# Magnetic Resonance Imaging Safety

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*Although magnetic resonance (MR) imaging does not use ionizing radiation, it has its own safety issues. MR safety concerns are associated with the static magnetic field, radiofrequency burns, scanner acoustic noise, and the use of gadolinium-based contrast agents. MR technologists have a responsibility to thoroughly screen patients and personnel before they enter the magnetic field and to research patient implants and devices to determine under what conditions the patient can be scanned safely. During long scans, MR technologists also must monitor patients to avoid adverse events. This article is useful for non-MR technologists who might work in the MR environment or who are considering cross-training in this important discipline.*

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**After completing this article, readers should be able to:**

- Discuss the fundamentals of magnetic resonance (MR) imaging.
- Outline proper safety procedures regarding ferromagnetic objects in the main magnetic field.
- Describe how to prevent radiofrequency-related thermal injuries.
- Understand the effects of MR-related acoustic noise and list measures to protect patient hearing.
- Explain the important role of the MR technologist in patient safety.

Magnetic resonance (MR) imaging is the product of discoveries throughout many years. In 1882, inventor Nicola Tesla discovered the rotating magnetic field in Budapest, and in the 1950s, the tesla (T) was designated as the unit of measurement for the strength of a magnetic field.[1] Also during this time, Herman Carr created a 1-D image using a magnetic field.[1] Shortly after, scientist Raymond Damadian found that the hydrogen signal in tissue affected by cancer differed from that of healthy tissue because tumors often contain more water. Damadian also noticed that cancerous tissue emitted radio waves for a longer duration than did healthy tissue when the nuclear magnetic resonance, as it was called at the time, was switched off.[1] In 1973, chemist Paul Lauterbur produced the first MR image (of a test tube), which earned him a Nobel Prize for discovering a method for imaging the human body without the use of ionizing radiation.[1]

In 1977, Damadian, with the help of 2 postdoctoral students, built the first human MR scanner, known as the *Indomitable*, and later performed the first human MR scan.[1] The first MR imaging scanners were available commercially in the early 1980s. MR technology has continued to progress. In 1987, real-time cardiac imaging was developed, and functional MR imaging was discovered in the early 1990s.[1] Functional imaging, which gives real-time information on brain activity, has become widely used by neurosurgeons and researchers.[1]

## Common Indications

During the early days of MR imaging, the modality was used predominantly for neuroimaging and musculoskeletal imaging; by the 2000s, cardiac, body, fetal, and functional MR imaging were refined and widely used among hospitals and imaging centers.[1] Common indications for MR neuroimaging include stroke, infection, multiple sclerosis, dementia, trauma, pituitary gland disorders, spinal radiculopathy,

or postoperative investigation.[2] MR is the first and only imaging modality to detect early multiple sclerosis lesions and monitor the course of the disease noninvasively.[3]

Common indications for musculoskeletal MR imaging include joint derangement, infection such as osteomyelitis, trauma, bone and soft tissue tumors, and vascular pathologies.[2] It often is ordered for athletes to rule out ligament and meniscus disruptions, as these often are better visualized with MR imaging than with other modalities. Common indications for body MR imaging, such as abdomen and pelvis scans, include tumors in organs (both primary and metastatic cancer), infection, congenital abnormalities, and for the evaluation of perianal fistulas. The use of cardiac MR imaging to evaluate cardiac ischemia, mediastinal masses, congenital abnormalities, and cardiomyopathy has become more popular in recent years.[2]

Vascular MR imaging, such as MR angiography and MR venography, is helpful in ruling out blood clots and stenosis and increasingly is performed without gadolinium contrast because of an imaging technique known as *time of flight*.[4] Although less common, fetal MR imaging combined with sonography is gaining popularity for evaluating fetal abnormalities.[2]

## Physics of Magnetic Resonance

Unlike computed tomography or radiography, MR imaging does not use ionizing radiation; it uses strong magnetic fields in conjunction with radio waves to measure relative water content in tissues.[3] When the patient is placed into the center of the bore of the magnet, called the *isocenter,* the patient's hydrogen nuclei line up either parallel or antiparallel to the static magnetic field, called *B0*.[4] Most nuclei are parallel to B0 and represent the net magnetization vector of the patient. These are called *spin-up nuclei*.[4] The nuclei with the strongest energy align antiparallel to B0 and are called *spin-down nuclei*. The hydrogen nuclei begin to wobble or precess (spin) around the main magnetic field. When a radiofrequency pulse is applied, the hydrogen nuclei flip at an angle against B0 and precess in phase (all together). The precessional frequency is the speed at which the nuclei precess around B0. If the radiofrequency pulse is applied at the same energy level of the processional frequency of hydrogen, the nuclei gain energy and resonance occurs.[4] This application of a radiofrequency pulse also is known as *excitation*. Some of the low-energy spin-up nuclei absorb a portion of this energy, causing them to flip and become spin-down nuclei. The higher the energy level, the greater the number of spin-up nuclei that flip down. Resonance causes these hydrogen nuclei to precess in phase with each other, known as *coherence*. During relaxation, the net magnetization vector moves back in line with B0, and a signal is transmitted to the receiver coil and then transferred to the scanner computer where the MR image is formed (see **Figure 1**).[4]

Protocols for MR imaging scans are composed of various pulse sequences constructed by the system software engineers. A pulse sequence is a series of radiofrequency pulses, gradient applications, and time periods.[4] Many types of pulse sequences exist, and each is designed for a specific purpose. Each pulse is timed perfectly to create the MR image appropriate for that examination. Repetition time (TR) is the length of time between each applied radiofrequency pulse sequences, and echo time (TE) is the time from the application of the radiofrequency pulse to the peak of the signal induced in the MR coil (echo).[4] By differing the MR pulse sequences used to measure the relaxation of the net magnetization vector, water content can be shown in various ways.[3] For example, a pulse sequence using T1 weighting shows fluid as dark, or hypointense, and T2 weighting will produce an image showing fluid as bright, or hyperintense.[4]

## Types of MR Scanners

The types of magnets often used for MR imaging include permanent, resistive, and superconducting, with superconducting being the most popular.[4] Permanent magnet systems use a static magnetic field generated using ferromagnetic substances, such as nickel and cobalt, because they retain their magnetism after exposure to a magnetic field.[4] Permanent magnet systems do not require a power supply, so their operating costs are low. They also have a small fringe field—the peripheral magnetic field outside of the magnet core—meaning there are fewer safety considerations compared with high-field systems, and they can be placed closer to public areas than can other types of systems. However,

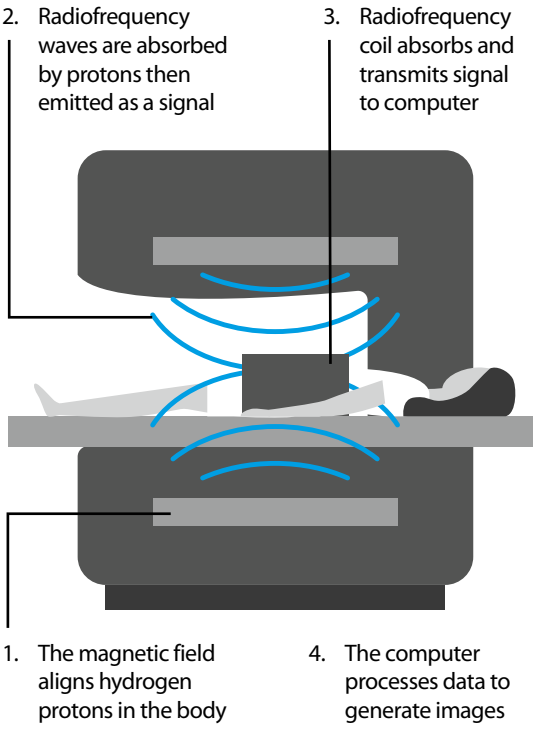


**Figure 1.** *Magnetic resonance (MR) image acquisition. © 2020 ASRT.*

these systems are heavy and cannot be switched off. Their lower field strength results in longer scan times and lower signal-to-noise ratios, generating inferior image quality.[4]

Resistive magnets operate using Ohm's law, which describes the degree of resistance along a wire. MR systems that use resistive magnets have a static magnetic field that is generated by a current passing through loops of coiled wire. Although it can be switched on and off, it requires a constant power supply and has a large fringe field, so there are more safety concerns.[4] The maximum field strength using a resistive magnet is less than 0.3 T because an increase in the magnetic field requires an increase in the current that can raise the temperature to a level that destroys the electromagnet. These systems are lighter and easier to move, and initial purchase costs are low. However, they have high operating costs, and because of the low field strength of these machines, they are not commonly used in the clinical setting today.[4]

Superconducting systems are high-field MR scanners classified as having a magnetic field strength of at least 1 T.[4] Most MR scanners worldwide have a field strength of 1.5 T, but the use of 3 T scanners is increasing. In 2017, a 7 T MR system was approved by the U.S. Food and Drug Administration (FDA) for clinical use, and systems with a field strength up to 14 T are being used for research. These high-field systems produce images of optimal quality. A 3 T scanner yields twice the signal-to-noise ratio of a 1.5 T scanner, which leads to shorter scan times.[4] Superconducting systems are the most common type of MR scanners used today because they produce high magnetic field strengths without causing resistance. To avoid the issue of heating in the coils, superconducting systems are designed using an alloy of niobium and titanium that becomes superconductive when cooled to below 4 K (–450°F). A superconducting magnet exhibits almost no resistance and can carry a powerful electrical current for as long as necessary without reaching high temperatures that would damage the machine. During system installation by the service engineer, an electromagnetic field is created by passing a current through the main scanner coil, which is known as *ramping up* the magnetic field.[4]

To maintain superconductivity, the loops carrying the current are cooled with cryogens to eliminate resistance. Cryogens used in MR imaging include liquid helium and sometimes nitrogen, which keeps the helium cold. Helium is a rare, expensive resource and is contained in a stainless-steel tank (a cryostat) situated inside the MR scanner. Helium displaces oxygen, and the unexpected release of helium gas can cause death from anoxia.[4] Modern scanners store as much as 1500 L of liquid helium, and an emergency situation that causes the cryostat to boil off the liquid helium is a serious safety concern because it would result in the release of over 1 000 000 L of gas.[4] This event, known as a *quench*, also can cause damage to the superconducting coils and the liquid helium is expensive to replace. For this reason, superconducting magnetic fields are not switched off suddenly, except when life-threatening danger is imminent.[4] An emergency quench can be initiated by pressing a large red button typically found outside the doorway to the MR room.[4] Superconducting systems are seen as superior to other types of MR systems, but

they come with several important safety concerns. MR technologists have a responsibility to keep patients, coworkers, and themselves safe.[4]

## Safety Guidelines

In 2001, a 6-year-old boy lying on a MR table died when a ferromagnetic oxygen tank was brought into a MR room at Westchester Medical Center in New York.[5] At the time, no formal MR imaging safety standards had been published.[4] This tragedy prompted the American College of Radiology (ACR) to create a Blue Ribbon Panel of MR safety experts, which included radiologists, physicians, PhDs, technologists, and legal representatives.[4] This group created the ACR White Paper on MR Safety in 2002, and it has guided MR facilities in the development and implementation of safety policies.[4] The guidelines cover zoning, pregnancy related issues, pediatric safety concerns, cryogen related issues, claustrophobia, and contrast agent safety.[4]

### *MR Personnel Levels*

The ACR white paper describes the levels of personnel and their ability to access the MR scan room as follows[4]:

- Non-MR – those with no MR imaging training, such as patients, their family members, or some facility staff members.
- Level 1 – staff members who passed minimal safety education training, such as an annual MR imaging safety module; this includes MR imaging front desk staff, transporters, floor nurses, and technologists in other disciplines.
- Level 2 – those who have undergone extensive training regarding the MR system and its various safety issues; this includes MR technologists, radiologists, and in some cases, radiology nurses.

### *MR Zones*

Because there have been detrimental accidents involving the main magnetic field and ferromagnetic objects, some of them fatal, the ACR recommends that all MR facilities have clearly marked zones to control access to the MR imaging system and fringe field to prevent further accidents (see **Figure 2**).[4] The 2013 ACR white paper on MR safety describes 4 zones[4,6]:

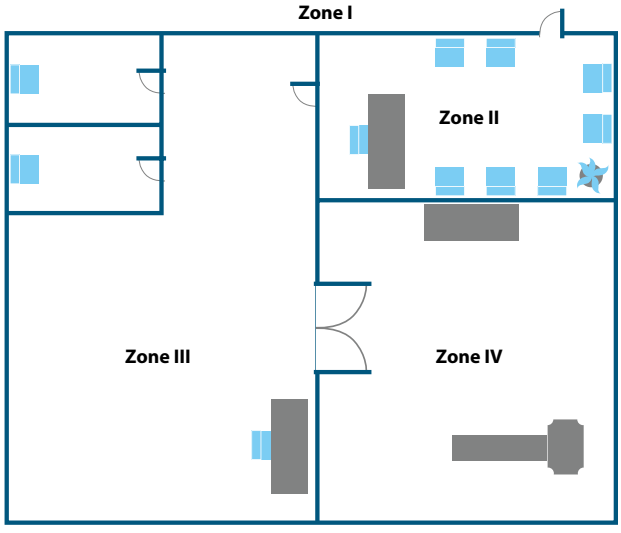


**Figure 2.** *Safety zone configuration of an MR facility. © 2018 ASRT.*

- Zone I – areas freely accessible to the public, including the parking lot, hallways, admission, and other areas of the clinic or hospital located outside of the MR imaging department.
- Zone II – areas between zone I (public access) and zone III (controlled access) and includes the MR imaging waiting room or the area of the hospital where unscreened inpatients wait before entering zone III. Patient movement throughout zone II should be supervised by MR personnel.
- Zone III – access is strictly guarded and should be restricted by a physical barrier and includes the waiting area for screened patients and the technologist's console area. Use of badge readers, lighted warning signs, and placards is common. Serious injury or death can occur in zone III from interaction between unscreened individuals or ferromagnetic materials and the static and time-varying magnetic fields. Non-MR personnel access is controlled and constantly supervised by appropriate MR personnel. Only level 2 personnel can escort non-MR personnel into zone IV. Also, zone III is the zone in which non-MR personnel must have passed a thorough screening process in zone II. This screening process should

be completed by MR personnel only, usually the MR technologist.
- Zone IV – includes the room that houses the MR imaging scanner (magnet) and presents the greatest risk. Entrance should be marked clearly as potentially hazardous from strong magnetic fields, and visible signs should be posted outside of every scanner room, stating, "This magnet is always on." Patients and staff members must be properly screened by level 2 personnel before entering. Level 2 personnel also should visually monitor all level 1 personnel in zone IV.

Many facilities use a ferromagnetic material detector, situated in zone III or at the doorway to zone IV, to identify ferromagnetic implants or objects the technologist might have missed while screening the patient or staff member.[5] All zones should be clearly marked with easily visible signs, and it should not be possible for a patient to skip a zone.[5]

### *Magnetic Shielding*

Without the use of magnetic shielding, the fringe field of high-field magnet systems would spread beyond the MR scanner room, possibly into areas with ferromagnetic objects or unscreened patients.[4] There are 2 main types of magnetic shielding: passive and active.

Passive shielding involves lining the scanner or the magnet room with steel plates. This shielding can weigh up to 40 tons and requires a bottom-floor room with a strong foundation. Passive shielding is used only when necessary because it is difficult to install and expensive.[4] Passive shielding is necessary for ultra-high-field 7 T research scanners and might be located up to 2 floors below the rest of the MR imaging systems in a special basement room.

Active shielding is used for most modern superconducting systems.[4] Active shielding involves the use of solenoid electromagnets placed around the outside of the main magnet coils, located at each of the magnet openings. Because these additional magnets also are superconducting magnets, they are located in the cryostat to prevent overheating. These magnets have an equal but opposite effect on the main magnet, which reduces the size of the fringe field.[4] According to MR safety measures, the total shielding used for an MR system should restrict the fringe field to 5 G (0.0005 T) in the scan room (zone IV). The active shielding used with today's MR systems restrains the 5 G fringe field to a few feet from isocenter.[4] In many MR scan rooms, the fringe field is easily designated with a line on the floor, known as the *5-gauss line*. This is the line at which ferromagnetic objects often begin to be pulled into the isocenter. The best practice standard is that ferromagnetic objects do not enter zone III.[6]

### *Site Planning*

When planning the installation of a new MR system, many factors must be considered to avoid catastrophic events related to the static magnetic field. Some architectural and planning considerations include[4]:

- an appropriate power source
- power restrictions for the area
- shielding for radiofrequency and the static magnetic field
- room ventilation
- other structures surrounding the proposed area
- noise restrictions
- locations with large metal components close by (eg, a subway train underneath the area)
- structural reinforcement
- spatial dimensions
- mechanical and electrical components
- static field strength and size of the fringe field
- MR safety zones

Building a new MR room and installing a new MR scanner is an expensive process; therefore, thought and planning should go into its design. For example, a facility might need to build a structure to house the MR scanner or incorporate it into an existing building, such as a hospital. Each situation comes with its own set of site considerations.[4] Field strength also is an important factor to consider.[4] As field strength increases, the size of the fringe field increases.

Mobile MR units are stored in trucks and driven to different imaging facilities as needed, often staying ramped up during moves, which greatly decreases set-up time.[4,7] Throughout the years, these scanners have become lighter, smaller, and better shielded.[7] These units come with their own safety considerations. They must adhere to traffic regulations, such as weight

restrictions and wheel base area, and the fringe field must be considered.[4] Also, the parking site must have a sufficient power source, level ground, and a parking location that is strong enough to bear the weight of the truck, the scanner, and its other components.[4]

## Missile Effect

There are 2 forces that cause ferromagnetic objects to move when inside the boundary of the main magnetic field.[4] The rotational force causes a torque, or twisting, of objects (eg, an aneurysm clip) and can result in severe consequences, such as hemorrhage or even death. The other type of force, translational force, causes ferromagnetic objects to be attracted to the center of the scanner and increases in strength as an object approaches isocenter.[4]

Some medical equipment and other objects might be marked with MR safe or MR conditional labels, meaning they have been tested and deemed safe to be brought into the scan room (see **Figure 3**). MR-conditional medical equipment, such as ventilators and monitors, should be stored beyond the 5-gauss line outside the fringe field.[4] Objects not labeled should be tested with a handheld magnet that has a strength of at least 1000 G (0.1 T) before allowed into the room. For example, a staff member should test their jewelry with a handheld magnet to determine whether it has a chance of becoming a projectile once it enters zone IV.[4] Objects labeled MR unsafe must never be brought into zone IV.

The missile effect is likely the most important safety issue with MR imaging, because it can have the most detrimental effects if best practices are not followed. The missile effect describes an event where an object, such as an oxygen tank, becomes a missile in the presence of a strong magnetic field. An object does not have to be large to become a projectile; paper clips and hairpins can travel into a 1.5 T MR magnet with a speed of up to 40 mph.[4] Ferromagnetic objects travel to isocenter, and if these items are in the scan room, they can injure a patient seriously inside the bore.[4] The force of the translational pull on objects into the magnet is proportional to the strength of the magnetic field, the object's distance from the magnet, the object's mass, and the object's composition.[4] Medical gear that nurses or physicians often carry, such as scissors, hemostats,

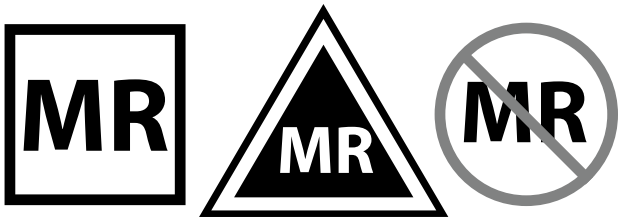


**Figure 3.** *Current MR labeling icons. A. Square label indicates that the object is MR safe. B. Triangular label indicates that the object is MR conditional. C. Round label with a diagonal slash indicates that an object is MR unsafe. Reprinted with permission from ASTM F2503-13 Standard Practice for Marking Medical Devices and Other Items for Safety in the Magnetic Resonance Environment.*

and stethoscopes might accidentally enter zone IV where they are attracted strongly to the static magnetic field.[4] There have been many instances where large objects, such as a ferromagnetic stretcher or wheelchair, have been brought into the scanner room and became a projectile (see **Figure 4**). This is a dangerous situation, and someone in the path of the projectile can get trapped and suffer severe injuries or potentially lose their life. In these cases, the quench button is used.[4]

## Radiofrequency Energy and Thermal Injuries

During an MR scan, exposure to radiofrequency (RF) energy causes temperature increases in the patient. The amount of increase is dependent on the frequency, field strength, and size of the patient.[4] As RF is absorbed, the patient's tissues are heated. Limits for the amount of RF heating a patient can be exposed to exist; therefore, it is necessary to monitor RF absorption. The FDA limit for RF exposure is measured by the increase in body temperature or by using the specific absorption rate (SAR).[4] The FDA limits temperature increases to 1°C in the core of the body but allows a higher increase in the periphery; for example an increase to 40°C in the extremities is allowed.[4] The majority of tissue heating occurs at the extremities and easily is dissipated.[4]

The regular measurement of patient core temperature is impractical, so SAR is used to calculate the expected increase in patient body temperature for a given sequence in watts per kilogram. SAR is dependent on RF pulse characteristics (watts) and patient

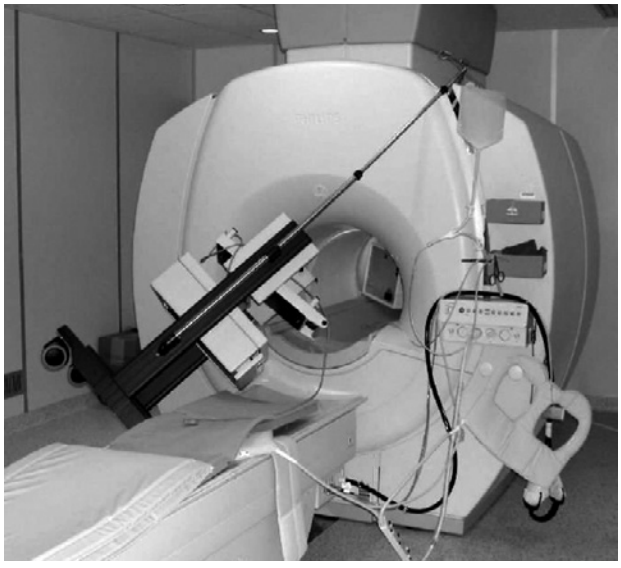

**Figure 4.** *An MR-unsafe drug-infusion pump pulled into the bore by the static magnetic field. Reprinted with permission from Karpowicz J, Gryz K. Experimental evaluation of ballistic hazards in imaging diagnostic center.* Pol J Radiol. *2013.78(2):31-37. doi:10.12659/PJR.883943*

characteristics (kilograms); therefore, it is vital that the technologist records the patient's weight accurately when inputting patient information during registration.[4] Specific absorption rate limits, set in place by the FDA, are calculated as follows[4]:

- whole body – 4 W/kg averaged over 15 minutes
- head – 3 W/kg averaged over 10 minutes
- head and torso – 8 W/kg per gram of tissue every 5 minutes
- extremities – 12 W/kg per gram of tissue every 5 minutes

### *Radiofrequency Safety Guidelines*

According to The Joint Commission, 70% of MR-imaging adverse events are related to thermal injuries caused by a scan.[8] The primary cause of RF burns is excessive power deposition.[8] During the scan, RF power is not deposited uniformly in the patient's body, causing certain regions to become hotter than others. Temperatures can exceed safe limits, and RF burns can occur.[8] Most burns occur when cables and wires come in to contact with a patient's skin. There is a risk of RF heating with the use of guidewires and catheters with a metal tip or temperature probe and with external fixators.[9] Also, many localized burns are not caused by cables or wires but by metallic medication patches, electronic devices near the patient, or clothing made with metallic threads.[4] Athletic clothing made with metallic microfibers has made MR-related thermal injuries a hot topic.[8] Many MR imaging facilities updated their policies and now require all patients to change into gowns, and some require patients to remove underwear if there is a chance it has metallic microfibers that might cause heating during the scan.[8] Some types of tattoos also have been shown to heat up during a scan.

Many MR imaging scans use surface coils, which are RF antennae that lie on top of the patient and receive signals from the body; then those signals are used to produce an image.[4] RF fields, such as the ones used in MR imaging, pose a significant risk of burns from the electrical currents produced in conductive loops.[4] Surface coils, electrocardiogram leads, and other equipment used in MR imaging should be used with caution.[4] The technologist should not allow conductive material, such as the cable of a surface coil, to form a loop with itself or a part of the patient.[4] Wires used in the MR environment should be insulated electrically and thermally because uninsulated cables can cause tissue or clothing to catch fire during a scan.[4] MR technologists must check all coils, cables, and wires to ensure the insulation and padding are intact. Wires or cables with broken or missing insulation should be removed from the MR room until they are repaired or replaced.[9] Many inpatients present to the MR imaging department with existing pulse oximeters and electrocardiogram wires attached to them. Checking the patient thoroughly for these MR-unsafe devices is crucial, because they are the most common cause of thermal burns in the MR environment (see **Figure 5**).[10]

According to a 2010 study, approximately 400 MR-related thermal injuries in the United States were reported in a 10-year period.[9] These incidents included first-degree, second-degree, and third-degree burns. Many of these burns were caused by the direct contact of limbs or other body parts with body array coils.[9] Some of the burns were caused by skin-to-skin contact, which created a closed conductive loop for the current

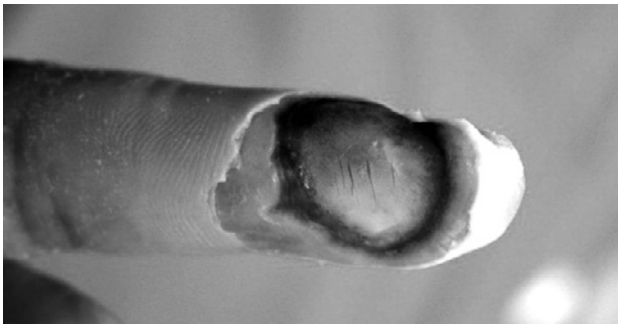

**Figure 5.** *A third-degree burn on the distal phalanx caused by an MR-unsafe pulse oximetry probe on a patient during MR imaging. Reprinted under the Creative Commons Attribution Non-Commercial License 4.0. Sung SJ, Park YS, Cho JY. Full thickness burn on the finger due to pulse oximetry during magnetic resonance imaging in a conscious patient.* Arch Plast Surg. *2016.43(6):612-613. doi:10.5999/aps.2016.43.6.612. creativecommons.org/licenses/by-nc/4.0/*

to pass through and resulted in a burn in the area of contact.[9] In addition to requiring patients to change into a gown, patients should be instructed to remove all metallic objects from their body including jewelry, watches, and drug-infusion devices, and store them along with other personal belongings, such as wallets and cell phones, in a locker.[9]

When the patient is in position on the MR table, insulation material should be used to prevent skin-to-skin contact points, such as between the thighs, where RF burns are known to occur.[9] Appropriate padding with a minimum thickness of 1 cm should be placed between the patient's skin and the transmit RF coil, unless the coil comes with padding over it.[9] The patient's skin should never touch the inside bore of the scanner because the inner walls can become hot during the course of a scan.[11] The heat is a result of eddy currents and resistive heating caused by currents passing through the scanner's gradients.[11] Modern scanners come with a cooling system, but it is still important that padding is used in studies where a patient is supine with their arms by their side, especially when the inherent transmit RF body coil is used for a scan.[9]

Only electronic devices that have been tested to be safe or conditional in the MR environment (eg, patient monitoring equipment) should be used. Because some electrically conductive implants, such as pacemakers or neurostimulators, have the potential to heat up during a scan, technologists should carefully follow all manufacturer recommendations and scanning criteria when scanning a patient with implants.[9] Perhaps most importantly, the technologist performing the scan should be properly educated in MR safety and should maintain visual and verbal contact with the patient throughout the scan. Many patients are sedated prior to their scans, especially pediatric patients and those suffering from claustrophobia. Because these patients cannot vocalize pain or burning sensations, extra care should be taken to ensure their scans do not have risks of thermal injury.[8]

## Acoustic Noise

Sometimes overlooked, the acoustic noise brought on by time-varying magnetic fields is another safety issue associated with MR imaging scans. A gradient system is used for spatial encoding of the MR signal and sometimes for generating echoes.[4] The noises the scanner makes during an MR pulse sequence is not caused by the main static magnetic field alone but by the alterations in the magnetic field, which induce currents in the gradient coils.[4] As a current passes through the coils during image acquisition, acoustic noise is created. This noise can sound like loud tapping, knocking, chirping, or squeaking.[12]

An MR scan can last from 10 minutes to more than 2 hours, and this noise has the potential to cause hearing loss when experienced for an extended length of time.[4] Changing or switching gradient output through the technologist's application of sequence parameters causes the acoustic noise levels to vary.[12] These parameters include slice thickness, field of view, repetition time, and echo time.[12] Other factors that can affect the level of gradient noise include MR-system hardware, scanner construction, the surrounding environment (eg, background noise in the scanner room), and the size of the patient.[12]

The FDA stated that MR systems should not be manufactured to create sounds louder than 140 dB, and they recommend that patients in the MR scanner should not be subjected to sound levels higher than 99 dB without hearing protection.[13] Research studies measuring the noise levels of MR sequences have shown the loudest sequences range from 114 dB to 115 dB on a

1.5 T scanner and 126 dB to 131 dB on a 3 T scanner.[12] For perspective, the sound level of a normal conversation is about 60 dB, sitting in the front row at a rock concert is approximately 110 dB to 120 dB, and the pain threshold is 130 dB.[13] How or where the patient is positioned inside the bore can affect noise levels by as much as 10 dB.[12] With higher noise levels, it is recommended that patients wear both earplugs and headphones.[12]

### *Effects of Acoustic Noise*

One research study found temporary hearing impairment in 43% of patients who had MR imaging scans without ear protection or with ill-fitted earplugs.[12] Acoustic noise from the MR scanner's gradients might be a special concern for certain subsets of patients, such as patients with psychiatric disorders, with confusion due to dementia or an underlying pathology, or that are sedated and fall asleep and wake up disoriented.[12] Neonates and pediatric patients in particular are sensitive to loud noises; however, research shows that fetal exposure to 1.5 T imaging during the second and third trimesters of pregnancy does not pose a risk of neonatal hearing impairment.[12] Patients with certain health conditions, such as a brain tumor, might be more sensitive to loud noises. In general, patients should be provided with hearing protection before scanning.[12]

Occupational exposure is another concern related to the loud noises caused by the MR system.[12] Employees who remain in the room during scanner operation, such as those who work in interventional MR or to help a patient get through an examination, should routinely use hearing protection.[12]

### *Noise Control Techniques*

The simplest, most affordable, and most common method of hearing protection is passive noise control in the form of disposable earplugs.[12] With proper fitting and use, earplugs can attenuate noise by 10 dB to 30 dB, which is adequate for the MR environment in most cases.[12] The FDA recommends that patients be required to use earplugs for all MR scans and that the earplugs be properly in place before the start of the first MR sequence.[6]

Disposable earplugs have some limitations. They can affect how well the patient can hear the scanning technologist. The technologist should remain in verbal communication with the patient in the scanner, but patients, especially those with current hearing loss, might have a difficult time hearing the technologist's questions and instructions when wearing earplugs.[12] Technologists can help by speaking loudly into the intercom and by reducing unnecessary background noise. Standard foam earplugs often are too large for the small ear canals of neonatal or pediatric patients. However, there are earplug manufacturers that make smaller-sized earplugs, and some can be cut in half if they are still too large. Infants should never be exposed to the loud noises of MR scanners without earplugs in, because they are more sensitive to loud noises than are older children and adults. Earplugs are helpful for MR-related acoustic noise, but they do not provide uniform noise attenuation across the hearing range.[12] For example, high-frequency noises can be well-attenuated, but lower frequencies might not be easily attenuated.[12] For some pulse sequences, peak MR-related acoustic noise often is found in the low-frequency range.[12]

Active noise control also has been shown to reduce MR gradient noises.[12] This method involves controlling noise from a specific source by introducing a sound wave with the same amplitude as the gradient noise but with an inverted phase (antiphase), thereby interfering with the noise source and cancelling it out.[12] This method was introduced experimentally in 1989 and has been improved since then.[12] Headphones with an active noise cancellation system provide a noise reduction of about 14 dB.[12] Some modern active noise cancellation systems use a continuous feedback loop with continuous sampling of the sounds so that the gradient noise is negated.[12] It is possible to attenuate the noises of the scanner while allowing for the transmission of music or vocal communication.[12]

Some MR system manufacturers have developed quiet pulse sequences, which drastically decrease MR acoustic noise while maintaining ideal image quality.[12] One MR system manufacturer offers a quiet suite software upgrade, which includes sequences that have almost no gradient noise.[14] This software addresses the sharp switching of the gradients to reduce noise as much as possible. One 3-D T1-weighted sequence,

often used for pediatric patients, has a 97% reduction in sound pressure.[14] This particular sequence when used with a transmit and receive head coil is inaudible over background noise.[14] Many other sequences, including turbo-spin echoes, spin echoes, and gradient echoes, offer the technologist an option to turn on acoustic noise reduction without affecting image quality.[14] This can increase scan time, but it also can be particularly helpful for some patients, such as sleeping infants or sedated patients.[14]

## Emergency Situations

Because the MR system's magnet is always on, medical emergencies are handled differently in the MR environment than in other imaging departments. When caring for sick patients, there is a chance they will go into cardiac or respiratory arrest, have a seizure, have an anaphylactic reaction after the injection of an MR contrast agent, or have other medical emergencies that require immediate attention. The chance of a medical emergency happening is higher in a large hospital where patients with more serious conditions are treated. Typically zone II is the recognized zone for patients to be taken for emergency treatment, but an emergent situation can occur anywhere and at any time, so MR technologists must be prepared.

If a patient inside zone IV needs urgent medical attention, 2 things should happen: the patient should be removed from zone IV immediately; and if the patient needs cardiopulmonary resuscitation (CPR), a basic life-support-trained technologist should begin performing CPR.[6] Every MR facility should have a predetermined location where patients that require emergency care are taken where emergency workers (eg, emergency medical services or the code blue team) can stabilize the patient without applying ferromagnetic objects to the static magnetic field, and so the emergency response team knows where to go and can quickly get to the patient.[6]

The ACR does not recommend quenching the magnet in all emergency situations. If a quench is needed, the ACR recommends removing patients and staff from zone IV before initiating it. Dissipating the magnetic field can take several minutes and theoretically causes a more hazardous environment.[6] It is more effective to immediately remove the patient from the scan room, while initiating CPR or other life-saving measures.[6] In many facilities, the protocol for a code blue or other medical emergency involves asking for help to move the patient out of the room while someone else calls the emergency response number for immediate medical help.[4] Modern MR scanners that have tables that undock from the magnet make moving these patients easier because they do not have to be moved over onto an MR stretcher before being removed from the scan room. Screening and access restrictions to zone III and zone IV should always be maintained, even in these urgent situations.[6]

## The Role of the MR Technologist

The American Registry of Radiologic Technologists offers 2 pathways to become a registered MR technologist: primary and postprimary. The primary pathway is for individuals pursuing their first credential, and the postprimary pathway is for individuals already registered in radiography, sonography, radiation therapy, or nuclear medicine who now want to be registered in MR imaging.[15] Each pathway has its own set of Registry requirements, but both require a technologist to have completed American Registry of Radiologic Technologists–approved structured education, met the clinical experience requirement, answered ethics questions, and passed the Registry exam.[15]

Safety is an important issue in MR imaging, and technologists can obtain additional certification by earning the Magnetic Resonance Safety Officer credential, available through the American Board of Magnetic Resonance Safety.[16] A Magnetic Resonance Safety Officer assists other technologists in following MR conditional guidelines when scanning patients with certain implants.[16] For example, they can assist with lowering the SAR to stay within scanning guidelines or determining for the department if it is safe to scan a certain implant.[16] These certification examinations take place in various locations around the United States, several times per year.[16] The American Board of Magnetic Resonance Safety also offers certifications for physicians (Magnetic Resonance Medical Director) and MR physicists (Magnetic Resonance Safety Expert).[16]

### *MR Screening Process*

One of the most important things an MR technologist learns during his or her educational program, particularly during the clinical experience, is how to safely and effectively screen patients and staff entering the MR environment. The screening process is crucial. The protection of patients and others from MR-related accidents depends on the technologist's thorough understanding of the risks associated with implants, medical devices, accessories, and other objects that could enter the MR environment.[17] MR technologists must pay constant attention to what enters the scan room at any given time. Proper department safety policies also are important in preventing accidents.[17]

The screening process begins during scheduling to prevent appointment errors for certain implants, such as a cardiac pacemaker, which might only be scanned on certain days of the week and only on certain strength scanners.[17] Ideally, MR examinations should be scheduled by someone familiar with the risks of the MR environment. Information gathered during order scheduling might include the following: whether the patient has a device that might be contraindicated or conditional, whether the patient is pregnant, or whether the patient requires sedation (for facilities that offer sedation).[17] Remembering that not all patients are MR candidates is important, and preliminary screening helps prevent unnecessary scheduling.[17]

When the patient arrives at the MR facility, a more detailed screening is completed in preparation for the examination. The patient should be given a written form to fill out to the best of his or her ability. This form serves as a legal document, which shows comprehensive MR imaging screening was done, including the date and time the screening took place. Having undergone a previous MR scan without incident does not guarantee subsequent MR scans will be safe for the patient because various factors, such as field strength, patient orientation, and area of interest, can influence the safety of the scan.[17] For this reason, obtaining a new written MR screening each time a patient prepares to have an MR scan is imperative.[17] For patients who cannot give an accurate history because of coma, memory loss, or confusion from illness, this written form should be completed by the patient's spouse, closest relative, or a physician who has extensive knowledge of the patient's medical and surgical history.[17] If the reviewing MR technologist finds the amount of information insufficient, the answers appear inaccurate, and surgical scars are not visible on the patient, radiographs of the skull, chest, abdomen, and pelvis might be ordered to rule out contraindicating implants, medical devices, or metallic foreign bodies.[17]

The written screening form might request the following information from the patient[17]:

- name, date of birth, and medical record number
- height and weight
- drug allergies
- reason for the MR imaging scan
- complete surgical history
- implants or mechanical devices present in or on the patient
- problems with previous MR imaging examinations (eg, contrast reaction)
- history of metal work (eg, grinding or welding)
- injuries to the eyes involving metal
- other foreign body injuries (eg, bullet or shrapnel)
- claustrophobia
- ability to lie flat and still for an extended period

For female patients, the screening form also might request:

- date of last menstrual period
- possibility of pregnancy

The ACR recommends that patients scheduled to receive intravenous gadolinium-based contrast agents should be asked about a history of renal disease, hypertension, or diabetes.[17,18] The ACR recommends that a glomerular filtration rate be calculated for patients answering yes to the previous questions.[18] This can be calculated using a blood creatinine value, the patient's age, and whether the patient is African American. Using a current glomerular filtration rate, the technologist can verify the patient's renal function prior to administration of contrast, which helps to reduce the risk of nephrogenic systemic fibrosis.[18] The ACR also recommends that MR scans should only be performed on pregnant patients to address important clinical questions that cannot wait until after delivery to be answered.[6] Some facilities require pregnant patients to discuss the risks with a radiologist and sign a consent

form before beginning the scan. Administering intravenous gadolinium-based contrast agents to pregnant women is not recommended.[6]

The written screening form might also state that the MR system magnet is always on and patients are required to remove metallic objects, drug-infusion devices, credit cards, or clothing with metal fasteners or metallic threads.[17] Many patients are not sure what materials their clothing is made of, so there might be a statement on the form asking all patients to change into a hospital-provided gown.[17] There might also be a statement regarding the requirement of hearing protection for anyone remaining in the magnet room during the scan, including patients and family members.[17]

Once this form is completed and signed, it must be reviewed by the technologist and then reviewed verbally with the patient.[17] A knowledgeable MR technologist should conduct a detailed screening. During the screening, the patient can ask for clarifications on surgeries or implants, provide documentation on implants or devices (if requested by the technologist), and ask questions about the scan.[17] Patients are unlikely to understand the risks associated with the magnetic field; therefore, a discussion with the patient on the risks might be necessary for an accurate account of their surgical history.[4] The patient should be informed about the scanning process regarding the length of the scan and what to expect regarding the loud noises and how much of their body will be inside the scanner.

Once screening is completed and the technologist decides it is safe to proceed with the examination, the patient should remove contraindicated objects and clothing. Inpatients, including their blankets and gown, should be checked thoroughly for ferromagnetic objects when moving from a ferromagnetic stretcher or wheelchair to a nonferromagnetic stretcher or wheelchair.[17] Family members accompanying the patient into the room also must fill out a screening form and place metallic objects in an assigned locker before entering zone IV.[17] As with any medical procedure, the decision to scan is made on a case-by-case basis with the help of a radiologist, and decisions should be made after considering risks vs benefits.[4] If the technologist has doubts about the safety of a scan, the patient should not be brought into the magnetic field.[4]

For patients with implanted metallic or mechanical devices, the MR technologist must verify that each implant is MR safe or conditional and review the scanning guidelines for conditional implants.[17] To do this, the technologist requests a card or document from the patient stating the implant's manufacturer, name, and model number, and the technologist compares it with information found through books, websites, and other resources to determine whether the implant or device is MR safe, MR conditional, or MR unsafe.[17] In some cases, the manufacturing company can be contacted for clarification. Some neurostimulators are approved only for scanning on a 1.5 T horizontal system under strict conditions.[18] Some cardiac pacemakers are MR conditional if scanned using specific guidelines (see **Figure 6**), but others are considered MR unsafe.[18] In MR facilities with multiple strength scanners (eg, 1.5 T and 3 T), patients should not be assigned to a scanner until the comprehensive MR screening process is complete. Most drug-infusion pumps are contraindicated for all types of MR scans and need to be removed before an examination.[18] There are thousands of types of implants and devices a patient could have and more are manufactured all the time. It is crucial that the MR technologist is current on the latest implants and diligently researches each implant before allowing a patient into zone IV.

If a patient has a history of injury from a metallic foreign body to the eyes, orbit radiographs should be ordered because the eye does not form scar tissue to prevent the metallic foreign body from shifting on entering the magnetic field.[17] The same precautions should be taken for patients with a history of bullet or shrapnel injuries. Patients must be cleared by a radiologist before the MR scan.[18]

### *Patient Monitoring*

In 1992, the Safety Committee of the Society for Magnetic Resonance Imaging published guidelines recommending that MR technologists monitor patients both visually (via a camera system or scanner room window) and verbally (via an MR system intercom).[19] These are the most basic methods for monitoring a patient in the MR environment and should be performed consistently with all MR patients. Maintaining

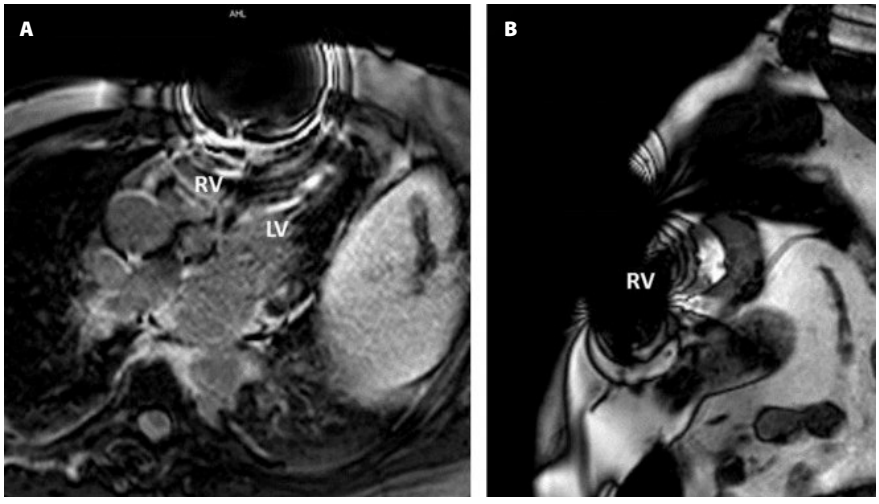


**Figure 6.** *Image of a magnetic susceptibility artifact in a cardiac patient with an MR-conditional pacemaker. A. Four-chamber view. B. Short-axis view. Image distortion hampers diagnostic image quality particularly regarding the right ventricle (RV) and anterior wall of the left ventricle (LV) is apparent. Reprinted under the Creative Commons Attribution Non-Commercial License 4.0. Nordbeck P, Ertl G, Ritter O. Magnetic resonance imaging safety in pacemaker and implantable cardioverter defibrillator patients: how far have we come?* Eur Heart J. *2015.36(24):1505-1511. doi:10.1093/eurheartj/ehv086. creativecommons.org/licenses/by-nc/4.0/*

verbal communication especially is important after the administration of gadolinium-based contrast agents, which are becoming increasingly common. Although adverse contrast events are rare, they do occur and can be serious or life threatening.[19]

Severe injuries and fatalities unrelated to contrast media use also have occurred during MR scans, and patient monitoring could help to avoid these situations.[19] An important part of the MR technologist's responsibilities is to identify patients requiring physiologic monitoring in the MR environment and to follow proper protocol to ensure the safety of these patients. Patients unable to alert the MR technologist of a problem during the scan should be monitored, especially patients with MR-conditional implants such as a pacemaker or stimulator.[19]

The Joint Commission guidelines indicate that patients sedated with anxiolysis and anesthesia should be physiologically monitored during the administration of and recovery from these medications; monitoring by nurses specializing in radiological procedures is ideal.[19] For inpatients, the floor nurse should accompany the patient being monitored and remain for the duration of the scan to observe vital signs.[9] The vital signs of the following types of patients should be monitored throughout the scan[19]:

- physically or mentally unstable patients
- patients not able to communicate
- neonatal patients
- sedated patients
- patients undergoing MR-guided interventional procedures
- patients with a history of gadolinium-based contrast reactions
- critically ill patients

If a patient requires emergency intervention, such as CPR, during a scan, they must first be removed from zone IV and then taken to a predetermined location in the department. There, the patient can receive initial help while waiting for the emergency response team.[6] This protocol minimizes the risk of further harm to the patient from the static magnetic field.[6]

## Conclusion

Although MR imaging is considered one of the safer imaging modalities because it lacks ionizing radiation, there are several important safety issues to be aware of. The MR department should use a 4-zone policy to establish safe access to the magnetic field, and MR technologists must thoroughly screen patients and personnel before escorting them into zone IV (the scan room). MR technologists must ensure that providers, including themselves, properly follow policy and do not bring objects with ferromagnetic components into zone III.[6] Ferromagnetic items in the scan room can result in serious injury or death to the patient from the

missile effect caused by the strong magnetic field.[4] RF energy can cause excessive heating and thermal burns, and technologists must follow proper procedures to prevent them. Acoustic noise during MR imaging can cause temporary hearing impairment. Patients and other individuals in the scan room should receive hearing protection.[4] Technologists also must help calm anxious patients because some patients feel claustrophobic in the scanner. There are serious risks specific to the MR environment, and technologists practicing in MR should be properly educated, and ideally, they should be registered with an appropriate national certification organization before beginning work. If a non-MR radiologic technologist or other health care provider is unsure about whether it is safe for them to enter a scan room, they should not hesitate to discuss their concerns with an MR technologist before entering.

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