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Avoiding MRI-Related Accidents: A Practical Approach to Implementing MR Safety

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Abstract

MRI is a ubiquitous medical imaging technology typically using superconductivity to generate a strong, homogeneous, and generally ceaseless magnetic field. MRI and its magnetic field pose many safety hazards, including magnetic forces on metals, tissue heating and burns, nerve stimulation, bioeffects, acoustic noise, and contrast agent complications. The primary concern is that a wide variety of patients, staff members, technologists, and physicians can approach the incessant magnetic field, creating great potential for accidents that could occur if metals from the environment, adornments, implants, and other unintended sources are also present in or near the field. Many accidents have occurred and are occasionally reported in the United States and countries all over the world. Through carefully structured oversight and the establishment of strict guidelines regarding access, responsibilities, and training, these risks can be mitigated, and accidents can be prevented. Fortunately, there is currently a wide variety of resources available to facilitate the successful implementation of an effective MRI safety program. This article presents a general overview of and the authors' experience with an MRI safety program in terms of risk management and training. The MR safety program requirements and regulations in the United States devised by The Joint Commission and the ACR are also discussed. With these resources and a carefully selected team, the risk for MRI-related accidents can be vastly reduced if not completely eliminated.

Key Words: MRI safety, risk management, training, regulations, standard practice

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INTRODUCTION

MRI is an imaging technique available in many hospitals and clinics. It relies on the principle that atoms with odd numbers of nuclei interact with external magnetic fields. Using superconducting magnets that can generate strong static, gradient, and radiofrequency (RF) magnetic fields, chemical environments within a patient's body can be studied. The MRI system poses multiple safety hazards to patients and staff members who are inside or near the magnet, and a carefully constructed and implemented safety policy with regular training can ensure that all remain safe near the magnetic field.

Potentially the greatest concern from an MRI safety standpoint is the strong static magnetic field. Numerous

accidents have been reported around the world in which someone brings a ferromagnetic object into the magnet room that is forcibly pulled toward the magnet [1-6]. Most clinical magnets are superconducting, and charging and discharging are so onerous and expensive that the static magnetic field is sustained between examinations, whether the magnet is "scanning" or not. The static field decreases with distance from the magnet at a rate of approximately $1/\text{distance}^3$ [7], although most modern magnets also use shielding to greatly increase the rate of field drop-off. Ferromagnetic device incident avoidance is assisted by a 5-gauss line traced on the floor to give staff members a sense of the extent and strength of the field.

A discussion of specific risks associated with the static magnetic field and their mitigation are discussed in the sections that follow. Many MRI accidents can be prevented with a carefully constructed and maintained magnet area combined with appropriate oversight and good safety training. A wide variety of published resources are available to guide departments to meet these

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goals from societies and organizations, such as the ACR [8], the International Society of Magnetic Resonance in Medicine [9], the US FDA [10], and the American Board of Magnetic Resonance Safety [11]. Specifically, the ACR's periodically updated guidance document on MR safe practices is a good starting point that provides a summary of many aspects of MRI safety and approaches to managing them [12]. For medical devices and implants, vendors and online resources provide crucial safety information about each device's MRI compatibility [13-15].

SAFETY ISSUES

There are a host of safety considerations for any MRI suite, which can be subdivided in many ways. Here issues associated with the static magnetic field are considered, specifically the effects associated with metallic devices internal and external to patients and personnel. Other safety issues associated with the gradient and RF magnetic

fields, acoustic noise, and gadolinium contrast agents are mentioned but are not the focus of this article. MRI safety issues are summarized in Figure 1, in which metallic devices' interaction with MRI are divided into several categories: environmental, adornments, implantable, and unintentional.

Environmental metallic objects encompass ferromagnetic objects associated with patient care and facility management that could become projectiles if brought near the MRI scanner. Common examples include chairs, maintenance and cleaning equipment, anesthesia devices, and standard oxygen cylinders. These devices can accelerate to high speeds, potentially injuring staff members or patients. Routine clinical operations should have multiple measures and policies in place to prevent such materials from getting close to the magnet.

Implantable devices are a constantly growing group of objects that must be identified by patient report, medical record, or screening to determine the make, model, and implantation date. Their status as MR safe, conditional, or unsafe (Fig. 2) can then usually be established via freely available databases [13] or vendors. The American Society for Testing Materials is a standards body that has developed standardized tests, specifically F2503-13 [16], for determination of these classifications. Although most orthopedic implants are nonferromagnetic, many

- Metal
 - Environmental
 - Chairs
 - Maintenance and cleaning equipment
 - Anesthesia devices
 - Oxygen cylinders
 - Implantable
 - Hardware:
 - Orthopaedic hardware: hips, knees, shoulders, etc.
 - Spinal constructs
 - Cranioplasty
 - Vascular devices: aneurysm coils/clips, surgical clips, stents, filters
 - Active devices
 - Pacemakers
 - Nerve stimulators
 - Implanted pumps
 - Implanted recording devices
 - Tattoo ink & Permanent cosmetics
 - Unintentional
 - Shrapnel/Debris
 - Ballistics
 - Adornments
 - Jewelry
 - Barrettes and pins
 - Makeup containing metal
 - Piercings
 - Clothing and zippers
 - Diaphragm
 - EKG Electrodes
- Bioeffects
 - Peripheral Nerve Stimulation (PNS)
 - SAR, General RF deposition
 - Heating
 - Current induction
 - Sensory & vestibular effects
- Acoustic Noise
- Pregnancy
- Gadolinium Contrast Agent & Renal Failure
 - Deposition
 - Nephrogenic Systemic Fibrosis (NSF)
 - Allergy

Fig 1. List of MRI safety considerations: summary of hazards with emphasis on objects that may pose a risk to patients and staff members during MRI. These are not all contraindicated but need to be evaluated to determine if they are acceptable risks for the patient given the clinical context and urgency of the examination.



Fig 2. MRI compatibility labeling. To prevent accidental movement of MRI-unsafe materials into the magnet room, the policy at the authors' institution is to label all equipment, fire extinguishers, phlebotomy materials, and so on, either MR safe, conditional, or unsafe to prevent accidental movement of ferromagnetic materials into the magnetic field and possible injury.

older devices, such as aneurysm clips, implantable cardiac defibrillators, and pacemakers, contain ferromagnetic components. If a device is deemed MR conditional and the clinical indication warrants the examination, the manufacturer's recommendations should be consulted before the patient enters the scanner area.

Unintentional metallic objects include shrapnel from bullets, manufacturing debris, and other metal structures; [Figure 3](#) shows MR images of patients with such unintended internal objects. Occupational history, including welding, grinding, metalworking, sculpting, and military warfare, all increase the risk for

ferromagnetic foreign bodies' undergoing unsafe forces in a magnetic field. These cases should be dealt with on an individual basis depending on the location of the foreign body, its proximity to vital organs, the level of suspicion regarding the material, the perceived length of time the object has been internal to the patient, the cooperativity of the patient, and the urgency of the clinical indication. Patient consent should be considered if the scan is to be performed.

Adornments encompass jewelry, pins, barrettes, zippers, and components of clothing people may wear that are removable ([Fig. 3](#)). These objects have the

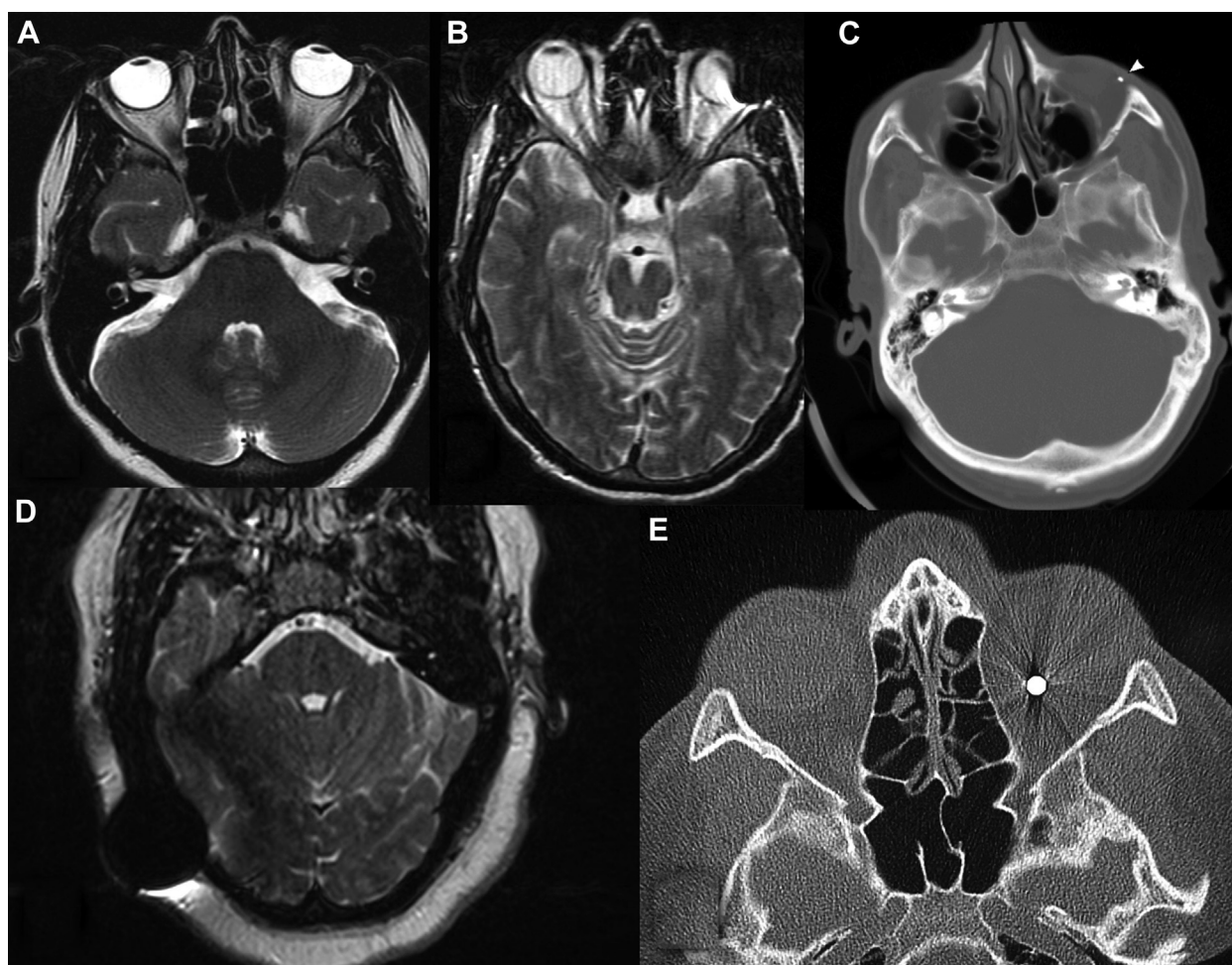


Fig 3. Sample of metal seen in clinical practice. Some metal within the body is intentionally placed, but occasionally it is accidental or unintentional. Most institutions ask women to remove mascara before an MRI examination because it often contains iron particles that cause artifacts along the front of the eyes (A). Screening forms should ask for a history of metal working, as patients may have intraorbital metal that chipped off during the course of metal work and caused injury. (B) MR image and (C) CT image of the left lateral orbit of a patient who forgot to report metalworking history; artifact is attributed to a metal fragment. One of the more common implanted metallic devices is a shunt device, which helps drain cerebrospinal fluid from the ventricles; this is demonstrated by the large artifact along the right side of the skull (D). Trauma, motor vehicle accidents, and bullet injuries can often introduce metal into the superficial or deep tissues, as seen on CT (E), in which artifact stems from an air-gun BB shot behind the globe next to the optic nerve, representing a contraindication to future MRI.

potential to be ripped from a person's body, causing injury to the person and others. Policies for screening, gowning, and object removal before personnel or patients' entry to the scan room should be in place to avoid potential hazardous situations.

There are a variety of other possible risks in MRI that are beyond the scope of the article but are included in [Figure 1](#). Tissue heating can occur as a result of high RF power deposition, which is especially problematic in regions with implanted metals such as wires and depends on their arrangement, length, and shape. Rapidly changing gradient fields can induce electric fields in tissue that lead to peripheral nerve stimulation, manifesting as a tingling or tapping sensation in affected nerves and muscles [13]. Gadolinium contrast agents have been shown to systemically deposit in tissue well after administration [17,18], cause nephrogenic systemic fibrosis in patients with compromised renal function, and contraindicate fetal imaging. Acoustic noise caused by gradient coils' vibrations within their housing can be high enough to damage a patient's or staff member's ears. Rarely, emergent situations may call for discharging the magnet (magnet quench); superconducting helium within the magnet is boiled off and vented, which can yield large amounts of heat and equipment damage, asphyxiation due to a disparity in scan room oxygen, frostbite due to low helium temperatures, fire hazards due to oxygen condensation, and positive pressurization of the magnet room leading to patient or personnel entrapment.

RISK MANAGEMENT

A safe MR environment is enabled by mitigation and/or elimination of safety risks. Appropriately trained personnel should be responsible for both proactive and reactive safety measures, including segmenting, controlling, and monitoring access to the MRI environment. All patients and personnel accessing the MRI suite should be thoroughly screened to prevent dangerous objects from entering the scan room. With careful consideration, control, and training, imaging with MR can be a relatively innocuous experience for both patients and personnel.

Current clinical standard of practice is to designate an MR medical director, a safety officer, and a safety expert to ensure MR safety. The American Board of Magnetic Resonance Safety [11] has recently generated a safety certification procedure for each position; although not a requirement for safe MRI operations, it can provide a standard level of safety assurance. The medical director is ideally an MR physician who ensures that safety

guidelines are created, implemented, and adhered to at all times. The safety officer is typically the MRI operating technologist, who is charged with safe operation and execution of MRI and monitoring of its associated environment. The safety expert is often a scientist or an engineer who is well trained in MRI fundamentals to a degree that permits detailed explanation of the sources and mitigation tactics of any safety concerns. It is advisable that a safety officer always be on site, as well as a medical director and safety expert who are either on site or at least accessible for communication.

The MRI environment is segmented to permit access control by the MRI safety officer, as depicted in [Figure 4](#). The scan room itself is designated zone IV, where all personnel and patients should be accompanied by highly trained "level 2" personnel (see below). The area directly adjacent to the scan room through its door is designated as zone III, where MRI technologists, operation consoles, clinical support equipment, and essential clinical personnel are situated. "Level 1 and 2" personnel (see below) may be in this area unattended, while all non-MR personnel and patients should be well screened and monitored by trained personnel. All patient and safety support devices, such as crash carts, oxygen cylinders, and emergent objects such as crowbars, fire extinguishers, and other fire-fighting equipment, should be screened for safety and clearly labeled as MR safe or conditional before their entry into zone III or zone IV. Outside of zones IV and III is zone II, where all personnel may move about freely, although all patients should be accompanied by personnel with some MRI training. Zone I is the common areas of the hospital itself; there are no restrictions in this zone.

Prevention of potential hazardous scenarios in MRI is spearheaded by careful screening of both patients and personnel using screening forms, ferromagnetic detection devices, and patient gowning. Careful consideration of the risks associated with the specific metallic implants in the specific magnetic field and imaging sequences in which they are subjected is essential. An example of a patient MRI screening form is depicted in ([Online Figure](#)); note that at our institution, if a patient indicates a history of shrapnel, bullet fragments, ferrous metalworking, or orbital metal, further evaluation via radiography or limited CT is executed. A radiologist is consulted to consider potential ferromagnetic material and the benefits of the scan to further evaluate the patient's risk. If a patient has an implant found to be MR conditional, scanning risks are mitigated by carefully following vendor or published guidelines stipulating the field strength,

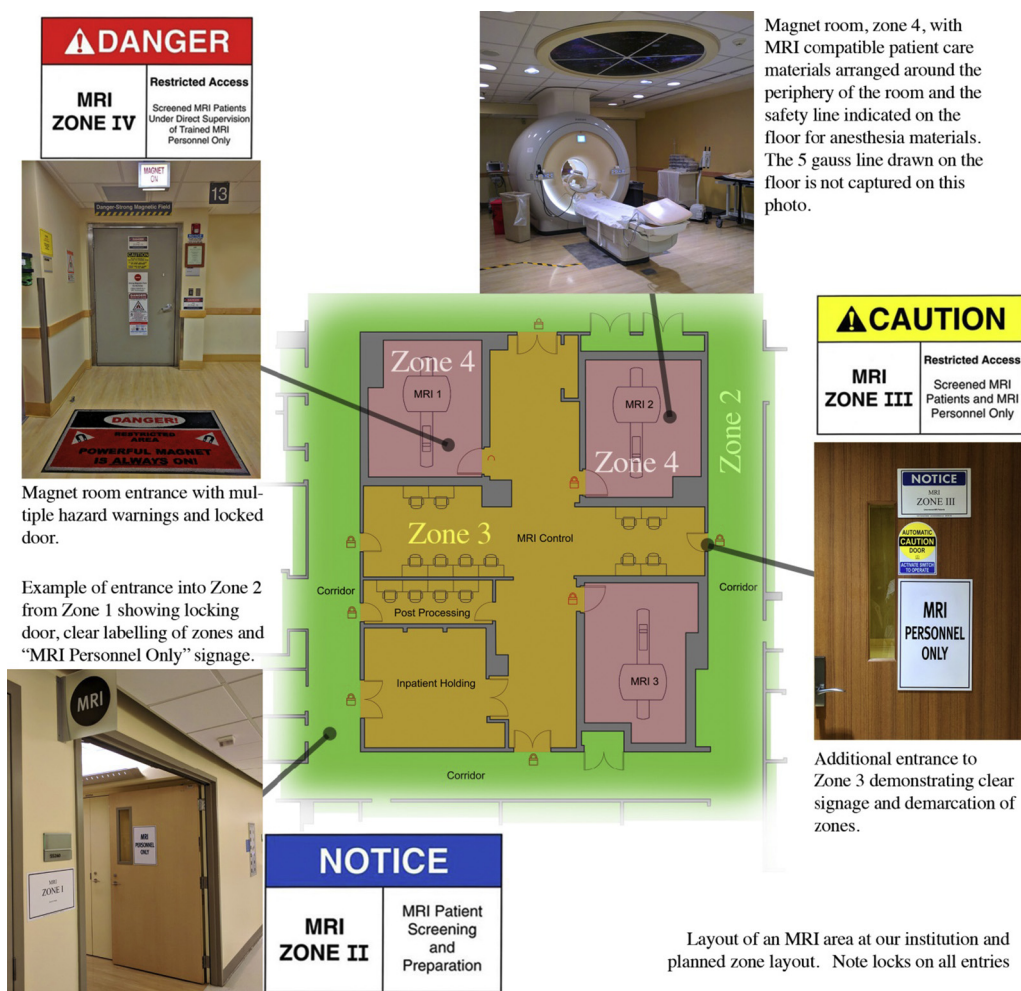


Fig 4. Example zone layout. The zone system provides strict demarcations of areas with increasingly restricted patient and staff access, starting with zone I in the radiology waiting area and attached corridors to zone IV in the magnet room. Note that each area has signage indicating passage into different zones, with increasing warnings about magnetic fields.

sequences, orientation, and position of the device for safe scanning.

The risk to the patient is occasionally deemed to be high, such as when gadolinium is administered to pregnant or renally compromised patients. Depending on the institution's policy, these patients may undergo a consent process to ensure that patients understand the inherent risk of MRI in their situation. This usually involves a radiology resident, a fellow, or an attending radiologist seeing the patient and discussing the situation and risks, followed by the optional signing of a consent form. At our institution, first-trimester patients and cardiovascular implantable device patients are consented.

TRAINING

Safety training is an important component of ensuring a safe MR environment. MR personnel are those

individuals routinely working in the MR environment with the necessary training to enter and work in zones III and IV (Figure 4). Level 1 personnel are typically MRI medical assistants, radiology nurses, and radiologists who are occasionally in the MR environment and thus require a minimal level of training. The institutional MRI medical director designates level 2 personnel, where an advanced level of training is disseminated or required of MR technologists, MR radiologists, and physicists, scientists, and engineers who routinely work in the MR suite. Non-MR personnel are personnel and patients who do not meet the standard of level 1 or level 2 and must be screened in order to access the MR environment. They may still receive minimal training if repeat access is necessary (eg, nurses, pain and anesthesiology personnel).

Table 1. Brief collection of MR resources available online for MR safety training and management

Resource	Link
ISMRM MR safety	https://www.ismr.org/mr-safety-links/
IMRSE MR safety videos	http://www.imrse.org/genpg.asp?pgname=VideoList
MRISafety.com	http://www.mrisafety.com/
ABMRS	http://www.abmrs.org/
FDA MR safety	https://www.fda.gov/Radiation-EmittingProducts/RadiationEmittingProductsandProcedures/MedicalImaging/MRI/default.htm
ACR MR safety	https://www.acr.org/Clinical-Resources/Radiology-Safety/MR-Safety

Note: ABMRS = American Board of Magnetic Resonance Safety; FDA = US Food and Drug Administration; ISMRM = International Society of Magnetic Resonance in Medicine; IMRSE = Institute for Magnetic Resonance Safety, Education, and Research.

Several resources exist for training of MR personnel (Table 1). The ACR guidelines document [12] is a good overview of MR safety and is an essential read for anyone working in the MR environment.

At our institution, basic MR training is an online safety video provided initially and annually to level 1 and level 2 MR personnel, with the latter requiring additional advanced training. Some non-MR personnel, such as anesthesiologists, also complete the annual training. We are in the process of making this training mandatory for all radiologists who visit or interact with MRI. Custodians are permitted in zone III only when level 1– or level 2–trained MR personnel are present.

REQUIREMENTS AND REGULATIONS

MR safety regulations have been in constant flux in recent years, with The Joint Commission (TJC) and the ACR publishing updated standards of care. As the public focus increases because of recent safety

issues, it is imperative that these guidelines be understood and followed in order to avoid future safety issues.

TJC published guidelines in 2015 that make several recommendations to ensure safety in the MRI environment (Table 2). They require organizations to maintain and document MR technologists' annual MRI safety training and optimal patient positioning to avoid thermal injuries [19]. TJC also requires organizations to manage and document patient safety issues involving nephrogenic systemic fibrosis, implanted devices, acoustic noise, and claustrophobia and to perform the appropriate corrective actions in each instance. Finally, TJC requires that all patient thermal and ferromagnetic object injury data be collected and documented on site.

Supplementing the continually updated ACR MRI safety guidelines publication [12], the ACR MRI accreditation program has recently implemented MR safety requirements [20] (Table 2). The MR

Table 2. Current ACR and Joint Commission regulations pertaining to MR safety

ACR	The Joint Commission
MR supervising physician responsibilities	
Develop, implement, and enforce policies and procedures to address safety issues, including contrast use and sedation, for pediatric patients	Requires organizations to manage MR safety issues related to implants, noise, claustrophobia, and so on, and also requires organizations to follow TJC-required activities related to these issues
MR safety guidelines, practices, and policies must be written, enforced, reviewed, and documented at least annually	Collecting data on patient thermal injuries, incidents in which ferromagnetic objects unintentionally entered the MR suite, and resulting injuries is also a TJC requirement
Medical physicist/MR scientist responsibilities	
Annual MRI performance evaluation must also include an assessment of the MRI safety program (signage, access control, screening procedures, and cryogen safety) as well as an inspection of the physical and mechanical integrity of the system	
Must complete an MR safety assessment checklist	

supervising physician is required to develop, implement, and enforce policies and procedures to address safety issues (including contrast use and sedation), and enforce, review, and document these policies at least annually. The medical physicist or MR scientist's annual MRI performance evaluation must also include an assessment of the MRI safety program (signage, access control, screening procedures, and cryogen safety), as well as an inspection of the physical and mechanical integrity of the system. The ACR provides an MR safety assessment checklist that must be completed by the medical physicist or MR scientist annually.

Other local regulations regarding MR safety may exist and vary on a state-by-state basis in the United States.

It is essential for organizations to maintain cogent and comprehensive MR safety policies, training, practices, and injury documentation. At our institution, MR policies adhere to the recommendations described here and are kept consistent among hospitals. These policies are reviewed every 2 years and updated as needed.

TAKE-HOME POINTS

- An MRI system poses a variety of hazards to patients and staff members, with the potentially main concern being the interaction of the magnetic field with metallic substances implanted or adorned on the patient's body or unintentionally or environmentally entering the scan room.
- Mitigation of safety risks can be achieved via careful site layout, personnel oversight designation, access control, device labeling, screening, and consenting.
- MR safety training enables the creation of a safe MR environment, with training levels determined by the personnel access requirements.
- MR safety regulation requirements set by TJC and the ACR should be well understood and followed in order to avoid MR safety issues.

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ADDITIONAL RESOURCES

Additional resources can be found online at: <https://doi.org/10.1016/j.jacr.2018.06.022>.

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