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PERSPECTIVE

Magnetic Resonance Imaging Safety: Magnetic Field–Related Hazards and Safety Measures

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ABSTRACT

Providing excellent soft tissue contrast as well as functional and metabolic information, combined with non-ionising radiation exposure, magnetic resonance imaging (MRI) has become widely used as a powerful diagnostic tool. With technological advances, MRI systems have evolved to include stronger static magnetic fields, faster and more powerful gradient magnetic fields, and enhanced radiofrequency transmission coils. These stronger MRI systems have the potential to introduce additional safety risks within the MR scanner room, even as they deliver improved efficiency and increased image quality. On the other hand, MRI technology has rapidly expanded into additional areas in recent years. For example, MRI is now incorporated into radiation therapy practice, as well as interventional and intraoperative hybrid suites. With the significant expansion and rapid development of the technology, the associated complexity and increase in MRI safety issues should be extensively studied. It is important to make great efforts to maintain and improve safety in the MRI environment. This article aims to provide an overview, from basic science explaining these potential risks to practical aspects of risk management, and to increase awareness of the unique safety challenges inherent in the MRI environment.

Key Words: *Magnetic fields; Magnetic resonance imaging*

中文摘要

磁力共振成像安全：磁場相關風險與安全措施

肖麗、李子飛、蔡璟、陳德養、黎田

磁力共振成像可提供優良的軟組織對比度以及功能和代謝資訊，而且不涉及電離輻射，已成為廣泛應用的有效診斷工具。隨着技術進步，磁力共振成像系統不斷演變，包括更強的靜磁場、更快速且

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更強大的梯度磁場，以及更高效的射頻傳輸線圈。這些更強大的磁力共振成像系統在提升掃描效率和影像質素的同時，亦可能在磁力共振成像掃描室引入額外的安全風險。另一方面，近年來磁力共振成像技術已迅速擴展至其他領域，例如已被納入放射治療、介入性程序及術中混合手術室。隨着技術顯著擴展和快速發展，相關的磁力共振成像安全問題變得更加複雜，潛在風險亦日益增加，值得深入探討。積極維護和提升磁力共振成像環境的安全性至關重要。本文旨在提供概述，解釋這些潛在風險的基本知識和風險管理的實務操作，以提高大眾對磁力共振成像環境中固有獨特安全風險的認識。

INTRODUCTION

Statistical analysis shows adverse events of magnetic resonance imaging (MRI) growing at nearly three times the rate of MRI procedure volume growth.[1] The potential risks in magnetic resonance (MR) are related to the three types of magnetic fields used in magnetic resonance imaging (MRI): the static magnetic field (B_0), the radiofrequency (RF) field (B_1), and the time-varying magnetic field gradients. Each of the three creates both their own and combined safety risks including projectile forces, torque force, biological effects, biomedical implant and device risk, cryogen-related bodily harm and asphyxiation, heat deposition and acoustic noise—all of which have the potential to cause significant harm or even death.

BASIC MAGNETIC RESONANCE SAFETY CONSIDERATIONS

The potential risks in MRI are associated with the three major electromagnetic fields: the B_0, the varying magnetic field gradients, and the time-varying B_1.[2] The ultra-low temperature helium found in superconductive magnets presents a risk. With the new generation of sealed, low-volume helium scanners, handling cryogenics may not be required.

Static Magnetic Field

Most clinical MR scanners in use today are superconducting electromagnets with a superconducting solenoid coil (niobium-titanium) immersed in liquid helium at -269°C (4°K). Even without an external power supply, the magnet's magnetic field remains unchanged because the electrical resistance of superconductors is negligible; therefore, the risk associated with the superconductive magnetic field is always present. Clinically available scanners have magnetic fields of typically 1.5 or 3.0 T. It is estimated that approximately 100 ultra-high field 7-T MR scanners have been released for clinical use in Europe and the US. The potential risks associated with a B_0 and its spatial field gradients with sharp slope near the scanner include biological effects on humans (such as vertigo, nausea or magnetophosphenes), as well as the translational and rotational forces acting on objects, with the associated device displacement and medical device disruption. For current-carrying objects, Lenz's force applied to the objects can result in movement in the magnetic field; however, patients with ferromagnetic heart valves are typically excluded from MRI.

Magnetic Properties of Materials

The interaction between the magnetic field and objects greatly depends on the magnetic properties of the materials and their shape. Based on the behaviour of materials in the magnetic field, materials are generally classified into three categories: (1) diamagnetic substances such as calcium produce negative magnetisation when placed in an external magnetic field; (2) paramagnetic substances acquire magnetisation in the direction of the applied external magnetic field; and (3) ferromagnetic materials are strongly attracted by the applied magnetic field. Magnetic susceptibility is defined as the magnitude of the extent to which an object becomes magnetised when placed in a magnetic field.[3] Table 1 lists the magnetic properties of a number of materials.[2,3] Most biological tissues contain a high proportion of water (H_2O) and have weakly diamagnetic susceptibility (χ), typically around -11×10^{-6} to -7×10^{-6}. Among the paramagnetic and diamagnetic materials, the χ of most substances encountered in routine clinical imaging lies in the range of approximately $-10^{-5} < \chi < 10^{-5}$. Most modern implants that claim to be MRI-safe are either diamagnetic such as copper, or paramagnetic such as titanium.

Forces on Metal Objects

The two types of forces exerted on metal objects are translational and rotational. The forces on diamagnetic or paramagnetic materials are generally weak to negligible, regardless of whether gravitational force is considered. Forces on ferromagnetic objects are of paramount

Table 1. Magnetic properties of materials.[2,3]

	Susceptibility	Magnetisation direction relative to the B_0 field	Typical materials
Diamagnetic	$-10^{-5} < \chi < 0$	Against	Water, soft tissue, deoxygenated blood, copper, calcium, most biologic tissues
Paramagnetic	$0 < \chi < 10^{-6}$	Aligned	Gadolinium, titanium, organic free radicals
Superparamagnetic	$10^{-6} < \chi < 10^{-2}$	Aligned	Ferritin, hemosiderin, superparamagnetic iron oxide contrast agents
Ferromagnetic	$10^{-2} < \chi$	Aligned	Iron, stainless steels, cobalt, nickel

Abbreviations: χ = diamagnetic susceptibility; B_0 field = static magnetic field.

concern, as they experience the greatest forces in the MR environment. The translational force (F_t) in Equation 1 increases when there are rapid changes in the magnetic field with high spatial field gradients. It is strongest at the edge of the magnet bore with a very sharp slope, inversely related to the third power of the distance ($1/r^3$). The rotational force (F_r) is generally greatest at the centre of the magnet bore, as it is proportional to the square of the B_0, as shown in Equation 2. V in the equation means the volume of the metal device. Elongated objects experience stronger torques compared with isotropic objects. Ferromagnetic medical implants may move rapidly in the B_0, and the temporary or permanent B_0 field–induced current may be substantial enough to hinder the normal function of electronically powered or magnetically programmed active implanted medical devices, such as disabling the reed switch of an MR Conditional pacemaker.

$$\text{Equation 1: } F_t \propto VB \times \frac{dB}{dr}$$

$$\text{Equation 2: } F_r \propto VB^2$$

For small asymmetrically shaped ferromagnetic objects implanted in the body, the rotational force may become the dominant safety issue. In a 10-year review of 1548 adverse MRI-related events reported to the US Food and Drug Administration (FDA), 133 (9%) involved projectiles.[4]

Bioeffects of Static Magnetic Fields

Patients or medical staff might experience vertigo, dizziness or nausea when approaching or moving towards the scanner. Different theories[5-8] have been proposed to explain this phenomenon in which the Lorentz force concept is the favoured explanation.[9] According to the Lorentz force law, Lenz's force is applied to the current-carrying objects when placed inside and moving within the magnetic field. The normal potassium-based ionic current within the middle inner ear endolymph will experience Lenz's force with head movement in the B_0. This force is transmitted to the ampulla, displacing the crista and hair cells of the canal, stimulating them to generate impulses within the vestibular nerve and resulting in vertigo. This is the predominant source of the physiological response associated with transient sensations of vertigo, dizziness or nausea in MRI. The Lorentz forces are also responsible for the magnetohydrodynamic effect. Human blood is conductive. A Lorentz force is created when ionic currents in the thoracic aorta flow through the magnetic field B_0. The Lorentz force deflects positive and negative ions towards opposite sides of the vessel when blood flows through a magnetic field. A voltage is induced. This voltage is superimposed on the T-wave of the electrocardiogram (ECG) used to monitor the patient and elevates it. The distortion of the recorded ECG by the magnetohydrodynamic effect results in faulty cardiac triggering for cardiac MR scanning and makes the cardiac MR examination quite challenging. This interferes with the interpretation of the ECG that renders it unreliable, especially when patients experience chest pain inside the scanner.

Some MRI patients might observe the flickering lights known as magnetophosphenes. They are generally considered to be the result of motion-induced currents when the eyes or head move through a B_0. According to the Faraday–Lenz law, an electric field (or current) is induced in a conductor whenever it moves through a B_0. The induced currents directly stimulate the retina when there is physical movement of a person's head within the B_0. The generation of electric currents in the tongue due to magnetically induced electric fields is viewed as the true cause of the metallic taste experienced by patients who undergo routine MRI examinations.[10]

Time-Varying Gradient Magnetic Fields from the Gradient Coils

There are three orthogonal linear gradient magnetic fields (expressed in mT/m) generated by three sets of coils (one

set for each of the x-, y-, and z-directions) for image spatial encoding and contrast manipulation during image acquisition. There is no concern about the static effects generated by the gradient magnetic field as the strength of the magnetic fields (the maximum amplitude per axis 40-80 mT) generated by gradients is much weaker than that of the main magnetic field (B_0). However, there are three potential MR safety concerns associated with the time-varying gradient magnetic field. Modern MR scanners are equipped with powerful gradients to facilitate rapid, high-resolution imaging or shorter echo times and echo spacing. Gradient coils are powered by high voltage up to 1500 V and high current of several hundred amperes on one side. On the other side, the gradients are switched on and off quickly with slew rates as high as 200 T/m/s in practice. Two major physical effects and the associated three potential MR safety concerns are produced by the rapidly changing currents flowing through the gradient coils.[11] The two major physical effects are mechanical vibration of the MR system and the induced currents in nearby conductive materials (the induced currents are proportional to dB/dt, i.e., the rate of change of the gradient field), respectively. The MR safety concerns include noise, nerve/cardiac stimulation, and tissue heating.

Noise

The movement and vibration of the coils due to mechanical forces are the primary sources of acoustic noise in MR scanners.[12] The sound pressures generated during routine MRI can reach as high as 100 to 130 dB depending on which pulse sequences are used. It is required and mandatory to provide hearing protection when acoustic threshold exposure limits exceed 99 dB by the International Electrotechnical Commission (IEC).[13-15] Some patients have headaches and hearing loss following MRI examinations when not wearing appropriate hearing protection.[16] The hearing protection should reduce noise to at least 99 dB for patients and 85 dB for personnel in the examination room. Although concerns have been raised about MRI scans in pregnant women due to potential risks to fetal hearing or other effects,[17,18] no harmful effects have been reported over the past 30 years for those scanned during the first trimester. Despite limited data on fetal hearing risks, it is still recommended to establish institutional policies for MRI exposure in pregnant patients. Pregnant healthcare practitioners are permitted to work in and around the MR environment throughout all stages of pregnancy.[19] Although permitted to work in and around the MR environment, pregnant healthcare practitioners should be advised not to remain within the MR scanner bore during actual data acquisition or scanning.[20]

Peripheral Nerve Stimulation

According to Faraday's law of induction as mentioned above, time-varying magnetic fields result in the generation of electric fields in conducting materials and an electromotive force. The gradient switching-induced electric fields in a human subject stimulate the nerves and muscle fibres and may cause what is referred to as peripheral nerve stimulation (PNS).[11,21] It is generally reported as a tingling or tapping sensation, although the severity of discomfort ranges from barely noticeable to physically dangerous at the other extreme, depending on the subject's physiological conditions. The patient's overall health, nerve sensitivity, and even stress or anxiety can affect their perception of the stimulation.[22] Meanwhile, the intensity of nerve and muscle fibre excitation is proportional to the dB/dt and the duration of its application. The IEC has established limits for gradient exposure to protect patients and subjects against PNS and cardiac stimulation,[23] which have been adopted by the US FDA and many other organisations. However, PNS stimulation limits for both whole-body and regional scans can be determined by averaging the individual stimulation thresholds of test subjects (at least 11 volunteers), based on studies conducted with appropriate ethics committee approval, rather than using derived values. The first-level controlled operating mode is defined such that 50% of all patients experience at least mild stimulation after reaching the stimulation threshold, while the normal operating mode limits the scanner to 80% of this threshold.[24,25] Cardiac muscle contraction requires levels of stimulation at least 10 to 100 times higher than those required for PNS, and a subject accidentally exposed to very high levels of dB/dt would almost certainly experience warning signs of PNS before reaching levels that pose a risk to the heart.[22]

Time-Varying Magnetic Fields and Medical Devices

Changing magnetic fields from both RF pulses and switched gradient fields generate electric (eddy) currents. In the presence of a conducting medical device or implant, thermal energy is produced both within the implant itself and in the adjacent tissues by these eddy currents. Heating of conducting devices and the adjacent tissues will be discussed later for RF pulses, while the heating due to the instantaneous power deposited by the eddy currents from the switched gradient field (dB/dt) will be covered here.

The degree of energy deposition can be quantified by the specific absorption rate (SAR), which is often expressed in units of power per mass of tissue (watts/kg). Each manufacturer provides a conservative estimate of SAR for all commercially available MR scanners. The SAR values are estimated automatically using a specific imaging protocol and patient-specific information as input, and a warning message will appear if regulatory limits are likely to be exceeded. Considering the factors contributing to SAR, it can be approximated by a simple model for the switched gradient field (Equation 3)[26,27]:

Equation 3: $SAR \propto (\sigma A^2 \left(\frac{dB}{dt}\right)^2 D)/2\varrho$

where σ is the tissue conductivity, A is the volume of the body size, D is the duty cycle (representing the percentage of time the gradient operates at maximum amplitude during a sequence), and ϱ is the tissue density.

Because gradient frequencies are quite low, lying in the range of kHz, gradients do not generate appreciable eddy currents in tissues. The thermal effects due to heat diffusion from the implant itself may be considered, and these effects are likely to come into play only near the regions of maximum dB/dt for large-volume implants.[28,29]

Time-Varying Radiofrequency Electromagnetic Field

B_1 is applied perpendicular to the main magnetic field (B_0) on the order of milliseconds. It tips the net magnetisation out of alignment with B_0 and MR signals are produced. B_1 is weak (μT) and oscillates at a frequency in the MHz range matching that of a proton, with resonance frequencies of approximately 64 MHz and 128 MHz for 1.5 T and 3.0 T, respectively. The primary safety concerns at these frequencies are whole-body and localised heating from the deposition of the RF energy.[30] In a 10-year review of 1548 adverse MRI-related events reported to the US FDA, 906 (59%) involved thermal injury, making it the most prevalent reported injury.[4] According to Maxwell's Laws, the time-varying B_1 is the source of an induced changing electric field. Such field deposits energy into tissues, and the power applied to tissue is generally a function of field strength, pulse sequence, and patient size. The primary safety concerns are the whole-body temperature increases due to heating absorbed in the patient and the potential for tissue damage from localised high-temperature exposures.[31-34] As internal temperature measurement is not easily performed during routine clinical MRI, SAR or specific energy dose (SED), which reflects the total energy delivered into the patient during the active scan period, is used to control system power output in modern MRI. This is approximated by Equations 4 and 5.

Equation 4: $SAR \propto (\sigma A^2 (fB_1)^2 D)/2\varrho$

Equation 5: $SED = SAR \times acqusition\ time$

Some MR manufacturers now compute and report both SAR and SED to limit scanning during a full exam if the accumulated SED is too high. In addition to the dosimetric unit used for diffusion heating over a large volume, B^+_{1rms} (the root mean square value of B^+_1) is used as an supplemental metric to SAR, which may be a better exposure measure for focal heating because it is more closely related to the induced electrical field and is less dependent on the patient. The major use of B^+_{1rms} is for MR Conditional implants. Implant manufacturers are responsible for providing the value for the safe use of their devices in an MR scanner.

It is generally believed that three physical mechanisms underlie RF-induced thermal injury.[31,35]

Radiofrequency-Induced Inductive Heating

Both the human body and metallic foreign bodies are conductors. The currents induced by RF excitation in modern MRI reside almost entirely along the surface of the conductive materials, or along the conductive loop if there are no areas of high resistance. The eddy currents induced by the changing RF magnetic fields are channelled into areas of high resistance (such as a metal-skin interface or breaks in the loop); however, the primary concern is that these current distributions can lead to resistive heating of tissue and RF burns.[36] This is analogous to resistive energy loss in a conventional electrical circuit governed by Ohm's Law. Resistive heating in tissue is a function of material conductivity, geometry, and location within the excitation coil. Implants located closer to the edge of the coil tend to experience higher electric fields. The skin itself is conductive, and skin-to-skin contact can lead to a high current concentration. The associated energy deposited may be substantial enough to cause tissue damage.[37] The point of contact is a potential region of high resistance where significant heating can occur.[38] For example, crossing of legs, ankle to ankle, thigh to thigh, and so on. This phenomenon is particularly relevant when patients are under general anaesthesia in an intraoperative MRI.

For smaller-sized conducting materials (<2 cm), there is no great concern for significant heating issues if there are no adjacent conductors within approximately 3 cm.[39] Otherwise, there may be enhanced heating due to

coupling effects. Larger and smoother conductors can generate a significant amount of current. These currents flow through only a tiny fraction of the total implant mass at its surface and do not cause significant heating of the implant itself. In soft tissues immediately adjacent to the implant or at sharp corners or disconnects, or when in close proximity to another conductor, however, RF-induced currents can become concentrated and resistive heating may occur.[28,29,40] Cases of thermal tissue damage caused by implants have been reported, such as from a deep brain stimulator and MR Conditional intracranial pressure monitoring devices.[41,42] These examples highlight the importance of strictly adhering to the manufacturer's guidelines.

Heating of a Resonant Loop

In some cases, certain electrical circuits might exhibit resonance absorption and release energy at a specific resonance frequency. It is a relatively uncommon situation. However, if the electrical circuits contain both capacitance and inductance elements to form resonant loops, they may generate a very large amount of current and a high level of inductive heating through resonant absorption and energy release at a resonance frequency.[43] This situation applies to the use of ECGs with cables or similar loops.

Antenna Effect

Another mechanism for RF heating is the so-called antenna effect. Straight wires and elongated conductive objects can act like antennas, capturing electromagnetic waves to extract power from them. According to antenna theory, the length of the wire or object must be sufficient to support the formation of standing waves and produce standing-wave patterns of voltage and current that are concentrated near their tips. Typically, when the length is close to one-half of the RF wavelength, maximum heating may be produced at the tips of the device. For MRI, the relevant length is approximately 26 cm at 1.5 T and 13 cm at 3.0 T. There have been incidents resulting in fire and patient burn injuries ascribed to the antenna effect of ECG leads and cardiac pacing leads as well.[44]

For MR safety, evaluation of impact on patient, fetus, family and staff, as well as interaction with auxiliary equipment and medical devices, is of constant concern. The electromagnetic field–related hazards are summarised in Table 2.

Table 2. Summary of primary safety concerns related to magnetic fields.

Source	Primary safety concern(s)
Static magnetic field (B_0)	Projectile hazards Medical device displacement Medical device disruption Bioeffects
Gradient magnetic field (G)	Peripheral nerve stimulation Noise Interference with auxiliary equipment
Radiofrequency field (B_1)	Tissue heating Medical device heating Medical device disruption Interference with auxiliary equipment (i.e., patient monitoring)
Cryogens (liquid helium at -270°C)	Bodily harm Asphyxiation

MEASURES AND MAGNETIC RESONANCE IMAGING SAFETY CHECKING PROCEDURES

Given the risks associated with the MR environment, it is essential to take effective measures and procedures to keep all personnel including patients, accompanying family members, and staff safe, and to ensure all auxiliary medical equipment and devices remain functional.

Safety Zones

The American College of Radiology (ACR) has divided the MRI suite into four zones corresponding to the potential safety concerns.[45,46] The purpose of this definition is to prevent unqualified staff and unscreened patients from accessing hazardous areas and to restrict MR-unsafe medical equipment or devices from being wrongly brought into the MR scanner room. There are other alternative schemes such as the three-area definition from the United Kingdom or Netherlands[47]; however, the ACR zone definition is widely adopted throughout the world.

As shown in Table 3,[45,46] Zone I is a public area that the general public can access freely without supervision, where the fringe field is less than 5 gauss. Zone II is a buffer area between Zones I and III for patient preparation and safety screening. Zone III is the area near the magnet room with potential hazards to unscreened patients and personnel; physical barriers are used to help control access. Zone IV is the MR scanning room with the highest risk, where all ferromagnetic objects are forbidden. Only properly screened personnel and patients are permitted to enter this area.

During the early implementation of MRI technology, the 5 gauss (0.5 mT) line or area was established as the

Table 3. Safety zones in the magnetic resonance environment.[45,46]

ACR zones			Occupants	Hazards
Zone I	MRI		General public	No MRI hazards
	MRI ZONE I	MRI access area		
Zone II	NOTICE		MRI patient screening and preparation	Immediately outside areas of hazard
	MRI ZONE II	MRI patient screening and preparation		
Zone III	CAUTION		Screened MRI patients or personnel	May present a physical hazard to unscreened patients and personnel
	MRI ZONE III	Restricted access Screened MRI patients and MRI personnel only		
Zone IV	DANGER		Screened MRI patients under direct supervision of trained MRI personnel	MR magnet room; has the greatest risk and all ferromagnetic objects must be excluded
	MRI ZONE IV	Restricted access Screened MRI patients under direct supervision of trained MRI personnel only		

Abbreviations: ACR = American College of Radiology; MR = magnetic resonance; MRI = magnetic resonance imaging.

threshold to define the limit beyond which ferromagnetic objects and the general unscreened public are strictly prohibited. It also served as a reminder that one is within a region where active medical device might pose a hazard due to exposure to the electromagnetic fields produced by MR equipment and accessories. Recently, the 9-gauss line has been updated to indicate the standard for identifying the 'magnet mode' area for certain active implantable medical devices, particularly cardiac devices, to prevent accidental activation or functional changes. The International Standard IEC 60601-2-33 for MRI safety requirements was amended to reflect this change.[23] Magnetic fields extend in all directions, and the 9-gauss line may extend into non-MR areas above, below, or adjacent to the MR magnet room, which should be carefully evaluated and clearly marked to restrict access by unauthorised personnel.[48]

Magnetic Resonance Imaging Screening and Safety Checklist

Personnel Screening and Management

The ACR Manual on MR Safety[49] suggests that all patients and non-MR personnel must undergo MR safety screening when entering Zone III.[50] Trained MR personnel have the responsibility and authority to decide whether a patient may be cleared for scanning. For non-emergent patients, the ACR recommends performing at least two separate screenings before granting access to the MR scanner room. Screening, in the form of a questionnaire, should be available. One of the screenings should be conducted when the examination is requested and should include questions such as: (1) any implanted cardiac devices (pacemakers, defibrillators, valves, stents, wires, etc.); (2) intracranial vascular coils or aneurysm clips; (3) neurostimulators; (4) bone growth or bone fusion stimulators; (5) cochlear implants; (6) the possibility of intraorbital metallic foreign bodies; (7) implanted infusion devices such as those for insulin; and (8) orthopaedic implants.

The second level of screening should be performed when patients themselves present to the MR suite for MR examination. Conscious patients should be screened at least twice, using metal detectors and verbal questioning, before being allowed to enter the MR scanning room (Zone IV). The screening form similar to the MR safety screening form provided by the ACR should be reviewed by staff with MR training, such as an MR nurse. MR radiographers or technologists should then review and evaluate the form in detail; ideally, both parties should sign it. MR radiographers should ask whether any device, foreign body, or implant is present that could pose a danger in the MR room, including both passive and magnetically or electrically active items. For patients who are unable to answer screening questions, such as children, it is acceptable to question family members, guardians, health carers or any decision makers. All patients should be asked to change into MR-safe hospital gowns and to remove all watches, hearing aids, hairpins, jewellery, drug delivery patches, eye makeup, artificial lenses (especially high-technology ones, such as implanted contact lens monitors intraocular pressure with a micro-sensor), and so on. For emergent patients,

screening with a metal detector is acceptable but it must be performed by MR-trained personnel or MR radiographers. Before entering the MR scanner room, all patients should undergo final screening. The use of ferromagnetic detection systems is recommended as an adjunct to enhance detection of ferromagnetic materials.[49] If a patient with a metalworking history reports the presence of metal in the orbital area, an X-ray should be taken or their previous X-ray history reviewed. The handheld metal detector should have a strength of at least 1000 gauss with the ability to detect ferromagnetic or magnetic objects. Metal detection equipment is helpful in screening non-MR personnel, especially those from other medical departments who may or may not have MR training, since they can easily forget to remove their personal items before entering the MR magnet room (Zone IV).[51]

For all non-MR personnel entering the MR scanner room, for example a family member or carer who wishes to accompany the patient, they should be screened using the same criteria as those applied to patients. For cleaning of scanning room, personnel who have received basic MR safety training may perform their duties under MR personnel supervision and only after undergoing the same screening procedure as patients. All MR personnel should undergo the same screening as patients to ensure their own safety in the MR scanner room and to protect the non-MR personnel under their supervision. Pregnant healthcare practitioners are permitted to work in and around the MR environment throughout all stages of their pregnancy. Although they are allowed to work in and around the MR environment, pregnant healthcare practitioners are advised not to remain inside the scanning room while data acquisition is in progress. These recommendations are based on the preponderance of data relating to 3T magnetic fields.

Device and Equipment Screening and Management

The US FDA introduced guidelines on testing and labelling medical devices and implants for safety in the MR environment, which apply to all medical devices that might be used in the MR environment.[52]

The square green MR Safe label indicates that the object or device is safe in all MR environments. It is non-magnetic, non-conductive and non-metallic, posing no known hazards in any MR environment. Caution should be taken with products marked as 'MR SAFE' as some of these products have been found with metallic components according to our experience, and should therefore be treated with care. The round red MR Unsafe label applies to objects or devices that pose potential harm to MRI patients or staff under all MR circumstances, for example, ferromagnetic objects. The triangular yellow MR Conditional label is for devices or objects that may be used safely in an MR environment, provided that the conditions for safe use are fulfilled.

The MR safety profiles for all accessory devices used in the MR suite must be well-established before being brought into Zone IV to avoid potential safety risks to patients undergoing MRI. All devices being used in the MR suite should be clearly marked with their MR safety status (i.e., MR Safe, MR Conditional, or MR Unsafe). Any new device or replacement must be tested for MRI safety before use in the MR scanner room. Non-clinical incidental objects, such as ladders or home-made phantoms (e.g., custom-built imaging test objects) with no manufacturer or third-party MR safety test results, as per American Society for Testing and Materials standard,[48] should be site-tested prior to use in the MR magnet room. Unmarked or unknown items must not be allowed into the MR scanner room. Never assume a device's MR Conditional or MR Safe status unless it is clearly documented in writing. All accessories used within the MR magnet room must be labelled either with MR Safe or MR Conditional. The operating conditions of the MRI system must be fully complied with, including limits on magnetic field strength, coils, spatial field gradient, gradient slew rate, SAR, or/and B^{+}_{1rms} as shown in the example below.

Different types of MR Conditional equipment have varying requirements for safe use in the MR suite. It is quite complex and impractical to label all gauss lines and spatial gradient magnet fields on the floor. In our practice and according to our data analysis, most MR Conditional devices can be used outside the 150/200 gauss (yellow) line. A simple rule we recommend is to place medical devices as far away from the magnetic bore as possible, provided this does not affect the physical connection with the patient. For example, infusion pumps can be located outside the 150/200 gauss line even if the manufacturer's safety label permits use within a higher gauss field, provided the tubing is long enough to reach the patient. This approach also accounts for the steep slope of spatial field gradients, allowing safe control space. It is vital that medical equipment requiring placement close to the patient and magnet core, that is, near the 1000 gauss line (the red line), such as ventilators,

be checked by MR safety personnel to ensure that the manufacturer's label confirms compliance with the maximum magnetic field or spatial gradient requirement, as specified in the instruction for use. In addition to the FDA MR Conditioned label, for daily operational convenience, it is good practice for MR safety officers to apply clear secondary labels to frequently used MR Conditional equipment. For example: "Don't exceed the 200 gauss line (the YELLOW line)." This helps avoid misplacement or confusion when equipment must be moved during patient transfer, as shown in Figure 1. These labels are for user convenience only; there is no need for concern over the gauss line issues. In practice, assessment and management must be carried out on a case-by-case basis.

Other suggestions for using MR Conditional devices or objects in the MR magnet room (Zone IV) include: (1) Consider the limits on connector tubing length and patient positioning when placing MR Conditional or MR Safe devices. (2) Ensure that the auto-lock brake of the device is engaged. (3) Secure the MR Conditional device to a non-movable object if necessary, e.g., using a plastic safety belt as shown in Figure 2.

Emergency Scenario

It is recommended that MR-trained personnel manage all emergency events, such as fire, quench, resuscitation, etc.[53]

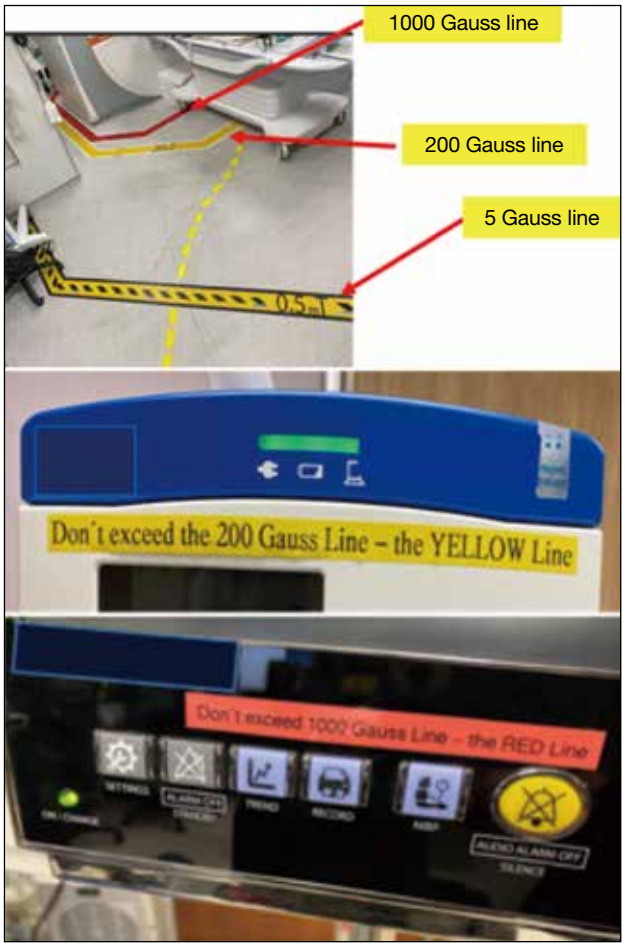

Figure 1. Gauss line labels for floor and magnetic resonance conditional devices.

Figure 2. Securing the magnetic resonance Conditional device to a non-movable object.

Resuscitation should not take place within the magnet room (Zone IV). On-site MR-trained personnel should remove the patient from the magnet room immediately. Consider quenching only if there is a threatening situation in which someone is trapped inside the magnet by a heavy object. Close the MR magnet room door (Zone IV) to prevent accidental access. Call for help according to local guidelines.

If smoke or fire is coming from the scanner, equipment room or console, on-site MR radiographers or technologists should stop any examination procedure immediately and evacuate the patient from the MRI suite. Perform an emergency electrical shutdown. Do not activate the magnet quench button unless absolutely necessary. Close and lock the scan room door to prevent inadvertent entry of any ferromagnetic materials into the scan room. The incident should be announced immediately via the intercom system. Activate the nearest fire alarm pull station, if available. Escort all patients in the MRI suite to a safe location. Only MR Conditional fire extinguishers may be brought into and kept within Zones III and IV. Firefighters must be informed of the existence of the MRI facility and the compatibility requirements of their fire-fighting equipment.

A quench is the procedure by which the magnetic field is removed through the release of liquid helium. The large volume of gaseous helium displaces oxygen in the MRI examination room and poses a risk of asphyxiation. In the event of a quench, stay calm and evacuate the patient. Call for help and report the event to supervisors. Service engineers should be contacted to assess the origin of the fire and the condition of the scanner.

In the event of all incidents or near-incidents, on-site trained MR radiographers and technologists should notify supervisors and the relevant parties.

NEW CHALLENGES

Introducing MRI technology into the operating theatre and radiotherapy settings presents new challenges, which may be explored further in a future article.

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