A Practical Guide to MR Imaging Safety: What Radiologists Need to Know[1]

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Abbreviations: ACR = American College of Radiology, eGFR = estimated glomerular filtration rate, FDA = Food and Drug Administration, GBCA = gadolinium-based contrast agent, NSF = nephrogenic systemic fibrosis, SAR = specific absorption rate

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SA-CME LEARNING OBJECTIVES

After completing this journal-based SA-CME activity, participants will be able to:

- Describe the major components of an MR imaging system as they relate to MR imaging safety guidelines.
- Identify key risk factors related to MR imaging hardware and contrast agent administration.
- List the different MR imaging safety zones and describe their restrictions.

See www.rsna.org/education/search/RG.

Magnetic resonance (MR) imaging can provide critical diagnostic and anatomic information while avoiding the use of ionizing radiation, but it has a unique set of safety risks associated with its reliance on large static and changing magnetic fields, high-powered radiofrequency coil systems, and exogenous contrast agents. It is crucial for radiologists to understand these risks and how to mitigate them to protect themselves, their colleagues, and their patients from avoidable harm and to comply with safety regulations at MR imaging sites. Basic knowledge of MR imaging physics and hardware is necessary for radiologists to understand the origin of safety regulations and to avoid common misconceptions that could compromise safety. Each of the components of the MR imaging unit can be a factor in injuries to patients and personnel. Safety risks include translational force and torque, projectile injury, excessive specific absorption rate, burns, peripheral neurostimulation, interactions with active implants and devices, and acoustic injury. Standards for MR imaging device safety terminology were first issued in 2005 and are required by the U.S. Food and Drug Administration, with devices labeled as "MR safe," "MR unsafe," or "MR conditional." MR imaging contrast agent safety is also discussed. Additional technical and safety policies relate to pediatric, unconscious, incapacitated, or pregnant patients and pregnant imaging personnel. Division of the MR imaging environment into four distinct, clearly labeled zones—with progressive restriction of entry and increased supervision for higher zones—is a mandatory and key aspect in avoidance of MR imaging–related accidents. All MR imaging facilities should have a documented plan to handle emergencies within zone IV, including cardiac arrest or code, magnet quench, and fires. Policies from the authors' own practice are provided for additional reference. *Online supplemental material is available for this article.*

Introduction

Magnetic resonance (MR) imaging, introduced in the 1970s, is now commonplace in modern medicine, with more than 60 million examinations performed worldwide in 2012 (1). Engineering advancements and improvements in image processing continue to reduce operating costs and barriers to entry, which has increased the widespread use of MR imaging. Image acquisition in MR imaging is unique and relies on subtle differences in the intrinsic behavior of hydrogen protons bound to different soft tissues and fluids to produce image contrast. This requires use of strong magnetic fields and radiofrequency coils, which presents a set of safety challenges distinct from those of all other radiologic modalities.

TEACHING POINTS

- MR imaging units consist of three primary systems, each with potential safety risks: the main magnet, gradient set, and radiofrequency transmit-receive system.
- Standards for MR imaging device safety terminology were first issued by ASTM International in 2005, are currently documented in the ASTM International F2503 guidelines, and are required by the FDA, with devices labeled as "MR safe," "MR unsafe," or "MR conditional."
- The 5-G line does not safeguard against a projectile incident, nor was it defined for that purpose.
- Radiologists and technologists should be particularly vigilant for any potential circuit loop that includes the patient; the extremities are often involved in these types of burns.
- Any magnet quench, intentional or not, should be considered an emergency, and all personnel should be evacuated from zone IV as quickly as possible.

Regulatory and professional society MR imaging safety guidelines have standardized many aspects of MR imaging site design, patient safety, and personnel workflow. These guidelines were developed on the basis of established knowledge of electromagnetism as well as experience from adverse events. Basic knowledge of MR imaging physics is necessary for radiologists to understand the origin of these guidelines and to avoid common misconceptions that could compromise safety.

This article provides an overview of MR imaging safety that is geared toward the practicing radiologist. This information is not meant as a comprehensive reference for all aspects of MR imaging safety, and all practitioners of MR imaging should consult their respective country's imaging regulations and their particular vendor to ensure practice safety. Practical guidance from experienced practitioners of MR imaging is included to help familiarize the reader with safety issues that commonly arise in MR imaging.

MR Imaging Hardware

MR imaging units consist of three primary systems, each with potential safety risks: the main magnet, gradient set, and radiofrequency transmit-receive system. We provide a brief overview of these components; further details of these systems and how they interact to obtain images can be found in several introductory MR imaging physics textbooks (2,3).

Main Magnet

The MR imaging magnet is essentially a large coil of wire wound around the axis of the bore. When an electric current is applied to this wire, a magnetic field is produced. Modern clinical MR imaging field strengths range from 1.0 to 3.0 T, with field strengths for research systems of up to 9.4 T. These fields are approximately 10,000–100,000 times the magnitude of the earth's surface magnetic field and more than 100 times stronger than the field at the surface of a refrigerator magnet. For imaging purposes, the magnetic field strength must be uniform across the imaging field of view (typically 30–60 cm); hence, the most common systems are cylindric. The current required to produce such a field is on the order of hundreds of amperes; as a comparison, a high-power microwave oven at the maximum setting draws approximately 5–10 A. To achieve such currents in a conventional electromagnet would require a massive amount of continuous power. Therefore, the majority of MR imaging magnets use superconducting wire, which has essentially zero electrical resistance provided that it is maintained at a very low temperature. For this reason, the coil of the main magnet is placed inside a well-insulated canister and is immersed in liquid helium. During installation of the MR imaging unit, the current in the superconducting magnet is ramped up slowly to obtain the desired magnetic field strength, a process that takes several hours. Shutting a magnet down safely requires a similar degree of technical effort. Once the main magnetic field is established, it is left on and can remain stable at several hundred amperes for years, as long as the liquid helium level in the cryostat is sufficient to maintain the coil in a superconducting state.

U.S. Food and Drug Administration (FDA) guidelines refer to a magnetic field of 5 G (0.0005 T) as the upper limit where the field strength is of no potential concern for the general public, including persons with implanted electronic devices (4). A line called the 5-G line is often drawn around the bore to show this limit (Fig 1).

Gradient Systems

MR imaging units make use of applied magnetic field gradients to spatially encode the MR imaging signal. Modern gradient systems can carry electrical currents of hundreds of amperes. Unlike the main magnetic field, gradient coils are subject to rapidly changing currents, which are necessary to provide encoding within the time constraints of pulse sequences. These rapid fluctuations in current result in microscopic movements of the coils, which lie within an audible frequency range; this is the source of the knocking and buzzing noises generated by an MR imaging unit during an examination. Gradient coils are fixed in place relative to the main magnetic field coils and are typically installed within the magnet bore. They require dedicated cooling systems to counteract the heat induced by the large and changing currents.

Figure 1. Photograph shows the 5-G line along the floor of one of our MR imaging systems. Newer magnets, such as this 1.5-T unit, use active shielding to bring the 5-G line as close as possible to the bore.

Radiofrequency Coils

MR imaging units require transmission coils to excite nuclear magnetization inside the patient's body for imaging and receive coils to acquire the nuclear MR signal after transmission. These coils are tuned to the proton resonance frequency of the subject, which, at typical clinical magnetic field strengths, happens to lie within the radiofrequency range of the electromagnetic spectrum; hence the term *radiofrequency coils*. Coils of different sizes and shapes are available to accommodate different anatomic areas, ranging from full-body coils to surface coils for small joints. In general, there is a signal-to-noise ratio advantage to having the receive coils close to the imaging target. Large transmit coils (eg, the body coil built into the bore) are capable of transmitting tens of kilowatts of radiofrequency power in short bursts.

Radiofrequency coils need to be very sensitive to acquire MR signal, which unfortunately makes them sensitive to unintentional background electronic noise. Every magnet room is encased by a thin metallic shield to block all external electromagnetic signals that might fall within the operating frequency. For this reason, the entry doors to an MR imaging suite are bulkier than conventional doors and contain specialized handles that form a conductive seal around the entire frame when turned to the closed position.

Guidelines, Regulations, and Safety Terminology

MR imaging safety guidelines and regulations vary considerably from country to country. Policies in the United States are used throughout this article as an example. U.S. MR imaging centers are subject to quality and safety standards through two major mechanisms: requirements set by the U.S. FDA, which govern patient exposure limits and contrast agent regulation, and agency accreditations from the American College of Radiology (ACR) and the Joint Commission, which are now required for Medicare reimbursement.

In 2013, the ACR Blue Ribbon Panel on MR Safety issued an updated guidance document on MR imaging safe practices (5). This guide was intended for a broad audience, including MR physicists, supervisors, and hospital safety officers, and thus provides additional detail beyond what is expected for the typical practicing radiologist. The document forms the basis for the safety aspect of ACR MR imaging institutional accreditation, which requires renewal every 3 years. An accredited center must have a documented MR imaging safety policy tailored for its practice that is reviewed annually by a supervising MR imaging physician, covering everything from signage and access control to patient screening and mechanical safety. These requirements overlap with those of the more comprehensive Joint Commission accreditation, which, like the ACR accreditation, requires periodic renewal and site visits.

The FDA is best known for approval and regulation of medications, which include intravenous contrast agents for MR imaging. However, the FDA also places specific limits on certain patient exposures within the MR imaging environment, including maximum field strength, noise, and radiofrequency power deposition in the patient's body. These specifications are available in the medical devices section of the FDA searchable database (6). Standard testing methods for MR imaging equipment and device compatibility are provided by ASTM International, formerly the American Society for Testing and Materials, under Committee F04 on Medical and Surgical Materials and Devices. Each test focuses on a potential electromagnetic interaction within an MR imaging system that could be potentially hazardous to the patient or a staff member. For example, Publication

F2182 details the method for measuring radiofrequency-induced heating of devices. All of these standards have been fully adopted by the FDA and by multiple international agencies and are published electronically (7).

Regulations, standards, and guidelines are being continuously updated as MR imaging becomes more widely available and newer techniques and technologies emerge. Regulatory agencies continue to clarify existing standards to reduce or eliminate confusion when screening patients for MR imaging examinations. For example, while this article was being drafted, the ACR Subcommittee on MR Safety issued a new standardization request detailing several aspects of device safety reporting, including how maximum magnetic gradient strength should be documented, and clarifying reports on torque deflection angle and radiofrequency transmission power (8). Increasing overlap and matching of the safety requirements set by the Joint Commission, the ACR, and the FDA have helped to create a more cohesive set of safety requirements.

Determining Medical Device and Implant Compatibility

Standards for MR imaging device safety terminology were first issued by ASTM International in 2005, are currently documented in the ASTM International F2503 guidelines, and are required by the FDA, with devices labeled as "MR safe," "MR unsafe," or "MR conditional" (9). MR-safe devices are nonhazardous in all MR imaging environments, whereas MR-unsafe devices are considered to be contraindicated in any MR imaging environment. An MR-conditional device is MR imaging–compatible only in specific operating conditions, with the following information required: main magnetic field strength, maximum magnetic field gradient, maximum specific absorption rate (SAR), and description of the testing conditions used to arrive at these data. MR-safe and MR-unsafe designations can usually be made according to scientific rationales. For example, a typical intravenous catheter composed of only polyurethane and silicone has no ferromagnetic component or conductivity and would be considered MR safe without testing. Alternatively, devices can be placed into any of the three safety categories on the basis of experimental data, obtained by using ASTM International–standardized methods.

Any metallic or (active) electronic medical device has the potential to cause harm within an MR imaging environment. For this reason, the screening checklist devotes a large section to screening for these devices (for a copy of the screening form used at our institution, see Fig E1 [online]). A detailed discussion of the hazards of the multitude of medical devices is beyond the scope of this article; only a few illustrative examples are used in the following sections. Fortunately, a vast database that categorizes MR imaging safety ratings and recommendations for nearly all known medical devices is available at *www.mrisafety.com* (10). This Web site is frequently updated, and a hard-copy reference, which additionally covers the ACR, ASTM International, and FDA guidelines, is also available (11). Many manufacturers also publish MR imaging safety information and guidelines for their devices on their Web sites.

In some cases, the lot and model numbers of the device are necessary to determine its degree of MR imaging compatibility. In these cases, a note from the patient's surgeon may be required to confirm the details. This can be difficult to obtain, especially if the surgery was performed at an outside institution, and the note may not have the needed information. Health care workers at outpatient facilities in particular may need to prescreen patients before their appointment to minimize this potential delay at the time of MR imaging.

MR Imaging Safety Risks

Each of the components of the MR imaging unit can be a factor in injuries to patients and personnel; potential mechanisms of injury are described in this section.

Translational Force and Torque

When a magnetic object is placed in the field of an MR imaging unit, it is subject to translational force and/or torque. Translational and rotational forces can result when any metallic object interacts with static or changing magnetic fields. The force on a magnetic object increases with ferromagnetic composition, total mass, and the gradient of the magnetic field strength at its location. The gradient of the magnetic field is a measure of how rapidly the field increases as the distance to the magnet decreases. Although the strongest magnetic field is at the isocenter of the magnet, the strongest forces are present where the gradient is largest. The largest gradients occur well away from the isocenter and in some cases may be near the ends of the magnet bore. Medical devices and implants contain varying amounts of ferromagnetic material and can be subject to these forces.

Most devices are passive—that is, they do not contain any electronic components. Examples include surgical sutures, vascular and biliary stents, clips, plates, and screws. Many of these devices are composed of nonferromagnetic materials that do not pose a risk of force-related injury. Those that do contain some ferromagnetic materials may be deemed MR safe if the amount of material is too

small to cause any substantial force or if the device is anchored securely (eg, most dental implants and orthopedic screws). However, other devices require more caution. Aneurysm clips, for example, are attached to soft-tissue structures only, and there has been one documented case of a fatality attributed to the rotation of such a clip while the patient was adjacent to the magnet; in that case, the ferromagnetic content was underestimated because the clip was incorrectly identified (12,13). Other devices have specific components that make them MR conditional or MR unsafe. For example, programmable ventriculoperitoneal shunts may contain metallic or even magnetic parts that are used to adjust valve pressure settings in vivo, resulting in MR-conditional requirements.

Several types of implants may require a waiting period before an MR imaging examination can be performed. Many cardiac and vascular stents, for example, do not become securely embedded into the vessels until 6 weeks after implantation. These stents are considered MR safe afterward, although imaging can be performed earlier on a case-by-case basis if there is a clinical necessity (14). Some gastrointestinal endoclips, typically used for hemostasis, can translate or rotate within a magnetic field, but the majority are sloughed off and passed at 2 weeks. Delaying a nonemergent MR imaging examination in this case would bypass any potential safety issues and could eliminate imaging artifacts.

Ballistic implants, such as shrapnel and bullets, warrant special consideration because their ferromagnetic composition may not be known and their anatomic position is variable. Although most fragments do not pose any translational or rotational hazard, proximity to nearby vital structures may preclude imaging (15–17).

Projectile Injury

The inherent high magnetic field strength of a clinical MR imaging unit poses a risk for projectile injury or MR imaging equipment damage if a ferromagnetic object approaches too close to the magnet and is pulled into the bore. These incidents typically involve objects external to the patient—not infrequently, medical support equipment. There have been several reported instances where cylinders filled with anesthetic gas or oxygen became projectiles, with one case resulting in death from a collision against the patient inside the magnet (18,19). Other examples of projectiles include non–MR-imaging-compatible beds, chairs, and intravenous bag poles. In one case, a gun that was unintentionally brought into the imaging suite was pulled into the bore, discharging a round despite having its safety engaged (20). In addition to the obvious threat of bodily harm, projectiles can also cause extensive damage to expensive hardware and additional loss of service for required downtime during repairs. Ferromagnetic metal detectors can be used to screen people and equipment passing into an MR imaging suite to prevent such accidents. Although these detectors are currently approved only for screening for external ferromagnetic objects, they may be used in the future for implant screening (21).

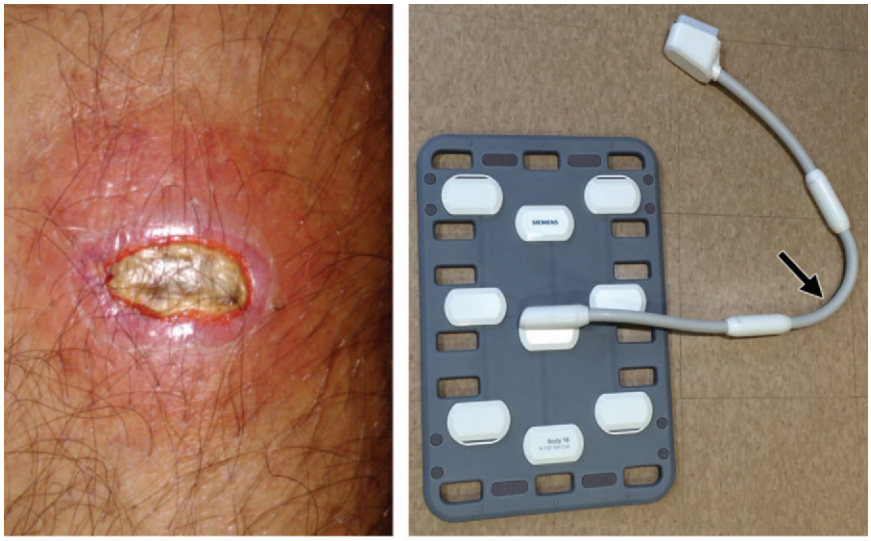
Newer magnets are built to minimize the field strength outside the bore of the magnet, a technique termed *shielding*. As a result, as one approaches the bore of the MR imaging magnet, the magnetic field will increase rapidly, so the subjected force on a magnetized object can be sudden and unpredictable. It should be noted that the 5-G line does not safeguard against a projectile incident, nor was it defined for that purpose. All equipment brought into the MR imaging unit room should be evaluated for MR imaging compatibility and labeled with proper terminology. Unlabeled or unverified equipment should be assumed to be unsafe.

Excessive SAR

Radiofrequency coil energy deposition is quantified in terms of the SAR, which is expressed in watts per kilogram. The FDA maintains limits on the maximum SAR and the maximum temperature increase in tissue. Current FDA guidance limits SAR whole-body exposure in patients with "normal thermoregulatory function" to 4.0 W/kg in the body and 1.5 W/kg for all other cases (4). SAR limits have also been declared for MR-conditional devices, specifically to reduce the risk of thermal injury.

The local power deposited in a tissue is proportional to the tissue conductivity and the square of the local electric field produced by the radiofrequency transmission system. The electric fields increase approximately linearly with the main magnetic field strength. Therefore, if the magnetic field strength is doubled—for example, from 1.5 T to 3.0 T—the SAR will increase by a factor of approximately four if other parameters are kept equal. As field strengths increase, techniques for estimating and managing the SAR will become more critical for patient safety.

SAR estimation requires knowledge of the electric field at each point inside the patient's body, along with knowledge of local tissue conductivity, both of which are variable (22). Most MR imaging units can provide an estimate of SAR by using the total radiofrequency power that is transmitted per unit time with the patient's weight and data on the transmit coil coverage to compute the global average SAR. Continuous computation is used to ensure that the SAR is within FDA limits. With



a. b.

Figure 2. Direct contact burn. **(a)** Photograph shows a third-degree burn on a patient's calf, which was pressed against the cable of the radiofrequency coil. **(b)** Photograph shows a phased-array coil similar to the one involved in the incident. The coil cable showed no indication of a burn. Arrow = approximate contact point.

most modern clinical imaging units, if any one of the FDA limits is going to be exceeded within an examination, the user is notified automatically, and the parameters must be changed so that the SAR limits are not exceeded.

Burns

Thermal injury from MR imaging is uncommon, with 419 reported cases between 2000 and 2010 in the United States (23). However, burns can be severe, life threatening, and difficult to predict. The majority of MR imaging–related burns occurred during routine examinations that involved typical pulse sequences. There are several recognized mechanisms for thermal injury.

Skin contact against radiofrequency transmit and receive coils and cables can result in direct burns. To minimize this risk, modern coils and cables are typically insulated and sealed within a thicker plastic protective sleeve to provide a minimum safe distance. Cables are placed away from the skin, which should have clothing or a sheet covering it, and nonconducting pads are used to provide additional separation between the skin and all electronic elements, including the side of the magnet bore, which usually contains both radiofrequency and gradient coils. Even when coils and cables are appropriately insulated, if they are pressed tightly against bare skin, a direct burn can potentially occur as a result of arcing through the insulation. This was the suspected injury mechanism for a patient who sustained a third-degree burn on his leg during MR imaging of the lumbar spine at our institution several years ago. During the examination, the patient moved his leg for comfort and inadvertently pinned the radiofrequency coil cable between his bare calf and the magnet bore. Perspiration resulted in greater contact between the skin surface and the compressed cable, which further increased conductivity (Fig 2).

More common are burns from electromagnetic induction, where generated current from changing magnetic fields produces an excessive amount of heat, analogous to an excessive local SAR. Gradient or radiofrequency coils provide the source of the fluctuating magnetic fields, but the current can be produced within any conducting material, either internal or external to the body. Wires and leads—for example, electrocardiography cables or jewelry (eg, piercings)—can form an inductive circuit if they are accidentally coiled. Objects with microscopic amounts of conductive material can produce enough heat to cause a burn. For example, some transdermal medicinal patches containing trace aluminum have caused superficial burns (24). Unless such patches are specifically verified by the manufacturer as MR safe, they should be removed for an MR imaging examination. If a patch is kept on the patient, special care must be taken to ensure that the patch is not too close to a coil, a cable, or the magnet bore.

Certain kinds of clothing may pose a risk; a cutaneous burn from a shirt that contained silver particles was recently reported (25). To avoid this possibility, many institutions, including our own, require all patients to change into hospital gowns for their MR imaging examination. A burn has even been attributed to iron oxide particles within a patient's wrist identification bracelet. That incident resulted in third-degree burns and compartment syndrome that necessitated surgical release (26).

Tattoos are known to cause susceptibility artifacts, but thermal injuries rarely happen and are suspected to occur only with very dark inks,

which are richer in iron oxide, or if the inking pattern forms a loop (27). Transient discomfort and first-degree burns have rarely occurred with permanent eyeliners, which do not necessarily contain ferrous materials (28,29).

Radiologists and technologists should be particularly vigilant for any potential circuit loop that includes the patient; the extremities are often involved in these types of burns. In one case, a loop was formed across the patient's pelvis along his thighs, which were not in contact with each other, and across a single point of skin-to-skin contact between his calf muscles; the induced circuit, with soft tissue and sweat acting as the conductors, resulted in a third-degree burn (30).

Surface radiofrequency coils, which usually lie in close proximity to the patient's skin, introduce a special safety risk. These are usually receive coils that do not produce radiofrequency power themselves. However, the transmit radiofrequency coils, which, as discussed previously, can deposit very high power, can induce huge currents through the receive coil because both operate at the same resonant frequency. To prevent this, receive coils contain electronics to block the resonance induction during radiofrequency transmission, but this works only if the coils are properly connected to the MR imaging system. It is critical that all coils are accounted for and properly connected before any imaging examination can begin.

In some cases, circuits and wires in the MR imaging unit or within the patient can accidentally be resonant at the frequency of the transmitted radiofrequency power, which then poses unpredictable and severe safety risks. For example, unintentional resonances of this kind can occur if a coiled cardiac pacer lead forms a resonant configuration; however, in many cases, the cause is far less obvious. A related variant is the "antenna effect," where an uncoiled wire resonates with the electric field of the radiofrequency coil, similar to a radio tuned to a station, generating large electric fields in the vicinity of the lead tip. This mechanism is suspected in the case of a patient who was imaged while a pulse oximeter was attached to his fingertip; despite proper cable placement and careful spacing with padding and cloth, a third-degree burn occurred at the lead tip, necessitating amputation of the digit (31). MR-conditional intracardiac pacemakers contain electronic filters that nearly eliminate the possibility of the antenna effect. However, abandoned intracardiac pacer wire leads lack such protection and are currently considered a contraindication to MR imaging.

Retained wires that are short and have no potential to form loops may be safe for MR imaging. A retained lead from prior temporary epicardial pacing is one such example; no additional screening is required for these patients (32).

Peripheral Neurostimulation

Induced electrical currents can produce painful neurostimulation in patients. This stimulation is most often felt in the arms and legs, where the gradient magnetic field is changing most rapidly, and is referred to as peripheral neurostimulation. The risk of peripheral neurostimulation is dictated by the rate of change of the magnetic field over time, termed *dB*/*dt* and expressed in teslas per second. The FDA requires only that dB/dt be set to levels that do not result in peripheral neurostimulation, without a specific number (4). Sensitivity to peripheral neurostimulation varies widely among individuals, and it is possible that an imaging examination that is well tolerated by one patient will be uncomfortable for another. MR imaging studies that pose the greatest risk of peripheral neurostimulation are those that involve high-bandwidth readouts and/or rapid gradient switching, such as echo-planar imaging. Reducing the read bandwidth or increasing the repetition time can reduce dB/dt.

Interactions with Active Implants and Devices

Electronic devices can interact in several ways with the main or gradient magnetic fields and the radiofrequency fields, potentially leading to adverse events. Newer MR-conditional electronic implants are now available with SARs and imaging time limits that are set by the manufacturer and are safe when specific conditions are followed. For example, cardiac pacemakers were originally an absolute contraindication to MR imaging because there was risk for radiofrequency pulses causing inappropriate asynchronous pacing and risk for burns from atrial and ventricular leads. However, there are now several MR-conditional pacemakers, made possible by decreasing the ferromagnetic components, using solid-state switches that are resistant to errant activation, and incorporating radiofrequency filters and lead designs to prevent resonant circuit burns (33). Recently, U.S. and Canadian multidisciplinary society guidelines were issued to better guide appropriate use of MR imaging in patients with cardiac implants (14,34). At our institution, every MR imaging request for a patient with a pacemaker is approved first by a cardiologist and a radiologist before the examination is scheduled, and a cardiologist monitors the patient throughout the entire MR imaging examination and checks the device before the patient is discharged.

Acoustic Injury

The FDA sets a maximum of 140 dB for an MR imaging system and a maximum of 99 dB for a patient with hearing protection (35). The majority of MR imaging unit noise originates from gradient coils because they are subject to rapid changes in current, which in turn interact with the main magnetic field through Lorentz forces. Pulse sequences that are gradient intensive, such as echo-planar imaging, are the loudest, but even these usually fall under the required maximum (36). Temporary hearing loss has been documented in patients who underwent routine MR imaging examinations without protective devices (37). It is common practice to require that patients use passive noise control, typically disposable earplugs or over-the-ear headphones, which can reduce noise levels by 10–30 dB. Newer-generation systems reduce noise levels by use of additional passive noise shields and active techniques such as noise-minimizing "silent" or "quiet" pulse sequences (38).

MR Imaging Contrast Agents

The use of gadolinium-based contrast agents (GBCAs) in MR imaging is well established. GBCAs are well tolerated by a majority of patients, and their safety profile is excellent and, by most measures, more favorable than those for iodinated contrast agents. Here we review key aspects of MR imaging contrast agent safety and give examples from our practice. A more comprehensive article on contrast agents (39), which provides further detail on the different types of GBCAs, a detailed overview of safety-related studies, and summaries of key ACR guidelines, can be found in this monograph.

Severe anaphylactoid reactions, while extremely rare, do occur, and the ACR recommends that patients with previous reactions be injected with a different contrast agent if one is needed for subsequent MR imaging and that at-risk patients be premedicated with corticosteroids and antihistamines. The GBCA premedication regimen at our institution is based on ACR guidelines (40). Patients at the highest risk for a reaction to GBCAs are those with a history of reactions to the same agent and those who have experienced multiple other allergic reactions. Sensitivity to GBCAs should be documented in the same manner as other medication reactions; for example, at our institution, a centralized database for a patient's reaction profile communicates with the electronic ordering and scheduling systems so that, in a patient with a documented GBCA allergic reaction or intolerance, when a contrast material–enhanced MR imaging examination is ordered or is attempted to be scheduled, a warning appears.

In recent years, much attention has been paid to the association of GBCAs and nephrogenic systemic fibrosis (NSF). First described in the literature in 2000 (41), NSF is a systemic fibrotic disease affecting the skin and internal organs that is similar to but distinct from scleroderma. Deaths can occur owing to respiratory failure and limited mobility (41–43). Patients with NSF have acute and/or severe chronic kidney insufficiency (estimated glomerular filtration rate [eGFR], <30 mL/min/1.73 m^2), and, with few exceptions, are known to have received a GBCA (44,45). The period between contrast medium injection and the development of symptoms is often less than 3 months, although longer latency periods have been reported (46,47). Nearly all cases have been observed in patients with stage 4 chronic kidney disease (eGFR, 15–29 mL/min/1.73 m^2), stage 5 chronic kidney disease (eGFR <15 mL/min/1.73 m^2), or acute kidney insufficiency (43–45,48,49). The exact mechanism behind NSF is not entirely understood, but it is hypothesized that in patients with renal failure, delayed clearance of the GBCA and alterations in the metabolic environment allow Gd^{3+} to disassociate and bind to available anions such as phosphate, resulting in toxic tissue deposition (50).

The ACR Committee on Drugs and Contrast Media considers a patient at risk for developing NSF in the following conditions (40): *(a)* undergoing dialysis; *(b)* chronic kidney disease stage 4 or 5 (eGFR <30 mL/min/1.73 m^2) without dialysis; *(c)* eGFR of 30–40 mL/min/1.73 m^2, without dialysis, due to potential short-term fluctuations in eGFR that may result in a level below 30 mL/min/1.73 m^2; or *(d)* acute kidney insufficiency.

Careful screening is required to identify these at-risk patients. In addition to a known history of renal insufficiency, other risk factors outlined by the ACR include a history of diabetes or hypertension requiring therapy, age older than 60 years, and prior renal surgery or malignancies (40). At our institution, we incorporate the Choyke questionnaire, which enables screening for all of the risk factors listed above (except age >60 years), as well as for a history of proteinuria and a history of gout (51,52).

The ACR Manual on Contrast Media provides a guideline outlining the timing of eGFR determination for at-risk patients (40). At our institution, we have adopted a revised algorithm that uses a slightly different eGFR scale and incorporates same-day testing. For our outpatient examinations, if the Choyke screening questionnaire is completely negative and the patient is younger than 60 years of age, the imaging examination can proceed with any of our standard protocols that use GBCAs, without the need for

eGFR calculation. If a patient is older than 60 years of age or has any positive answers on the questionnaire, eGFR is calculated by using the Modification of Diet in Renal Disease (MDRD) equation and a serum creatinine level obtained within 30 days of the MR imaging examination. If the patient's eGFR is 45–60 mL/min/1.73 m^2, we check for any prior eGFR result to ensure that there has not been a decrease in the eGFR of 10 mL/min/1.73 m^2 since a prior eGFR calculation within 6 months or from the patient's baseline level (if multiple prior measurements are available). If such a decrease has occurred, we perform a point-of-care serum creatinine test at the time of examination to calculate a new eGFR. If the patient's eGFR is less than 45 mL/min/1.73 m^2, we always perform a new eGFR calculation at the time of examination.

Once the current eGFR is established as described, if the eGFR is 30 mL/min/1.73 m^2 or greater and has not decreased by 10 mL/min/1.73 m^2 within the past 6 months or from baseline, we administer a GBCA from either Group II (gadobenate dimeglumine, gadoteridol, or gadobutrol at our institution) or Group III (gadofosveset or gadoxetate disodium). If the patient's eGFR is 30–45 mL/min/1.73 m^2 and has decreased by 10 mL/min/1.73 m^2 or is 15–29 mL/min/1.73 m^2 and remains stable, we administer a Group III GBCA. If a patient's eGFR is 15–29 mL/min/1.73 m^2 and has decreased by 10 mL/min/1.73 m^2 or is less than 15 mL/min/1.73 m^2, we discuss the case with the referring clinician, as we would recommend alternative imaging modalities, including contrast-enhanced computed tomography (CT), if they are available. This is also our recommendation for patients who are undergoing chronic hemodialysis. However, if an MR imaging examination with a GBCA is still determined to be the best option for the patient, we consult with the nephrology service to arrange for hemodialysis and proper follow-up after GBCA administration. It should be noted that there is no direct evidence that immediate and/or prolonged hemodialysis in these patients offers any protection against NSF; current European and ACR guidelines recommend this but acknowledge that the theory is speculative (40,53).

For all inpatients, we calculate an eGFR within 24 hours if an MR imaging examination with a GBCA is desired and apply the same rules described previously. For subsequent GBCA administration for MR imaging, we recommend waiting at least 10 hours for patients with a stable eGFR of 60 mL/min/1.73 m^2 or greater, at least 48 hours for patients with a stable eGFR of 30–59 mL/min/1.73 m^2, and at least 96 hours for patients with a stable eGFR of 15–29 mL/min/1.73 m^2. For patients with a decrease in eGFR of more than10 mL/min/1.73 m^2 or for patients in whom there is a desire to give a GBCA for a subsequent MR imaging examination in a time period less than that recommended, we discuss the case with the referring clinician to decide on the best course of action.

GBCAs are excreted in minimal amounts in breast milk; amounts are estimated to be less than 0.04% of the total dose (54,55). Therefore, the amount transferred to a nursing infant would be at least 100 times less than the permitted dose of 200 μmol/kg of body weight for neonates (54). On the basis of the small amount of a GBCA that is excreted and absorbed, the ACR states that it is safe to continue breast-feeding after maternal intravenous GBCA administration. However, an informed decision should be made by the mother, including the option to temporarily suspend breast-feeding for 12–24 hours after GBCA administration (40).

Pediatric MR Imaging

MR imaging is especially appealing in the pediatric setting because it eliminates risks associated with ionizing radiation. All MR imaging safety principles apply to this patient population as they do for adults. However, the pediatric patient is more vulnerable to anxiety, and younger patients may not have sufficient language skills to follow commands to minimize image motion artifacts; these issues pose additional technical and safety concerns. To alleviate patient anxiety, family members may be allowed to accompany patients during examinations, but they must undergo the same complete MR imaging safety screening process. Also, many cases require the use of sedation or general anesthesia to ensure that images of diagnostic quality are obtained. Guidelines on appropriate monitoring and management in these cases are provided by the American Academy of Pediatrics and the American Academy of Pediatric Dentistry (56).

Reports of NSF in the pediatric patient population are rare (57). The ACR recommends that adult guidelines for identifying at-risk patients and for administering GBCAs be followed. Also recommended is that caution be used in administering GBCAs to neonates and infants because of their potentially low glomerular filtration rates and renal immaturity.

MR Imaging of Unconscious or Incapacitated Patients

MR imaging may be indicated in patients who are unable to provide answers to the screening profile. The screening form may be completed by the patient's health care proxy and be confirmed

with one of the patient's health care providers (physician, physician assistant, or nurse practitioner), who can also review the medical records. At our institution, if no health care proxy is available, two primary health care providers review and confirm the checklist. In all of these cases, as with routine screening, the forms are then reviewed by level 2 MR imaging personnel (see the section on "MR Imaging Personnel and Non–MR Imaging Personnel).

If the medical history is incomplete, recent CT or radiography studies can be reviewed, or screening radiographs can be obtained, starting with the skull, chest, and abdomen. The MR imaging personnel performing the examination should also perform a physical examination of the patient to look for surgical scars that might warrant radiography prior to MR imaging (5).

MR Imaging of Pregnant Patients

At present, although results of only a few studies with small numbers of patients, variable data, and confounding factors are available, there is no definitive evidence of harmful effects from performing routine (nonenhanced) MR imaging examinations in pregnant patients. However, long-term safety has not yet been definitively demonstrated, and there is lack of consensus as to whether risks to the fetus, including possible teratogenic effects and acoustic damage, are real (58). Although animal studies have demonstrated deleterious effects of MR imaging exposure on the fetus and therefore have raised concerns, these studies are not applicable to humans, and their results cannot be extrapolated. A recently published retrospective case-control study (59) on the safety of MR imaging at 1.5 T in 751 human fetuses showed no adverse effects of MR imaging exposure in utero on neonatal hearing function or birth weight percentiles.

The ACR considers use of MR imaging to be relatively risk free during pregnancy, and no special consideration is recommended for the first, versus any other, trimester in pregnancy (5). Nevertheless, caution should be exercised when considering MR imaging in a pregnant patient, and there should be a risk-benefit analysis of imaging alternatives before proceeding with the MR imaging examination. It is prudent to screen all girls and women of reproductive age for pregnancy before granting them access to the MR imaging environment. Moreover, in our institution, all pregnant patients must sign an "MRI in Pregnant Patient" consent form provided by a physician (either from the radiology department or from the ordering service) before they undergo any MR imaging examination. The physician obtaining the consent must explain the potential risks and benefits to the patient. The possible risks, although not conclusively documented to be present, include but are not limited to the following: possible bioeffects of the static magnetic field of the MR imaging system, risks associated with exposure to the gradient magnetic fields, potential adverse effects of the radiofrequency energy, possible adverse effects related to the combination of these three magnetic fields, and possible effects of acoustic noise in the MR imaging environment on the fetus. The anticipated benefits include the gaining of information that cannot be acquired by means of an alternate, nonionizing imaging modality and the detection of information that affects care of the patient or fetus during the pregnancy, without the possibility of waiting until after the pregnancy to obtain that information.

No adverse outcomes to fetuses have been reported after a review of studies in pregnant patients who received GBCAs, although the sample sizes of these studies were small (60). Although no adverse effects to the fetus or neonate have been established, intravenously administered GBCAs are known to enter fetal circulation and to persist within the amniotic fluid. The FDA has classified GBCAs as pregnancy category C drugs, meaning that their safety in humans has not been proven but that they may be used in cases where the potential benefits outweigh the risks (61).

Additional details regarding the imaging of pregnant patients are covered in a separate review article in this monograph (62).

Pregnant MR Imaging Personnel

Radiologists, technicians, and other health care providers who are pregnant are allowed to work around and in the MR imaging environment throughout all stages of their pregnancy. Although they are allowed to position patients, image and archive, inject contrast material, place radiofrequency coils, and enter the MR imaging room in response to an emergency, it is recommended that they do not remain in the MR imaging bore or magnet room during data acquisition or imaging (5).

MR Imaging Equipment Zoning and Siting

The strong main magnetic field of MR imaging units and the fact that the magnetic field is always on creates important safety issues in and near the MR imaging environment. Although patients and MR imaging personnel are the focus of many safety policies, greater hazards may be associated with individuals who are not patients and who do not regularly work in the MR imaging environ-

ment, as they may be more likely to unknowingly bring ferromagnetic materials into the MR imaging environment or accidentally bypass screening checkpoints (5). Specific examples of the latter include physicians, nurses, and nonimaging technologists who enter the MR imaging suite in urgent situations; security and cleaning personnel who are responding to emergencies or are unaware of MR imaging safety hazards; and patients' family members and friends.

The division of the MR imaging environment into four distinct, clearly labeled zones—with progressive restriction of entry and increased supervision for higher zones—is a mandatory and key aspect in avoidance of MR imaging–related accidents. The zones are labeled I–IV, with zone I being the least restricted and zone IV being the most restricted. Access is progressive—for example, a person with zone III access automatically has access to zones I and II. The four zones are defined as follows:

Zone I.—Access in this zone is unrestricted and includes all areas that are freely accessible to the general public; this is the area through which patients and others access the controlled MR imaging environment.

Zone II.—This is the interface between the uncontrolled, publicly accessible zone I and the strictly controlled zones III and IV. Zone II may be used to greet patients, obtain patient histories, discuss medical insurance questions, and screen patients for MR imaging safety issues. Patients in zone II are not free to move at will and should be under the supervision of trained MR imaging personnel.

Zone III.—This is the area where there is a potential danger of serious injury or death from interaction between unscreened people or ferromagnetic objects and the magnetic field of the MR imaging unit. The imaging unit control room is typically in zone III, as are any hallways or areas with unopposed access to the magnet room doors. Access to zone III must be strictly restricted by lock or passkey systems, accessible and supervised only by MR imaging personnel. Only MR imaging personnel shall be provided free access to zone III, and non–MR imaging personnel are not to be provided with independent access until they undergo the proper education, training, and certification to become MR imaging personnel themselves. Zone III, or at the very least, the area within it wherein the static magnetic field strength exceeds 5 G, should be demarcated as being potentially hazardous. It is important to know that the magnetic field is

Figure 3. Entrance to one of our magnet rooms, designated as zone IV, is labeled with standard signage, including a reminder that the magnet is always on.

three-dimensional. Thus, the restricted area may extend not only in all directions on the same floor of the facility but also potentially through the floor and/or ceiling to adjacent floors.

Zone IV.—This is the MR imaging unit magnet room itself and therefore is the highest-risk area. This zone should be clearly marked (with a red light and a sign stating that the magnet is always on) as potentially hazardous because of the strong magnetic field (Fig 3). Persons accessing zone IV must be under the direct visual observation of MR imaging personnel.

A layout of one of the magnet suites at our institution is provided as an example of the different zones (Fig 4).

MR Imaging Personnel and Non–MR Imaging Personnel

The ACR has defined different levels of MR imaging personnel as follows (5): *(a)* level 1 MR imaging personnel—those who have passed minimal safety educational efforts to ensure their own safety as they work within zone III; *(b)* level 2 MR imaging personnel—those who have been more extensively trained and educated in the broader aspects of MR imaging safety issues; and *(c)* non–MR imaging personnel—all those not having successfully complied with MR imaging safety instruction. This category includes patients.

The Joint Commission recommends the following restrictions to access to zones III and

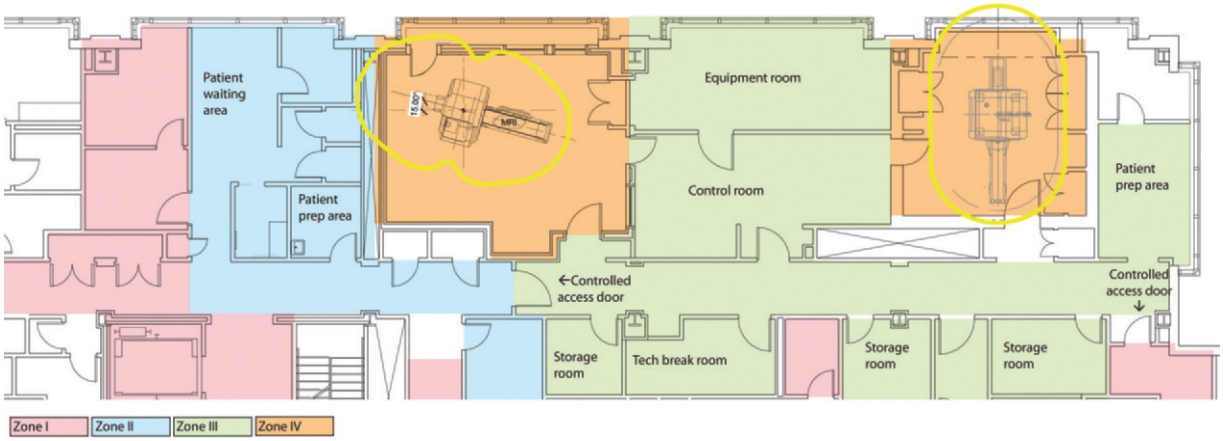


Figure 4. Drawing shows the layout of one of the magnet suites at our institution, which houses two 1.5-T systems, with zones demarcated by color code. The 5-G line is marked in yellow for each magnet.

IV (63): *(a)* restricting access of everyone not trained in MR imaging safety or screened by staff trained in MR imaging safety from the imaging room and the area that immediately precedes the entrance to the MR imaging room (zones III and IV), and *(b)* making sure that these restricted areas are controlled by and under the direct supervision of staff trained in MR imaging safety.

Non–MR imaging personnel must undergo safety screening every time they enter zones III and IV and must be under the direct supervision of level 2 personnel at all times in zones III and IV. A sample screening form from our institution is included in Figure E1 (online); the ACR guidelines also provide a generic version (5).

Screening is a time-consuming process, and thus it is prudent to have everyone who enters zones III and IV on a regular basis trained to be level 1 or level 2 personnel as is appropriate to their roles. For level 1 personnel, training includes content to educate a wide range of staff members about the basics of MR imaging so that they will be able to act in a safe manner within the MR imaging environment. The people who take this training may include environmental services staff members, distribution and shipping personnel, maintenance and facilities staff members, public safety officers, transport personnel, receptionists and schedulers, radiology staff members not regularly involved in MR imaging, first responders, code teams, respiratory teams, and nurses and other clinicians (eg, anesthesiologists). The training material for level 1 personnel should describe what MR imaging is, with a particular focus on its hazards and safety issues. It should discuss that MR imaging uses powerful magnets and radiofrequency waves, which can pose several hazards to patients and staff members, including projectile effects, burns, auditory risks, and device malfunctions; safety screening; common implanted devices of concern; common objects that should not be brought into the MR imaging suite; MR imaging zoning; and emergency protocols in case of a quench or fire. This training should be performed on a yearly basis, and a record should be kept of it. At our institution, we use a computer-based education module that has a combination of slides and a video, but printed handouts or lectures could also be used. A test should be given and passed to confirm a minimum level of understanding for each person given privileges and to provide documentation. Level 1 personnel should also fill out a safety screening form that is kept on file and is confirmed to be accurate yearly.

After training and safety screening are performed, level 1 personnel can have unrestricted access to zones III and IV on an annual basis. The ACR states that level 1 personnel can move within zones III and IV freely. Level 1 MR imaging personnel are explicitly permitted to accompany non–MR imaging personnel into and throughout zone III. However, even though level 1 MR imaging personnel have access to zone IV, they are not permitted to directly admit, or be designated responsible for, non–MR imaging personnel in zone IV. At our institution, we are more conservative and require all level 1 personnel in zone IV to be under the direct observation of level 2 personnel.

Level 2 personnel should include all radiologists who enter into zones III and IV on a regular basis, including radiology residents and fellows. Radiologists and trainees who rarely enter the environment (eg, nuclear medicine physicians and trainees or interventional radiologists who may never enter zones III and IV) could be level 1 personnel, which would allow them to enter the MR imaging environment in an emergency. Physicists or MR imaging scientists who will

work in the MR imaging environment should also be level 2 personnel. Any physician extenders, such as nurse practitioners and physician assistants, who are employed regularly in zones III and IV should be level 2 personnel. All MR imaging technologists and technologist aides must be level 2 personnel. One of the level 2 personnel at each MR imaging site is the MR imaging medical director, whose job includes ensuring that MR imaging safe policies and procedures are established, updated, and followed by all staff members, as well as overseeing MR imaging safety issues that arise during the operation of the MR imaging site. Each MR imaging site must also have a diagnostic medical physicist or MR imaging scientist to evaluate the performance of the MR imaging unit and receiver coils and to document that each unit meets the requirements for imaging performance set by the Joint Commission, the ACR, or other regulatory body.

Level 2 personnel must undergo safety screening, as level 1 personnel do. The training for level 2 personnel includes the same material as for level 1 personnel, with the addition of more in-depth material on the safety screening process, the portable objects that can be brought into zone IV and the U.S. FDA labeling criteria for these, and the safety response and emergency procedures in the MR imaging environment. These are needed for all level 2 personnel because they have the responsibility of overseeing non–MR imaging personnel in zones III and IV (and at our institution, level 1 personnel in zone IV) and of safety screening non–MR imaging personnel (including patients) entering zones III and IV. In the event of a shift change or lunch break, no level 2 personnel shall relinquish their responsibility to supervise non–MR imaging personnel while still in zone III or IV until such supervision has been formally transferred to another of the site's level 2 personnel.

Level 1 and level 2 personnel should be clearly informed that if they have any device implanted, undergo surgery from which ferromagnetic material remains in their body, or experience a metal injury, they must update their screening form immediately. These screening forms should be kept in employee health records, with screening forms that have positive responses initially reviewed anonymously to maintain confidentiality as much as possible. If further information about an implant is needed, the person needing access should be able to obtain and provide this information anonymously. In some cases, such as when radiographs are needed to screen for implanted devices or ferromagnetic foreign bodies, complete anonymity may not be possible, but any such radiographs or workup should clearly be performed with Health Insurance Portability and Accountability Act compliance.

The Joint Commission recommends that MR imaging technologists participate in continuing education, which includes annual training on safe MR imaging practices in the MR imaging environment (63). This annual education should include the following: *(a)* patient screening criteria that address ferromagnetic items, electrically conductive items, medical implants and devices, and risk for NSF; *(b)* proper patient and equipment positioning activities to avoid thermal injuries; *(c)* equipment and supplies that have been determined to be acceptable for use in the MR imaging environment (MR safe or MR conditional); *(d)* MR imaging safety response procedures for patients who require urgent or emergent medical care; *(e)* MR imaging system emergency shutdown procedures, such as system quench and cryogen safety procedures; *(f)* patient hearing protection; and *(g)* management of patients with claustrophobia, anxiety, or emotional distress.

The Joint Commission and/or the ACR require each institution to have written policies covering all of these topics. An annual requirement for technologists, in addition to their level 2 training, should be a continuing education program that covers these topics. This could be a computer-based module with a test, similar in format to that for MR imaging safety training for access to the MR imaging environment, printed educational material, a video of a lecture with documentation of completing this training, or a written test. Again, a test provides documentation of a minimum level of understanding for each person given privileges.

MR Imaging Emergencies

The main magnetic field of an MR imaging unit places unique constraints on how emergencies are handled inside an MR imaging suite, in particular within zone IV. All MR imaging facilities should have a documented plan to handle emergencies within zone IV, including cardiac arrest or code, magnet quench, and fires, and all MR imaging personnel should be familiar with this plan.

Resuscitation equipment, including the crash cart, should be verified and labeled as MR safe or MR conditional and sited in close proximity, either within zone II or zone III (5). Other emergency equipment within the MR imaging room, such as fire extinguishers, also needs to be MR safe or MR conditional. It is especially critical that all potential emergency responders are aware of the hazards associated with zone IV, as it is easy to forget to properly screen for potential

ferromagnetic projectiles during an emergency response. Thus, if a medical emergency or fire occurs within zone IV, any ongoing imaging examination should be terminated, and every effort should be made to move the patient and all personnel outside zone IV while preliminary resuscitation or stabilization is begun by appropriately trained and certified MR imaging personnel. It would be ideal for an emergency plan to require that one of the MR imaging personnel remains at the entrance to zone IV specifically to ensure that first responders enter the area only if necessary and that they do so safely.

As discussed previously, the main magnetic field is left on constantly, and a proper shutdown requires down-ramping of the current in a slow and controlled manner. However, if an emergent situation arises when the magnetic field must be shut off immediately (eg, a patient is pinned by a projectile), a magnet quench can be initiated. All MR imaging systems have a specific button that initiates this process. A quench occurs when a portion of the superconducting coil is warmed above the superconducting threshold and ceases to be superconducting. This causes a sudden increase in temperature throughout the entire main coil, leading to a rapid increase in electric resistance. While this shuts off the magnetic field very rapidly, the rapid coil heating causes the surrounding liquid helium, typically thousands of liters, to boil off in an explosive manner. Magnet rooms are generally equipped with a quench pipe that is intended to vent this boil-off safely out of the building. However, the massive release of energy from a quench is unstable, and such pipes have failed. The sudden large volume of helium gas can act as an asphyxiant, and the fog created from the low-temperature gas can eliminate visibility. If the magnet room door swings inward and is closed, the sudden increase in room pressure can also prevent the door from opening. The door itself, which is designed for radiofrequency shielding and is typically heavy, can also become a hazard if it swings open or shut from the sudden pressure gradient across its frame.

It is important to consult with the magnet vendor and the designer of the magnet suite to determine best practices in the event of a quench. Any MR imaging emergency action plan should specify the conditions in which a quench should be initiated, the personnel authorized to initiate it, and detailed steps on how to properly evacuate the patient and individuals near the magnet. Our institution's magnet quench protocol is shown in Figure E2 (online) as an example. It is also vital for operators to understand the difference between the quench button and the emergency power shutoff or shutdown button, which shuts off many of the electrical systems surrounding the magnet without initiating a quench. A magnet quench can also occur spontaneously, secondary to faulty equipment, power failure, or inadequate liquid helium levels. Any magnet quench, intentional or not, should be considered an emergency, and all personnel should be evacuated from zone IV as quickly as possible.

All MR imaging personnel should be familiar with the risks posed by any quench. An action plan that lays out personnel responsibilities in the event of a quench should also be in place. A quench can activate building smoke detectors, summoning the municipal fire department to the magnet area. Hence it is crucial to secure the magnet area after a quench to ensure that first responders enter the area safely and only if they are needed.

Conclusion

MR imaging safety risks are unique and require a thorough knowledge of MR imaging hardware, electromagnetic principles, and contrast agents to recognize potential sources of injury. Minimizing these risks, however, also requires application of this knowledge in a practical and effective manner. Although regulations and standards help form the backbone of MR imaging safety policies, the development of a culture of safety ultimately relies on the ability of radiologists, technologists, and administrators to tailor their policies to suit their individual facility and the needs of their patients.

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