Guidelines

Guidelines for the safe provision of anaesthesia in magnetic resonance units 2019

Guidelines from the Association of Anaesthetists and the Neuro Anaesthesia and Critical Care Society of Great Britain and Ireland

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Summary

There has been an increase in the number of units providing anaesthesia for magnetic resonance imaging and the strength of magnetic resonance scanners, as well as the number of interventions and operations performed within the magnetic resonance environment. More devices and implants are now magnetic resonance imaging conditional, allowing scans to be undertaken in patients for whom this was previously not possible. There has also been a revision in terminology relating to magnetic resonance safety of devices. These guidelines have been put together by organisations who are involved in the pathways for patients needing magnetic resonance imaging. They reinforce the safety aspects of providing anaesthesia in the magnetic resonance environment, from the multidisciplinary decision making process, the seniority of anaesthetist accompanying the patient, to training in the recognition of hazards of anaesthesia in the magnetic resonance environment. For many anaesthetists this is an unfamiliar site to give anaesthesia, often in a remote site. Hospitals should develop and audit governance procedures to ensure that anaesthetists of all grades are competent to deliver anaesthesia safely in this area.
What other guidelines and statements are available on this topic?
The first Association of Anaesthetists guideline on provision of anaesthetic services in magnetic resonance (MR) units was published in 2002 [1], with an update on safety in MR units published in 2010 [2].

Why were these guidelines developed?
There is an increase in the number of units providing anaesthesia for magnetic resonance imaging (MRI) and in the type of intervention performed within the MR environment. These guidelines are intended to inform and advise anaesthetists, as well as the multidisciplinary team, about safety aspects and best practice relating to anaesthesia within the MR environment.

How does this statement differ from existing guidelines?
These guidelines include new material on several topics including revised terminology, changes to the number and type of implants and devices that can be scanned, different layouts of interventional scanning units, and the types of surgery or intervention that can now be performed within the MR suite.

Recommendations

Service organisation and training

1 All hospitals providing a service for anaesthesia within the MR unit should have a lead anaesthetist responsible for provision of anaesthesia for MRI.
2 Training should be provided for all grades of anaesthetist delivering anaesthesia in this remote area; all anaesthetists should have an understanding of the hazards involved in anaesthetising a patient in the MRI unit.

3 Anaesthesia/sedation for a patient needing an MRI scan, including intensive care unit (ICU) patients, should take into account the patient’s pathophysiological status and the remote location of the MRI unit.
4 Whenever possible, anaesthesia in remote sites should be provided by appropriately experienced consultants.
5 When care is delegated to a trainee or Specialty and Associate Specialist (SAS) doctor, they should have the appropriate competencies and level of training.
6 It is not acceptable for inexperienced staff, unfamiliar with the MR environment, to manage a patient in this environment, particularly out-of-hours.
7 Patients must be accompanied to the scanner by appropriately trained staff members, and if an anaesthetic machine is being used, then the anaesthetist should be supported throughout by an anaesthetic assistant who should be suitably skilled, trained and familiar with the anaesthetic requirements.

Patient and staff safety

8 All patients and staff must be screened for the presence of implants and devices that may be a contraindication to a safe scan. The referring team should discuss the safety of the devices with the MR Responsible Person and the anaesthetist to plan a suitable management strategy.
9 Anyone remaining in the scanning room should be provided with ear protection during scanning.
10 The MRI for patients should only be undertaken if the diagnostic benefit outweighs the risk. This discussion must involve the multidisciplinary team, particularly for a patient on the ICU.
11 The MR safety checklists for general anaesthesia, intra-operative MRI and for transfer of ICU patients should be used in conjunction with the World Health Organization (WHO) checklist.
Introduction

Magnetic resonance imaging is a widely used diagnostic tool used to investigate many conditions; anaesthesia has been used to facilitate MR scanning since the 1980s. The number of scanners in the UK is increasing rapidly, and there are more than 6.2 scanners per million population in the UK and 13.5 per million in Ireland; this equates to about 460 scanners across both countries [3, 4]. Many units now perform interventions within or adjacent to a MR scanner, and increasingly patients will need to be anaesthetised for either the scan itself or the intervention. In addition, the magnetic field strengths that are in routine use have increased, and more patients are now scanned with active implanted medical devices such as neurostimulators, pacemakers and drug pumps, which adds to the challenges for the anaesthetic team. The combination of a continuous strong magnetic field, reduced patient access and a site frequently remote from the operating theatre suite means that these cases are complex; clearly established guidelines and risk management processes are essential.

The increasing need for anaesthesia within the MR environment means that more anaesthetists will be involved in providing this service. When new procedures are planned, it is essential that the anaesthetic department is involved in any development of the service.

The aim of this document is to update the guidelines published by the Association of Anaesthetists in 2002 and 2010 [1, 2], and to offer practical support for the provision of safe anaesthesia within the MR scanner.

Hazards

Magnetic resonance imaging is based on the interactions between a static magnetic field generated by a scanner and the tiny fields that arise from individual atomic nuclei with their own net spin. It exploits the slight energy difference between states of such nuclei in the magnetic field. Applying an oscillating field at the correct frequency, typically in the radiofrequency (RF) range, causes some nuclei to move to a higher energy state. As they relax back to the lower energy state, they re-emit energy at the same frequency and this is detected by a receiving coil. Images are formed by perturbing the uniform static field with small, dynamic gradient fields, thus altering the frequency of interaction. This allows both spatial localisation and control of various aspects of image contrast [5].

Magnetic resonance imaging hazards can be divided into five broad categories:

Displacement force from static magnetic field

Ferromagnetic objects within the 3 mT field contour will experience an attractive force, pulling them towards the centre of the magnet and a torque as they attempt to line up with the field. Conductive objects passing through the field may experience additional temporary forces and induced currents while in motion. With most modern MR scanners the magnetic field is always on, even between scans, so constant vigilance is important. Even small objects become dangerous projectiles, sufficient to injure or kill anyone in their path, and larger objects can trap or crush a patient or staff member. Foreign bodies in tissue may become dislodged, leading to damage or haemorrhage; this is a particular hazard in the eye or near blood vessels. Implanted pacemakers, defibrillators, neurostimulators and other devices may be inactivated, reprogrammed, dislodged or converted to an asynchronous mode by the magnetic field. Careful screening of equipment, staff and patients and carers before entry to the magnet room is, therefore, essential.

Induced currents from time-varying magnetic fields

Smaller dynamic magnetic fields, known as gradient fields, are manipulated rapidly during image acquisition; these can induce a current sufficient to stimulate the peripheral nerve and muscle cells, sometimes causing discomfort. Magnetic resonance scanners apply limits on gradient field manipulation to avoid the more extreme consequences of induced currents, such as limb movement or ventricular fibrillation.

Acoustic noise

See below.

Heating from radiofrequency fields

A powerful radio transmitter interacts with patient tissue at the resonant frequency of the scanner and can lead to power dissipation, which may be non-uniform, within the patient. There is a corresponding increase in temperature. The scanner continuously monitors RF power to limit this effect, although other factors such as ambient temperature, airflow, humidity, clothing and localised RF hotspots play a role in temperature change. RF heating can create a risk of severe and rapid burns from any conductive material left on the patient’s skin; contact with metal in clothing, ECG leads and other equipment must be limited unless the device is known to be safe. Similar risks apply to conductive material
within the patient, particularly pacemaker or neurostimulator wires, and all implants must be carefully screened for RF safety.

**Helium escape**

When a superconductor is used to maintain the main static magnetic field, the cryostat typically contains around 1000 litres of liquid helium within a few degrees Celsius of absolute zero. In the event of a spontaneous or emergency field shutdown, known as ‘quench’, the liquid helium expands to a gas and must be vented very rapidly. The MR suite is designed to vent this to the outside of the building via a quench pipe, but if this fails or becomes blocked, some or all of the gas may enter the suite, necessitating rapid evacuation. Magnetic resonance suites usually have oxygen sensors, ventilation controls and a pressure equalisation mechanism to alert staff, ensuring that safe evacuation is always possible. All staff should be aware of the departmental emergency quench procedure.

**Patient safety**

It is crucial that patient safety is the main focus for the whole team, and that patients understand the additional risks involved with procedures within the MR scanner. All patients must be screened for devices and implants that may contra-indicate a safe scan. This is the responsibility of the imaging department operating the scanner, who will have local rules tracing responsibility back, through radiographers and radiologists, to an MR Responsible Person supported by an MR Safety Expert [6]. Screening is particularly important in patients who are transferred from the ICU, and for those who cannot give an accurate history. It is important to assess the exact make and model of any medical implants in the patient’s body in advance of the procedure. Similar devices performing ostensibly the same function may be affected in very different ways by MRI scanning, and the MR Safety Expert may need time to contact a manufacturer or obtain up-to-date condition documentation before the scan.

For MR purposes, all equipment and implants fall into one of three formal categories: MR Safe, meaning it contains no material that would present a hazard at any field; MR Conditional, meaning it is safe to scan under specified conditions detailed by the manufacturer and based on testing; or MR Unsafe, meaning it presents an unacceptable risk to patients or staff if used within the MR environment [6–8]. The term ‘MR compatible’ is ambiguous and should no longer be used.

**Passive implanted medical devices**

Some passive implanted medical devices may contain metal components that may either heat up during scanning, produce artefact of the image or discomfort for the patient if the implant moves during the MR scan itself. These implants include vascular access ports, catheters, cardiovascular stents or heart valves, orthopaedic, ocular and penile implants, as well as tissue expanders and breasts implants. The RF identification tag on certain breast implants can heat up during the MR scan. In most cases the scan can still proceed under certain conditions, but it is important to discuss these implants with the MR Responsible Person who can access the appropriate manufacturer’s guidance [6].

**Implanted cardiac devices**

All implanted cardiac devices must be checked and will be subject to certain conditions, as described by the device manufacturer [9, 10]. Most prosthetic heart valves, mechanical or bioprosthetic, and all coronary stents are considered safe in the MR environment at field strength up to 1.5 T and many will be safe up to 3 T. Previously, the presence of a pacemaker or internal defibrillator was an absolute contraindication to performing an MRI scan [11, 12]. However, this is now a relative contraindication, as in 2006 MR conditional pacemakers were introduced that allow patients to have non-cardiac MRI scans under controlled conditions. These conditions are always detailed by the device manufacturer. If the pacemaker and leads are described as MR Conditional by the manufacturer, and the patient is not pacemaker dependent, it may be safe to turn off the pacemaker or turn it to a fixed mode for the duration of the scan [13]. This should only be done after discussion with the patient’s cardiology team. The patient is then monitored throughout the scan and the pacemaker reprogrammed afterwards [14, 15]. The scan itself may be subject to additional technical constraints detailed in the written conditions from the manufacturer. Implantable defibrillators are usually a contraindication for MR, but in some cardiac centres scanning is possible, with appropriate monitoring and resuscitation support [13].

**Programmable shunts**

The pressure settings on valves of programmable shunts for hydrocephalus may be changed by an MR scan, which could lead to under- or over-draining after the scan. Patients with these devices must be assessed by their neurosurgical team before scanning, to confirm the correct settings and to reset the device after the scan if required. Many programmable
Neurostimulators and implantable programmable devices

Neurostimulators are now implanted for many indications, for example, vagal nerve, deep brain or spinal cord stimulation, and may be affected by RF and magnetic fields. In addition, they may cause thermal injury during scanning. It is recommended that patients with implanted stimulators do not undergo MRI, but the risks may be balanced against benefits to allow scanning under controlled conditions. Increasingly, neurostimulators are being developed that are MR Conditional; advice on the recommended scanning times and modes are available from the manufacturer. An increasing number of patients have implanted baclofen and analgesic pumps or an in-dwelling telemetric intracranial pressure monitor, which will need to be discussed with MR staff. There have been incidents when the entire dose of a baclofen pump was discharged on scanning, thus necessitating the pump to be emptied before scanning [17]. Most of the major neurostimulator and pump manufacturers require these devices to be checked after an MR scan, and it is important to liaise with the supervising pain or neurosurgical team when these patients are booked for an MR scan.

Biohacking (self-implanted technological enhancement of the human body)

Clinicians need to be aware of body modification-incorporating implants (such as transdermal or extra-ocular devices). These may be implanted with specific technological functions – a practice known as ‘biohacking’. Examples include implantation of multiple tiny magnets under the fingertips to allow users to sense electromagnetic fields and the insertion of RF identification chips capable of near-field communication to open doors or login to computer systems. These should be considered when a decision is made to scan a patient, they are probably low risk, but may cause artefact.

Gadolinium

Up to 30% of MR scans require intravenous (i.v.) contrast to improve the resolution of tissues and to demonstrate vascular structures. The most commonly used agent is gadolinium based. This is generally safe, although severe anaphylactoid reactions have been reported with an incidence of up to 0.01% [18]. Other mild side-effects, including headaches, nausea and dizziness, can be seen in 1–5% of cases. Gadolinium is renally excreted within 24 h. The older gadolinium compounds may be associated with nephrogenic sclerosing fibrosis, a condition in which deposits of fibrous tissue develop predominantly in the skin, but occasionally in musculature, particularly cardiac muscle. This condition only occurs in patients who have end-stage renal failure. If the eGFR is < 30 mL min⁻¹.1.73 m⁻², the risk of administration of gadolinium must be balanced against the diagnostic benefit. Current guidance is that in children and in adults with a low GFR, administration of gadolinium should not be repeated within a period of 7 days [19].

Gadolinium macrocyclic contrast compounds are now available that bind gadolinium much more tightly than the old compounds; these have not been associated with any cases of nephrogenic sclerosing fibrosis in the literature. Estimation of eGFR may not be required if these newer compounds are used. The safety profile of gadolinium-based contrast agents in children < 2 years old and pregnant women is unknown [20].

Acoustic noise

The switching of the gradient fields within the main magnet creates loud acoustic noise. When this noise level exceeds 80 dB(A), which is likely in most scanners, hearing damage is possible. The UK guidelines require that all people remaining in the scanner room are provided with MR Safe hearing protection [6, 21–23]. Protection may be in the form of earplugs, ear defenders or both. This provision is particularly important for anaesthetised patients, who are unable to alert the operators to hearing discomfort. Staff should be trained in the selection and use of hearing protection, and its use in each individual patient should be documented in the patient’s notes. Recent studies suggest that temporary hearing loss is possible with a 3 T scan, even with the use of standard hearing protection. Care must be taken to use effective hearing protection, and to warn patients and staff of this risk [24, 25].

For the anaesthetic team, a set-up allowing remote monitoring from the control room is ideal. If this is not possible, ear protection must be worn by staff who remain within the examination room, but the noise may make communication difficult.

Staff safety

It is the responsibility of the radiology department to screen and train all staff working within the MR environment (see also Supporting Information Appendix S1; Checklist 1). Screening should use the same protocols as those used for patients, and a record of both screening and training should be kept by the department. These records should be
reviewed on a regular basis. In many units, access is restricted to appropriately trained personnel in order to maximise safety.

**Electromagnetic fields**
Sudden movement within the strong magnetic field can cause very weak electrical currents to be induced in some tissues. This may cause staff to experience nausea and vertigo caused by excitation of the semicircular canals within the inner ear, or flashing lights caused by the effect on the retina.

The Control of Electromagnetic Fields at Work Regulations 2016 now requires employers to carry out risk assessments for staff working in the MR environment [7, 26].

**Pregnant staff**
See ‘MR scanning in pregnancy’ below.

**Equipment and monitoring**
Most diagnostic units exclude all unlabelled or MR Unsafe equipment [7] from the examination room, but more complex rules may be needed in interventional settings where standard ferromagnetic surgical equipment is used outside the MR environment. When no viable MR Safe or MR Conditional alternative can be found, the equipment may be physically controlled with a tether or with clear workflow controls using a standardised operating procedure (SOP).

The level of monitoring and equipment for anaesthesia in the MR environment should conform to national guidance, and be the same as that provided within the operating theatre [27]. It is recognised that MR Conditional equipment may be different to that used elsewhere in the hospital, and anaesthetists should familiarise themselves with this equipment before use. Individual units should assess the safety of the equipment used with respect to magnetic fringe fields and with input from the local MR Safety Expert (often a clinical scientist), where equipment can be placed. Many units use markers on the floor to identify safety ranges. Where possible, the unit set-up should allow monitoring in the control unit while scanning is taking place.

Fibreoptic pulse oximeters should be used, as there have been reports of burns caused by induction currents using standard oximeters. Electrodes used for ECG and EEG monitoring must also be removed before scanning, as they may cause burns. Specific MR Safe ECG electrodes are needed to monitor the patient during anaesthesia or sedation. Care should be taken interpreting the ECG trace when the patient is being scanned. Harmless field strength-dependent ECG changes can include T-wave elevation, which may sometimes become larger than the QRS complex, and a reduction, or even inversion, in R-wave amplitude. These changes can be explained by an induced current in the blood as it flows through the thoracic aorta within the magnetic field. The ECG will revert to normal once scanning ceases.

Non-invasive blood pressure monitoring is easily achieved by using plastic rather than ferromagnetic connections. For invasive blood pressure monitoring, the length of the line must be minimised to reduce damping; the pressure bag for the saline flush should not have metallic components. The length of the capnograph sampling line should be minimised to reduce the time-lag in changes in the waveform. Both peripheral and central temperature can now be measured with specifically designed probes. Other devices, such as intracranial pressure monitors, are usually removed before the scan; in some cases, the scan can be performed under specific controlled conditions, which will be determined by local rules and the manufacturer’s safety information.

**Layout and design**
The MR scanners typically use field strengths between 0.5 T and 3 T, although some 7 T scanners are now entering clinical use. The body part to be scanned is usually placed at the centre of the magnetic field, as most diagnostic scanners use a cylindrical-bore design. The patient is within the bore, thus limiting access by clinical staff. For this reason, alternative designs, broadly described as ‘open’ systems, have been popular for interventional applications such as image-guided biopsy or cardiac catheterisation, and for claustrophobic or obese patients. Most of these systems achieve lower field strengths with a reduced image quality.

In the last decade, arrangements comprising a standard cylindrical-bore magnet adjacent to the surgical area have become increasingly popular for providing diagnostic-quality imaging during interventional procedures.

A wide variety of MR unit layouts are possible [28], but typically address two main factors, access control and visibility.

**Access control**
The space around an MR scanner is divided into two areas. The immediate vicinity of the scanner, where the static magnetic field creates a risk of projectiles and hazards to implants, as well as RF heating risks, is known as the ‘MR environment’. A second larger area including adjoining rooms, such as the control or anaesthetic preparation room, is known as the ‘MR Controlled Access Area’. The suite
should be designed such that suitable electronic or physical locks prevent unauthorised access to the MR Controlled Access Area, and that all routes to the MR environment pass first through these outer spaces.

**Visibility**

A window, usually containing a fine mesh for RF screening, should allow line-of-sight visibility of the scanner, the patient, and all potential access routes into the MR environment. The latter is of particular importance in an interventional setting when the scanner room might be accessed through multiple doors, from both the control area and the anaesthetic preparation area.

Anaesthetic input into the design of a hospital MR suite is essential to ensure that appropriate space for anaesthesia and emergency procedures is planned for. In designing the layout of the MR suite, consideration should be given to placement of the anaesthetic machine, piped gas outlets and suction. In control room design, enough space should be allowed for remote anaesthetic monitoring equipment and line-of-sight patient monitoring for all staff, anaesthetists and radiographers. The route for urgent access should be clearly marked to ensure that staff are neither provided free access into the MR environment nor stopped too far from it (see ‘emergency procedures’ below).

Possible changes in use of a unit should be considered at the time of installation, as a diagnostic suite may later be used for anaesthetised patients or the types of cases performed in an interventional suite may change. Once an MR suite is operational, any modification or redecoration is often prohibitively expensive due to the always-on magnetic field and the need for proven RF-cage integrity.

Several example layouts are shown in Supporting Information Appendix S2. These are all working units in the UK, simplified for illustrative purposes, and show the three main functional layouts in current use: diagnostic MR units, single-room interventional units and two-room interventional units in which the surgical and MR spaces are separated by a door, with independent access.

**Personnel and workflow**

Named individuals with personal access to the MR Controlled Access Area are known as MR Authorised Persons. Within this definition, the Medicines and Healthcare products Regulatory Agency (MHRA) guidelines recognise a concept of supervision and subcategories of authorisation depending on whether the individual may enter the MR environment supervised, unsupervised or may themselves supervise others [6]. Imaging departments will define local rules using similar terminology. It is important to document clearly at each site the category to which anaesthetists, anaesthetic assistants and other non-radiology staff belong to, and the level of training required for access. After appropriate training, anaesthetic staff would be designated MR Authorised Persons and work in the MR environment under the supervision of a radiographer.

Defined standard operating procedures for anaesthesia in the MR environment are essential for safe working practice. These should include a modified WHO checklist [29] and a specific MR safety checklist, leading to a signed safety form kept in the patient’s care record. Examples of such MR safety checklists are given in Supporting Information Appendix S1, and should be adapted to the local environment. Many hazards in the MR unit occur around entry to the MR environment; it is therefore particularly important to have a clear ingress checklist completed immediately before entering the scanner room (see also Supporting Information Appendix S1; Checklist 2).

**Emergency procedures**

Particular consideration should be given to emergency procedures such as cardiac arrest. During a diagnostic scan, the procedure would be to immediately evacuate the patient from the MR environment to allow resuscitation and support from the wider team, who may not be aware of the limitations of working in proximity to the MR scanner. The roles of the radiographer and anaesthetist during evacuation of an anaesthetised or sedated patient should be well defined in an SOP, and regularly reviewed.

In an interventional setting, where moving a patient during surgery may be difficult or impossible, a clear SOP for which personnel and equipment may enter the room during an emergency is essential. The management of the cardiac arrest should be in accordance with current guidance [30].

**Anaesthesia and sedation**

For patients requiring anaesthesia or sedation for diagnostic MRI, consideration should focus on the safest way to ensure that the patient can remain still within a noisy and claustrophobic environment. The MR study itself is made up of multiple image sequences, some of which take up to 10 min to achieve; scanning may take up to 2 hr in total. Any movement during this time degrades and distorts the images. The main aim for the anaesthetic team is to facilitate excellent images, by keeping the patient still and safe in an isolated site, with limited access to the airway and all the attendant issues related to a strong magnetic field.
Anaesthetic input may be required for those with movement disorders, learning difficulties, claustrophobia or a reduced conscious level, when positioning is limited by pain, and for patients from ICU. In most cases, general anaesthesia will be required; in some cases, sedation may be used, but consideration must be given to the length of scan and noise level that may make sedation difficult. When anaesthetists are asked to provide sedation in the MR unit, the patient should be monitored according to national guidelines. The anaesthetic team should be aware of the potential for airway complications; this could include the need to move the patient out of the MR environment to secure the airway, and should also factor in the time taken for assistance to arrive. This should be taken into account when planning sedation, and may involve extra assistance from the start. Induction of anaesthesia should be in a dedicated area with an appropriately trained anaesthetic assistant, and monitoring should be in accordance with guidelines [31]. Good communication is essential between the referring team, radiologist and anaesthetist so that the detail required, any coil changes and the length of the scan can be determined. This may dictate the need for ventilation or spontaneous breathing during the scan. Where a laryngeal mask or non-armoured tracheal tube is used, the pilot balloon must be secured away from the area to be scanned, to prevent image distortion from the internal ferromagnetic spring.

Maintenance of anaesthesia can be achieved by inhalational agents or i.v. techniques. Magnetic resonance Conditional anaesthetic machines and ventilators are available, which will be sited as determined by the field of the individual magnet. Only MR Safe vaporisers and gas cylinders should be used within the scanning room. Use of standard equipment may lead to serious accidents [32]. Standard infusion pumps should not enter the MR environment; there is a selection of MR Conditional and MR Safe pumps now on the market that may be used, although they cannot administer complex sedation regimens or target-controlled infusion anaesthesia. Specific safety issues relating to the use of total i.v. anaesthesia during scanning include: a high index of suspicion for problems with infusions as the i.v. cannula is not visible; failure to hear pump alarms due to ear plugs or the position of the anaesthetist in the viewing room; and long infusion lines, so that misconnection or high pressure may result in the anaesthetic agent not being delivered to the patient. The high-pressure alarm limit on infusion pumps may be adjustable. The anaesthetist should ensure that an appropriate combination of infusion lines, pump(s) and pump settings are used so that infusions do not stop due to excessive resistance of the infusion tubing or high-pressure alarm cut-out. Some infusion pumps may be used if placed within a specially designed RF shield enclosure (Faraday cage). An alternative is for the pump(s) to be situated outside the scanning room. Care should be taken to avoid patient awareness or movement of the patient during the scanning [33, 34].

After anaesthesia, patients should be cared for by appropriately trained staff in a recovery area.

Consent
For diagnostic scanning the only intervention is the anaesthetic; however, the referring clinician or radiologist is responsible for seeking formal written consent for the MR scan itself, as (s)he will have discussed other options including not performing the imaging, and the impact on diagnosis and prognosis of that omission. The anaesthetist explains the anaesthesia to facilitate the scan, but currently this does not require separate written consent in addition to that taken for the scan [35]. If patients are referred from another hospital, consent should be taken by the referring clinician and a written agreed policy developed to avoid problems on the day of the scan. In exceptional circumstances, the anaesthetist may seek consent for the scan itself if they understand the reasons for performing the imaging. Each unit should develop their own local written consent procedures to ensure that the scan proceeds as smoothly as possible.

Training and supervision
All patients requiring anaesthesia and i.v. sedation should be cared for under the direction of a named consultant; this also applies when an anaesthetist is asked to provide sedation. Whenever possible, anaesthesia in remote sites should be provided by appropriately experienced consultants. When care is delegated to a trainee or SAS doctor, they should have the appropriate competencies and level of training.

National guidance for all grades of anaesthetists in MR units, non-theatre environments, remote sites, intra-operative care, sedation and neuroanaesthetic services have been provided by the Royal College of Anaesthetists [27, 36–39]. Salient points include:

- All staff should be provided with opportunities to familiarise themselves with all equipment by way of documented formal training sessions.
- All staff (whether permanent or locum/agency) should undergo an appropriate induction process that includes the contents of relevant policies and standard operating procedures. This should be documented.
• It is not acceptable for inexperienced staff, unfamiliar with the MR environment and safety issues including cardiac arrest procedures, to manage a patient in this environment, particularly out-of-hours.
• All staff involved with caring for a patient in the MR scanner should understand the unique problems caused by monitoring and anaesthetic equipment in this environment [5].
• An appropriate ‘pre-list’ check of the anaesthesia systems, facilities, equipment, supplies and resuscitation equipment should be performed before the start of each list.
• All procedures should be compliant with National Safety Standards for Invasive Procedures (NatSSIPs) [40] and the Safe Surgery Checklist [29].
• For emergency cases, if the consultant on-call is not a neuro-anaesthetist but the case requires one, there should be a clearly defined and understood process for the provision of specialist advice from neuro-anaesthesia colleagues.

Every hospital offering anaesthetic services for MRI should have a locally agreed safety assessment, with a documented sign-off, before a solo anaesthetist of any grade undertakes MRI cases under general anaesthesia for adults or children. Ideally, for trainees, this should be developed by the lead anaesthetist responsible for MRI, together with the College Tutor; for consultants and SAS doctors, this should be between the lead anaesthetist for MRI and that individual. There should also be agreed levels of supervision for trainees, particularly out-of-hours. The environment in which MR scans are undertaken varies immensely, and advice on the need for supervision of any one anaesthetist will depend on the degree of local support. These issues should be addressed during the local induction process, or before undertaking an MRI case. Supervision of trainees attending children will similarly be reflected in local polices.

The sign-off for undertaking a solo MRI case outlined below is a suggested framework for anaesthetists of all grades that can be adapted for local use:
• Documented experience of directly supervised anaesthesia for MRI.
• Demonstration of knowledge of the safety aspects of a static magnetic field, for example, training on induction, a supervised training list and/or an e-learning module.
• Demonstration of knowledge in management of medical emergencies, including cardiac arrest, within the MR scanner.

It is recognised that, in some hospitals, no solo trainee anaesthetist can work in the MR unit.

**Anaesthetic assistance**
When there is an anaesthetic intervention in the MR unit, for instance if there is a potential for the anaesthetic machine to be used, then an appropriately skilled and trained anaesthetic assistant with a nationally recognised qualification must be present throughout to support the anaesthetist for the duration of the scan. The anaesthetic machine and equipment should be checked before transfer or induction [41].

**Paediatrics**
Younger children, as well as those with learning difficulties or involuntary movement disorders, will require sedation or general anaesthesia to enable satisfactory images to be produced. A child-friendly environment and atmosphere help minimise the need for sedation. Parental presence, distraction with the involvement of play specialists, or the use of in-built entertainment systems can be used to improve the compliance of children.

When the voluntary co-operation of the child is not practical, sedation or general anaesthesia should be provided to the same standards of care as would prevail in an operating theatre. In a child who will not be able to cooperate with scanning, consideration should be given as to whether the scan can reasonably be deferred until the child is of an age to be able to cooperate.

**Pregnancy**
Medicines and Healthcare products Regulatory Agency safety guidelines describe potential hazards from MRI during pregnancy [6]. These include: static magnetic fields > 4 T; low frequency time-varying magnetic field gradients; RF fields; excessive noise effects on the fetus; and systemic heat-load. The risk of systemic heat-load relates especially to the potential for hyperthermia to cause teratogenic effects, and is of most relevance during the period of organogenesis in early pregnancy. However, there are no proven adverse effects from any of these factors. It is difficult to advise women about such unknowns, and put this information into the context of potential benefits of the investigation. The decision to go ahead with an MR scan should be a multidisciplinary decision that includes the mother. It should be accepted that some women will refuse to undergo a scan if there is even a theoretical risk to themselves or their baby.

The MHRA advise that pregnant staff do not remain in the scan room while imaging is underway, primarily due to
concerns about acoustic noise exposure. In an interventional situation where staff work in the immediate vicinity of the scanner aperture during scanning, time-varying gradient and RF fields may also be of concern [42]. Pregnant women, such as the mother of a paediatric patient, should only remain in the scan room while scanning is underway after the benefits and risks have been discussed.

ICU patients
Performing MR scans in critically ill patients is a considerable challenge due to the increased risks of the patient's critical condition and the distant location of the scanner, as well as those relating to the MR environment itself. The procedure requires careful planning and meticulous attention to detail [6]. Except in exceptional circumstances, a decision to perform an MR scan should be made by the consultant intensivist after discussion with the multidisciplinary team and radiologist.

Urgent diagnostic MRI in the critically ill patient is generally limited to neuro-imaging where rapid treatment will have a substantial effect on patient outcome. In other situations, the risks associated with the investigation may outweigh the benefit and the scan can be deferred until the patient is less unwell. If the decision is made to proceed with the scan, a review of monitoring should be made, as devices such as intracranial pressure transducers may be MR Unsafe or MR Conditional [43]. As the patient may be unconscious or lack capacity, there may be limited information about implants or previous surgery. Lines for i.v. infusions should be long enough to allow infusion pumps to be located in a safe area while scanning. The physiological stability of the patient determines whether the scan should proceed and the grade of anaesthetist who should accompany the patient (see ‘Training and supervision for anaesthetists of all grades’ above). The anaesthetist must be accompanied by a suitably skilled anaesthetic assistant when an anaesthetic intervention is planned (see ‘Anaesthetic Assistance’ above).

Checklists may help to complete this complex task (see also Supporting Information Appendix S1; Checklist 3).

Assistance for non-anaesthetic ICU clinicians with airway competencies
Intensive care unit clinicians of all grades who are not anaesthetically trained may take patients for an MR scan and the Working Party is aware that some centres use advanced critical care practitioners to do this. A critically ill patient must be accompanied by a clinician with suitable training, airway skills, competencies, experience and knowledge of the hazards of taking a patient to the MR scanner, and be accompanied by a suitably trained assistant if the patient is intubated or critically unwell. The assistant should be adequately trained in the safety aspect of the MR environment and be familiar with the location, safety equipment and how to seek help in an emergency. This applies to temporary and permanent members of staff. If an anaesthetically intervention is planned (see above), then an anaesthetically trained clinician with a suitably skilled anaesthetic assistant should provide anaesthesia.

An example of a care pathway in checklist format is provided in Supporting Information Appendix S1.

Intra-operative MRI
Intra-operative MRI (iMRI) is used to enhance the accuracy and safety of invasive and therapeutic procedures [44]. It has a particular use in neurosurgery, where it has improved the safety and outcomes for tumour resection [45, 46], epilepsy surgery [47, 48] and the insertion of deep brain stimulators [49, 50].

Advantages include:

- The proximity of the MR scanner to the operating theatre enables scans to be performed at stages throughout surgery, which allows re-registration for navigation; this enhances the accuracy of surgery.
- Maximal tumour resection may be achieved in one procedure [51].
- Infants and young children may have the postoperative MR sequences immediately following surgery, thereby avoiding the need for a second general anaesthetic within 48 hours [52, 53].
- More accurate placement of deep brain stimulators in the treatment of movement disorders, resulting in reduced mortality and morbidity, shorter procedure time and surgery in patients who would not tolerate an awake procedure [54].
- Favourable seizure outcomes and fewer complications in epilepsy surgery, for example, significantly reduced incidence of postoperative visual field deficit [55].

Anaesthetic considerations include:

- During neurosurgery, a unique head frame is used that combines a solid receiver coil with fixed titanium pins, which results in a rigid structure with little room for adjustment. Positioning may be challenging because the patient has to be carefully manipulated into the optimal surgical position within the fixed head frame.
- Some operating tables in iMRI suites have limitations which affect positioning, and can reduce comfort in awake patients.
If the patient is in the prone position, access to the tracheal tube is severely limited by the lower coil [53].

The choice of anaesthetic technique will be influenced by the proposed intervention and patient factors; however, the anaesthetist should pay particular attention to securing the airway and patient positioning.

The condition of pressure areas should be checked and documented both pre- and postoperatively.

Anaesthesia may be very prolonged as several scans may be taken. Each scan will add approximately 45 min to the case, and extra time is needed to redrape the operative field to maintain a sterile environment. Consideration should be given to allow staff sufficient breaks, in order to prevent fatigue and loss of concentration [56].

For lesions in eloquent areas requiring cortical and subcortical mapping, intra-operative scanning is usually undertaken with the patient awake, and therefore it is necessary for the anaesthetist to stay in the MR suite during scanning [57].

There are two arrangements in use within iMRI operating suites: the MR scanner may be located within the theatre suite itself; or the scanner and operating theatre are in adjacent rooms. If the MR scanner is situated within the theatre suite, strict safety procedures should be followed to restrict personnel and equipment allowed within the MR environment. All staff present in theatre should have undertaken safety training, and there should be adherence to policies relating to movement of equipment and the patient. In a two-room set-up, MR Unsafe equipment and monitoring can be used, but must be changed before scanning. This set-up reduces some of the risks, as access to the MR environment may be controlled by the MR radiographer, and in most cases the anaesthetist and the anaesthetic assistant, familiar with working within the MR field, are the only theatre staff to accompany the patient into the scanning room. In both types of iMRI suites the patient is moved into the scanner via the operating table itself, or on a transfer trolley that links to the MR table. All transfers result in an increased risk to the patient; great care should be taken to ensure that there are no trailing wires, i.v. lines or ventilator circuits that may become caught or dislodged. All monitoring must be maintained. Liver ablation procedures and focused ultrasound cases are carried out entirely within the MR scanner and involve only minimal patient movement, but all equipment used must be MR Safe.

As there may be several hours between induction of anaesthesia and the first intra-operative scan, it is easy to overlook metal items that may be left next to the patient, or incompatible monitoring leads. It is essential to have robust checks at critical times during the case, including before anaesthetic induction, before draping for surgery and before scanning. The content of each checklist will be dependent on the particular iMRI set-up. An example of a checklist is found in Supporting Information Appendix S1; Checklist 4. The MR safety and theatre WHO checklists have different functions, and both should be undertaken with the relevant teams.

As the layout of iMRI suites will vary, each hospital should develop individual operating guidelines. When setting up a service it is advisable to use a small team of key personnel who can quickly build up expertise. Once a safe routine has been established, SOPs may be written and embedded within the wider department.

A glossary of relevant terms can be found in Supporting Information Appendix S3.

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The Safe Anaesthesia Liaison Group of the Royal College of Anaesthetists, the Association of Anaesthetists and NHS England commissioned a working party, chaired by Dr G. Wilson, to provide recommendations to ensure the safe transfer and treatment of intensive care patients requiring MRI. The section ‘MRI and ITU patients’ is a summary of their recommendations. We have based the checklists in Supporting Information Appendix S1 on those from the National Hospital for Neurology and Neurosurgery and the Royal Berkshire Hospital. The Working Party also acknowledges the assistance of the Paediatric Intensive Care Society and the Medicines and Healthcare products Regulatory Authority.

References
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**Supporting Information**

Additional supporting information may be found online in the Supporting Information section at the end of the article.

**Appendix S1.** MR Safety Checklists. These are examples of checklists, and should be modified to suit individual MR environments.

**Appendix S2.** Example layouts for diagnostic MR suites (top), intra-operative MR suite with single room (bottom left) and intra-operative MRI suite with dual rooms (bottom right).

**Appendix S3.** Glossary.
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