRI control room and receive information wirelessly from the master, which stays in the MRI suite. These monitors are expensive, costing in the order of

![Figure 4. This is a chair stuck in the magnet core. Fortunately, no one was hurt in this incident. (Figure from http://www.simplyphysics.com/flying_objects.html)](Figure from http://www.simplyphysics.com/flying_objects.html)
$AU120,000, approximately three times a comparable non-MRI compatible monitor. Non-MRI compatible monitors invariably contain ferromagnetic components, so may be unsafe. Care should be taken to consult the product specifications before equipment labelled “MRI compatible” is purchased or used, as some such items may still contain ferromagnetic components and will have a maximum magnetic field to which they can be exposed.

c) **Non-invasive blood pressure cuffs:** If the tubing connectors are plastic, not metal, these will function normally and are safe.

d) **Invasive blood pressure transducers:** These are not ferromagnetic, and are safe to use. Transducer cables should be kept out of the magnet bore, so as to avoid image distortion.

e) **Pulse oximeters:** Standard pulse oximeters can malfunction in the MRI suite and have also been reported to cause patient burns due to overheating. MRI compatible pulse oximeters utilise fibre-optic cables. These function well but are fragile and expensive to repair, so great care must be taken with their use.

f) **Electrocardiogram (ECG) monitoring:** The ECG is useful in the MRI suite only to demonstrate a rhythm, as artefactual ST and T wave changes are common, precluding any meaningful assessment of myocardial ischaemia. Any conductor moving through a magnetic field will have a current induced in it. This is especially so for objects moving at right angles to the orientation of the magnetic field. For this reason, blood flowing through the aortic arch will generate a small current that will be detected by the ECG. This manifests as peaked T waves, predominantly in leads I, II, V1 and V2. V5 displays the least ECG change. The intermittent fields cause artefact spikes.

Standard ECG cables are insulated copper, and generate heat in the MRI scanner. This is especially so if the cables are allowed loop. Carbon fibre leads have less potential to heat. All leads should be kept as close as possible to the centre of the magnet bore and should all run in a straight line from the praecordium towards the patient’s feet. They should not lie directly on the patient’s skin, because of the risk of burns. Braiding the leads to make one thick cable prevents one lead from forming a large loop.

The ECG dots must be MRI compatible, again to avoid burns. Some MRI scanners have inbuilt ECG monitoring using wireless transmission of a signal from chest leads. However this is only to allow cardiac gating for thoracic scans, not for diagnostic purposes.

g) **Capnography:** Long sampling tubing may result in mixing of end-tidal gas with dead space gas. As a result, end-tidal measurements may not be accurate, although they are adequate for apnoea monitoring and for trends. Long tubing also gives rise to a long lag time.

h) **Temperature probes:** Thermistor probes are not practical because of the ferromagnetic content of their cables.

i) **Anaesthetic machines:** Standard Boyle machines and non-MRI compatible anaesthesia workstations are unsuitable for use in the MRI. While MRI compatible machines are available they cost in the order of $AU 80,000 with a ventilator. This is approximately double the price of a comparable non-MRI compatible machine. At least one portable MRI-compatible anaesthesia machine is available, at about the same cost as a standard machine (Magmedix Portable Anesthetic machine for MRI, model 2200). This 57 × 57 × 42 cm device,
incorporating a ventilator, soda lime canister and vaporiser, resembles a machine for military use.

j) **Ventilators:** MRI compatible ventilators are available and are generally included with MRI compatible anaesthetic machines. Many stand-alone ventilators contain ferrous components and electronic circuitry that may malfunction when exposed to the magnetic field. The Dräger Oxylog 2000 is a simple fluidic ventilator that functions normally in the MRI area. However, it does contain a small amount of iron, so needs to be positioned sufficiently far from the magnet and anchored so that it does not become a missile risk. The distance from the magnet should be determined by biomedical engineers before an anaesthetist takes such a ventilator into the suite. Being a long distance from the patient means that accurate estimation of tidal volumes is difficult, due to compliance of the circuit and gas compression.

k) **Breathing circuits:** Circle, Bain and T-piece circuits can all be used if they are all plastic. Care should be taken to exclude PEEP valves that contain metal springs. In spontaneously ventilating patients, a Laerdal airbag (Laerdal Medical Corporation, Stavanger, Norway) with a reservoir bag or a blue “T-bag” (T-bag oxygen enhancement device, Ultimate Medical Pty Ltd) can be used.

l) **Laryngoscopes:** Although laryngoscopes may be non-ferrous, the batteries are highly ferromagnetic and cannot be used in close proximity to the magnet. A technique has been described for substituting lithium batteries and aluminium spacers, allowing appropriate laryngoscope to be used anywhere in the MRI suite.5

m) **Endotracheal tubes:** While standard tubes themselves cause no difficulties, the spring in the pilot balloon can cause artefact. If this interferes with the area being scanned, the pilot balloon tubing can be knotted and the spring cut off. Reinforced tubes will cause significant artefact due to the metal coil.

n) **Laryngeal masks (LMA):** Reinforced LMAs or FastTrachs are unsuitable for use in MRI as they cause excessive artefact. Classic LMAs are suitable. Again, the pilot balloon may cause artefact but this can be minimised without having to cut the balloon off by taping it as far as possible from the area to be scanned.

o) **Vaporisers:** Early generation vaporisers are not accurate in the MRI suite, due to malfunctioning of the bimetallic strip temperature compensation. Modern generation vaporisers (e.g. Datex Ohmeda Tec7) are MRI compatible. Regardless, as in the operating theatre, ANZCA guidelines mandate the use of agent monitoring.

p) **Syringe pumps:** Common syringe pumps are not compatible with MRI. They function accurately up to 100 Gauss,9 but pose a missile risk. They should therefore be placed outside the scanning suite, with long minimum volume tubing running through a wall port. This leaves a large amount of dead space in the line, leading to drug wastage.

6. **The effect of our equipment on the MRI**

Inadequately shielded electrical equipment will emit RF signals that will interfere with the MRI scanner, causing artefact. Non-ferrous metals close to the area being scanned can create similar problems. Large non-ferrous objects in the scanning suite should not be moved once the scan has commenced as this also can affect the magnetic field.
7. Implanted metallic devices

a) **Pacemakers:** A permanent pacemaker constitutes a contra-indication to MRI scanning. Currents generated in the pacemaker circuitry, even at low field strengths (e.g. 17 Gauss), can cause serious malfunctions.\(^{10}\) This has resulted in at least one death in Australia. Reports exist of patients with pacemakers being scanned in low field strength scanners (0.5T),\(^{11}\) but the risk-benefit ratio needs to be seriously considered.

b) **Cochlear implants:** These devices contain a magnet that holds the external component to the subcutaneous receiver and is also involved in signal transmission. This magnet may move and cause injury.\(^{12}\) If it is known at the time of cochlear implant insertion that future MRIs will be required, the internal magnet can be omitted and the external component secured with adhesive patches. In such a case, an MRI could be performed, although significant artefact could be expected in head scans.

c) **Orthopaedic prostheses:** The metal components of these prostheses are generally titanium or chromium/cobalt. Screws and plates are stainless steel. While these implants may cause some image artefact, they are safe in the MRI scanner. External fixation devices often contain iron, so are contraindicated.

d) **Prosthetic heart valves:** These valves and annuloplasty rings undergo minimal heating and torque and are safe in MRI,\(^{13, 14}\) although some artefact may be caused.

e) **Aneurysm clips:** These are variable. Earlier models were ferromagnetic, so could move in the magnetic field, with potentially disastrous consequences. Most modern clips are non-ferromagnetic and are safe in MRI.\(^{15}\) Due to this variability, manufacturers’ specifications should be checked.

8. Other

a) **Quenches:** Sudden evaporation of the liquid helium due to a rise in temperature can lead to a dangerously hypoxic environment in the MRI suite. This may not be noticed as helium is colourless and odourless. A controlled quench will allow the gas to escape to the atmosphere via quench pipes, but damage to the casing of the scanner could allow helium directly into the room. As helium is lighter than air it will rise, so oxygen analysers should be positioned high in the room.

b) **Tattoos and make-up:** Some tattoos and make-up contain metal pigments. These can cause image artefact or heat, causing skin discomfort, although burns have not been reported.

c) **Magnetic media:** Exposure to greater than 30 Gauss can cause corruption or memory loss with credit cards, computer discs, digital watches and personal electronic organisers inadvertently brought near the magnet.

d) **Biological effects of MRI:** If patients are moved in or out of the scanner quickly, currents can be induced in nervous tissue, causing transient visual symptoms or unusual tastes.\(^{13}\) This is particularly so in high strength magnets (e.g. >4T).

e) **MRI in pregnancy:** MRI does not involve exposure to ionising radiation, unlike CT or plain X-rays. There is no evidence of teratogenicity from MRIs. Therefore, if imaging is indicated during pregnancy it is the modality of choice. Having said that, there is no definitive evidence of the safety of exposure to high strength magnetic fields in pregnancy; thus, exposure should be avoided if possible, especially in the first trimester, and the risk-benefit ratio carefully considered.\(^{16}\)
f) **Contrast:** The most common agent, dimeglumine gadopentetate (Magnevist, Schering Pty Ltd), has a high therapeutic index compared to iodinated agents. Anaphylactoid reactions have been reported as having an incidence of approximately 1:100 000. The dose (0.2 mls/kg) should be injected over one minute to minimise pain on injection, as the preparation is hyperosmolar.

g) **Noise:** During scanning, noise levels in the magnet core approximate 95dB, equivalent to light roadwork. Earplugs may assist in patient comfort.

### Anaesthetic technique

It is difficult, though not impossible, to comply with ANZCA guidelines for monitoring without an MRI-compatible monitor. A case in a remote and potentially hazardous location, with poor access to the patient, is not the time to relax monitoring standards.

Considerable debate exists regarding the relative merits of sedation and general anaesthesia for MRI. Proponents of the former often have mild sedation administered by non-medical personnel, although failed scans due to inadequate sedation are common. If the patient’s anaesthetic requirements exceed conscious sedation, it is the author’s experience that a formal general anaesthetic with an LMA or ETT is preferable to deep sedation.

If an MRI-compatible anaesthetic machine is available, the anaesthetic technique need not vary greatly from that used in the operating theatre. In such cases, the anaesthetist can stay in the scanning room with the patient. If the patient requires intubation, this should be done outside the scanning room. If an LMA is to be used and the patient allowed to breathe spontaneously, care should be taken that there is not excessive head movement with ventilation, as this will degrade the images.

If no compatible machine is available, the patient must receive total intravenous anaesthesia via syringe pumps outside the scanning room. In this case, the anaesthetist will sit in the control room (i.e. not in the scanning room) during the scan, to allow control of the pumps. This presents potential problems, and the anaesthetist should ensure that monitors can be seen, and should not hesitate to interrupt the scan to enter the scanning room should the need arise. (Even this is not foolproof, as a report exists of a malfunctioning door to the scanning suite locking an anaesthetist out from his patient, a baby under general anaesthesia!) A three-way “multiflow” can be connected to the patient’s IV cannula, with fluid connected to one limb, a propofol

![Figure 5. A blue “T-bag” makes a very lightweight and compact “circuit” for spontaneously ventilating patients receiving total intravenous anaesthesia. Manual ventilation (with small tidal volumes) can be instituted by occluding the opening to atmosphere and squeezing the blue bag.](image-url)
infusion with long tubing to a pump in the control room on the second limb, and a drug injection line, again with long tubing to the control room, on the third.

The most common indication for anaesthesia for MRI in adults is claustrophobia. These patients can breathe spontaneously on an LMA. A blue “T-bag” provides the most lightweight and compact “circuit” (Figure 5). These bags have a volume of 300 mls; at tidal volumes exceeding this, room air will be entrained, decreasing the inspired oxygen fraction. In most patients an FiO2 of 0.5-0.7 can be achieved. Using a Bain circuit and high flow rates of 10-15 l/min, 100% O2 can be delivered. However, if this is required, the suitability of spontaneous ventilation on an LMA should be reconsidered. If the patient requires ventilation, an Oxylog ventilator can be placed a suitable distance from the scanner. Lightweight 22 mm corrugated tubing (e.g. Corr-a-flex® II, Hudson RCI®) comes in long rolls and can provide a suitable connection between the patient and the ventilator, without the need for multiple double-male connectors. As mentioned, the tidal volume set on a ventilator will be greater than that actually delivered, due to high circuit compliance; capnography should be used.

The issue of where to wake the patient depends on individual circumstances. If facilities or staffing in the MRI department are not suitable, it may be safer to transport the patient to the theatre recovery room for emergence.

Conclusion
In summary, anaesthesia in the MRI suite can be daunting and potentially hazardous, if undertaken without prior thought and planning. However, as demand for this service increases (including even intra-operative MRI for neurosurgery!), anaesthetists should become familiar with the requirements in the MRI suite. In this way, the high anaesthetic standards expected in the operating theatre can also be achieved in this challenging environment, providing patient comfort, safety and high quality images.

Further information
A number of excellent resources are available online:

• http://www.users.on.net/~vision/ — the Adelaide MRI Website — This website, maintained by Greg Brown, a radiographer at Royal Adelaide Hospital, is a great resource, with links to every other site you could want.

• http://www.cis.rit.edu/htbooks/mri/ — a very detailed review of the physics of MRI by Dr Joseph Hornak of the Rochester Institute of Technology.

• http://www.mrisafety.com — the official website of the Institute for Magnetic Resonance Safety, Education and Research, including a list of over 1300 implants and other devices that have been tested for MRI safety.

• http://www.apsf.org/resource_center/clinical_safety/mri — an excellent review of safety in the MRI suite by Dr Charlotte Bell, Associate Professor of Anesthesiology at Yale.

• www.simplyphysics.com — among other things, good (in a schadenfreund sort of way!) photos of projectiles stuck on magnets.

References


