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Implementation of a Comprehensive MR Safety Course for Medical Students

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Abstract

This article proposes the design of an educational MR safety module using an available comprehensive multiple-choice exam for instructing medical students about basic MR and patient related safety. The MR safety course material can be implemented as a traditional didactic or interactive lecture in combination with hands-on safety demonstrations. The goal of the course is to ensure that medical students receive a basic understanding of MR principles and safety considerations. This course should prepare medical students for consideration of patient screening and safety when ordering MR studies. A multiple-choice exam can be used to document the proficiency in MR safety of the medical students. The course can be used by various medical school programs and may help to ensure consistent quality of teaching materials and MR safety standards.

Keywords

Magnetic Resonance Imaging; MRI; safety; education; medical students; quality assurance

Introduction

Magnetic Resonance Imaging (MRI) is a cross-sectional imaging technique with superior soft-tissue contrast compared to other imaging modalities e.g. ultrasound, Positron Emission Tomography (PET), Computed Tomography (CT), and other imaging devices that use x-rays. MRI has lead to new insights in anatomical, physiological and functional imaging. The continued growth of MRI in the last decades has led to more than 25,000 MRI scanners that were sold world wide, millions of MRI exams performed, and thousands of healthcare professionals that were educated in MRI safety to protect patients and other healthcare workers from the hazards associated with MRI (1).

The purpose of this article is to describe a comprehensive approach to educate medical students who will be the physicians of the future in the safety aspects of MRI. There are

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multiple commercial MRI safety courses available that are offered online (2-6). The expected audiences of these courses are participants in the field of medical imaging including MR technologists, radiologists and medical physicists. The content of most of these courses follow the ACR Guidance Document for Safe MR practices but none of these courses focus specifically on medical students (7). An MRI Safety course for medical students should be different from other MRI safety courses. Medical students do not necessarily have the same technical background as specialists in the field of medical imaging. Nevertheless, medical students will become the MRI-referring physicians of the future and would benefit from having a comprehensive MRI safety training included in their medical school curriculum. The course proposed here will focus on medical students because as physicians they will refer patients for MRI exams and will often have to evaluate MRI safety and compatibility of new medical devices and implants. They will also often be the first health care professionals who will talk to their patients about the MRI exam, potential risks, and MRI safety (8). Referring physicians who understand the principles of MRI safety can help contribute to MRI safety screening since they know the patient's medical history better than the radiologists or technologists who will only meet a patient very briefly during screening and preparation for an exam. A pre-screening of patients before their MRI exam by a referring physician offers an additional safety check which can streamline procedures directly before the exam in a radiological imaging facility and can improve MR imaging results (9). This article proposes a comprehensive MRI safety course for medical students that includes the basics of bio-effects and risks of the magnetic fields that interact with patients and health care professionals in an MRI suite (10).

Proposed MRI Safety Modules for Medical Students

The following four and half hour, 7 module course about basic MR and patient-related safety is proposed for inclusion in medical school curricula (10, 11). The duration for each component of the course is suggested, though this could be altered to suit the institution's or instructor's preference and audience's skill level.

1. "Importance of MR Safety for Non-radiologist Physicians" (30 minutes)
2. "MR Principles and Magnetic Fields" (30 minutes)
 - i. Magnetic Fields in MRI
 1. Static magnetic fields (B_0),
 2. Radiofrequency field (B_1)
 3. Gradient fields (G_x , G_y , G_z)
 - i. MRI Zones
 - ii. "Effects of Magnetic Fields in an MR Suite" (30 minutes)
 - iii. Attractive/Projectile forces on ferromagnetic objects
 - i. Thermal effects
 - ii. Peripheral nerve stimulation

- iii. Acoustic Noise
- iv. “MR Screening Procedures” (1 hours)
- v. Implanted devices
- vi. Definition of MR Safe
- vii. Definition of MR Conditional
- viii. Definition of MR Unsafe
 - i. Foreign Metal Objects
 - ii. Pregnancy
 - iii. MR contrast agent reactions and renal insufficiency
 - iv. Claustrophobia in MR Imaging
 - i. Evaluating the need for sedation/anesthesia
 - ii. “MRI Operating Modes and the Implications” (30 minutes)
 - iii. “Emergency Procedures in the MR Suite” (30 minutes)
 - iv. “Hands-on Demonstrations to Illustrate MRI Safety Concepts” (1 hour)

Module 1: “Importance of MR Safety for Non-radiologist Physicians”

Radiologists are well-trained in the area of MRI Safety during their residency programs and subsequent professional appointments. However, radiologists often have little or no contact with patients before their MRI exam. Though they are the more knowledgeable about MRI appropriateness criteria, they often require assistance from referring physicians to determine the risks vs. benefits of MRI imaging procedures of high-risk patients (12). This is particularly relevant in circumstances where new implants have not yet been tested for MRI compatibility (13, 14). Alternatively, situations do occur where, despite the fact that an implant is known not to be MRI compatible, there are circumstances where the MRI risk is clinically acceptable. For example, many cochlear implants are fixed with ferromagnetic materials and are prone to displacement even when scanning other parts of the body with MRI (15). The increasing frequency of cochlear implants requires a team of physicians to evaluate the patient's risk of implant displacement (and subsequent need for surgical revision) with the medical necessity of the MRI imaging for whatever serious, unrelated condition the patient may have. A critical decision must be made depending on the area being scanned, particulars about the implant, and the patient's likelihood to tolerate revision (meaning, how stable they are for surgery if the implant is displaced while in the MRI). A team of providers needs to decide whether or not to go forward with the MRI scan by balancing medical necessity vs. risk. These teams are composed of physicians from several different disciplines involved in the patient's care. A radiologist often cannot individually

determine the medical appropriateness of MRI imaging in such a high-risk patient without input from the ordering physician, and in this particular case, also the audiology and neurosurgical team. Thus, a wide range of physicians may require a basic understanding of MRI safety including but not limited to anesthesiologists, cardiologists, audiologists, orthopedic surgeons, neurosurgeons, and general practitioners. A comprehensive MRI safety course for medical students should include a module that explains the need for non-radiologist physicians to be competent in basic MRI safety.

Module 2: “MR Principles and Magnetic Fields”

The content of this course module should cover the following material.

Magnetic Fields in MRI

In an MRI unit there are three major magnetic fields that can pose a hazard (16, 17):

1. static magnetic field B_0 which is in clinical scanners in the range of 0.2T to 3T (18, 19)
2. radiofrequency (RF) field B_1 which is in the order of μ T (20)
3. gradient fields which are in the order of 100 mT/m with slew rates up to 200 T/m/s (21)

These three magnetic fields have different potential interactions with the patient.

1. The static magnetic field B_0 of superconducting magnets is more 10^4 times stronger than the magnetic field of the earth and it can attract ferromagnetic objects and accelerate them in the direction of the opening of the bore of an MRI scanner. It can also interfere with implanted devices such as pumps and pace makers (1, 14, 17-20, 22-40).
2. The radiofrequency (RF) field B_1 is produced by the integrated system antenna or by local transmit receive RF-coils. Transmitted RF leads to energy deposition that can cause heating in tissue, especially when implants are present (12, 16, 19, 23, 39, 41-60).
3. The gradient field is used for the spatial encoding of the MRI signal and can cause peripheral nerve stimulation, implant heating and is responsible for the noise in MRI suites which can reach levels of 100 dB or more and potentially cause hearing damages (19-21, 28, 30, 33, 39, 47, 61-67).

MRI Zones

The ACR guidance document on MR safe practices from 2013 suggest different zones for an MRI facility (68, 69). It is important to discuss the purpose of the different zones with medical students and make them specifically familiar with the MRI zones of the MRI units in the hospital that they are training in (13, 70). MRI facilities and hospitals restrict access to the MR suite by establishing four zones around the MRI scanner. The boundary of each zone in this four-zone safety system is defined by its purpose and distance from the MRI

scanner (20). Since the magnetic field extends in three dimensions, some zones may extend into other areas or floors of the facility (71).

Zone I consists of all areas freely accessible to the general public. Zone I includes the entrance to the MR facility and the magnet poses no hazards in these areas.

Zone II is a buffer between Zone One and the more restrictive Zone III. Patients are under the general supervision of MR personnel in Zone II. This zone often includes the reception area, dressing room and MRI screening room.

Zone III is an access-restricted zone, which is achieved by physical barriers such as doors with coded access. Only approved MR personnel and patients that have undergone MRI screening are allowed inside Zone III. The MR control room is located in Zone III.

Zone IV is the magnet room. Access into the magnet room should only be possible by passing through Zone III.

Access between each zone is controlled via locked doors and key cards, including the Zone I-II, Zone II-III, and Zone III-IV interfaces. It should not be possible to skip MRI safety zones by an alternative entrance (even for staff members). Zone III and Zone IV are often referred to as the MR Suite. The MRI suite should be designed in a way that the walls of Zone IV - the magnet room - includes the five Gauss line (or 0.5 mT line) of the fringe field of the magnet. The five Gauss line defines a border to an area in which the magnetic field could affect implanted devices such as pacemakers (14). If the 5 Gauss line extends outside the magnet room, which can happen with ultra high field magnets in research facilities, then additional physical boundaries are established to limit access to avoid interferences of the magnetic field with implanted devices (72). Hospital and MR facility personnel that work near the MRI scanner must be made aware with warning signs about the powerful magnetic field and its associated hazards. These warning signs must be clear to lay people (including patients/volunteers and non-medical staff) that they are in a hazardous area and that they should not try to gain access to restricted MRI zones. An MR safety program should be established for each individual facility to train employees about the hazards associated with the magnetic field (73).

Module 3: “Effects of Magnetic Fields in an MR Suite”

This course module should focus the following topics.

Attractive/projectile forces on ferromagnetic objects

The static magnetic field B_0 of an MRI machine will attract ferromagnetic objects and accelerate them toward the bore of the MRI scanner. Common ferromagnetic objects such as coins, hairpins, or scissors can be torqued or displaced by the large static magnetic field (12, 16). Larger ferromagnetic objects, such as steel oxygen tanks can become dangerous projectiles (32). There is often a misconception that larger objects will resist attraction to the field and so this education course should emphasize the relationship between object size, material components, and projectile risk. Even well established hospitals continue to have problems with medical equipment (such as anesthesia or ventilator systems) becoming

lodged in the bore of the magnet due to insufficient MRI safety training of ancillary medical personnel (31, 32). The static magnetic field can also influence the fluid in the inner ear which is responsible for maintaining balance. Medical students should be instructed that patients undergoing MRI scans may experience dizziness when moving into a high magnetic field gradient (such as in the fringe field at the entrance to the bore).

Thermal effects

Another important aspect that medical student should be aware of are bio-effects of radiofrequency fields (50). Radiofrequency fields can cause heat in the human body (51, 56). The amount of RF-energy that is absorbed by the human body and transformed into heat is described by the specific absorption rate (SAR) (74). SAR is the mass normalized rate at which RF power is coupled to biological tissue with units of watts per kilogram (W/kg) (41). Future physicians should be aware that infants, children and patients with thermo-regulatory disorders might experience increased body core temperatures due to RF-induced heating during MRI exams (42, 59, 74, 75), and that obese patients may be exposed to larger RF energy deposition. It is also important to discuss the effect of examination duration with respect to the risk of thermal injury and to advise against excessively long examination times. In order to better counsel their patients before MRI exams, the medical students should be instructed that each patient can expect to feel a warming sensation during scanning. In some cases, prolonged exposure can lead to perspiration which can become a further hazard for contact burns. If a patient feels particularly localized heating then they should alert the operator by pressing the patient alarm and the technologist should act accordingly. It is important to explain this process to conscious patients prior to the MRI and to closely monitor anesthetized or sedated patients.

Medical students should be informed that additional important steps in preparing patients for MR scans are necessary to avoid burns and/or thermoregulation problems even for patients without implants (13, 14, 76):

1. Removal of unnecessary metallic objects contacting the patient's skin (e.g., drug delivery patches with metallic components, jewelry),
2. Use of insulation material of a minimum recommended thickness of 1 cm to prevent skin-to-skin contact points and the formation of closed-loops from touching body parts.
3. Use of only electrically conductive devices, equipment, accessories (e.g., ECG leads, electrodes), and materials that have been thoroughly tested and determined to be MRI safe.
4. Avoidance of excessively long duration scans
5. Avoidance of practices that limit the ability of the patient to cool down (for example, wrapping the patient tightly in a blanket).
6. Use of extra diligence when scanning obese patients since they may have comparatively high local heat deposition and awareness that an obese patient is less likely to tolerate exams, which deposit very high RF energy.

7. Registration of the correct patient details into the system (particularly weight/mass) since some MRI systems adjust the transmitted energy based on these demographics.

Further details can be found in the Guidelines to Prevent Excessive Heating and Burns Associated with Magnetic Resonance Procedures (77).

Peripheral nerve stimulation

During MRI exams the time-varying gradient magnetic fields may stimulate nerves or muscles in patients by inducing electrical fields (62). Gradient magnetic field interactions with biological tissues depend on the frequency of the gradient field, the maximum and average flux densities, the presence of harmonic frequencies, the waveform characteristics of the signal, the polarity of the signal, the current distribution in the body, the electrical properties, and the sensitivity of the cell membrane (21, 28, 30, 61, 62, 65, 67). Physicians should be aware of this bioeffect so they can explain this to their patients before referring them for an MRI exam.

Acoustic noise

The quickly switching gradients are also responsible for the high acoustic noise during an MRI exam (21, 62). Hearing protection such as head phones and earplugs are essential to avoid hearing damage in patients and any person in the MRI suite during scanning (30). This should be clearly conveyed in the educational module for medical students and also included in the hands-on presentation proposed below.

Module 4: “MR Screening Procedures”

This course module should cover the following important material about MR screening procedures.

Medical students should be made aware of the fact that MRI screening is essential before any MRI exam since the relative risk of injury is dependent upon the magnetic properties of the foreign body, the geometry and dimensions of the object, and the strength of the static magnetic field B_0 of the MRI system (12, 16, 19, 23, 32, 78, 79). It is therefore essential to require that patients and accompanying persons remove all objects from their pockets and hair before they enter the MRI suite (31-33). Patients should also be asked to wear MRI gowns before the scan to avoid that their clothing items have metallic fasteners, loose metallic components, or metallic threads (80).

Implanted Devices

Medical students should know where they can look up the MRI safety and compatibility of medical implants and devices as future referring physicians (13, 14, 76). Several books and a searchable on-line catalog list MRI-safe devices and implants with their field strengths and gradient limitations (http://www.mrisafety.com/TheList_search.asp) (12, 16, 33-35, 51-58).

In patients with implants it is important to know that the potential for injury is related to the proximity of the implant to vital vascular, neural or soft tissue structures (33). Orthopedic

implants, materials, and devices that were implanted in the last three decades in the US and Europe are made from non-ferromagnetic materials and are usually labeled MR safe or MR conditional (according to specific instructions for scanning patients with the implants) (51). Other older implants may be contraindicated and deemed MRI Unsafe. The interaction and torque of ferromagnetic implants should be explained, including how the forces on these objects change as they move through the fringe field of the main magnetic field (B₀). Magnetic field interactions of these implanted devices can cause severe artifacts and heating (14). However it is important to instruct the students that even non-ferromagnetic implants are subject to heating due to eddy currents that propagate in metals exposed to oscillating magnetic fields (53, 54). MRI-related heating may specifically be a problem for some orthopedic implants such as external fixation systems (12-14, 16, 54, 58, 76, 78, 81). There are additionally some devices that will malfunction once exposed to such a powerful magnetic field because the forces cause permanent and irreparable damage. Finally, there are new implants that have not been tested or labeled yet for MRI compatibility (15). This can pose a unique challenge requiring close collaboration between the radiology team, the ordering physician, and the physician who placed the implant. Therefore, any MRI safety module for medical students should contain a thorough description of implant safety.

Foreign Metal Objects

Unknown metallic objects inside the body need to be included in the MR Screening Procedures. A variety of professions and life experiences can leave metal particles, slivers, or objects in the body. Some examples include a history of professional or amateur operation of metal cutting machines, which may unknowingly deposit metal slivers inside the body (of particular concern is the sensitive tissue around the eyes). Veterans and active military members may have shrapnel or bullet fragments in their tissue (either known or unknown.). The MRI safety screening should be carefully designed to assess the likelihood of foreign metal bodies. Questions such as “Do you have any foreign metal bodies?” are seldom effective. An alternative, effective line of questioning is “Have you ever served in the military, and if so, were you ever wounded?” Careful attention should be paid to interviewing subjects with diminished memory capacity in order to ascertain the likelihood of the presence of a foreign metal object.

Pregnancy

Medical students should also be aware of the following ACR-SPR practice guideline (82): “Present data have not conclusively documented any deleterious effects of MR imaging at 1.5 T on the developing fetus (83). Therefore, no special consideration is recommended by the ACR and the SPR for any trimester in pregnancy (82). Pregnant patients can be accepted to undergo MR scans at any stage of pregnancy if, in the determination of a level 2 MR personnel-designated attending radiologist, the risk-benefit ratio to the patient warrants that the study be performed (73, 82). The radiologist should confer with the referring physician and document the following in the radiology report or the patients' medical record (82):

1. The information requested from the MRI study cannot be acquired by ultrasonography.

2. The data are needed to potentially affect the care of the patient or fetus during the pregnancy.
3. The referring physician does not feel it is prudent to wait until the patient is no longer pregnant to obtain these data.“

MRI contrast agents should not be routinely administered to pregnant patients according to the ACR Manual on Contrast Media (68). Gadolinium is a pregnancy class C drug, meaning that the safety in humans has not been proven (7, 84).

MR Contrast Agents

Medical students should be informed about adverse effects of MRI contrast agents. MRI contrast agents that are approved by the FDA are Gadolinium chelates with differences in stability, viscosity, and osmolality (85).

Gadolinium based contrast agents are well tolerated and acute adverse reactions are encountered infrequently (86). Acute adverse events after injection of 0.1 or 0.2 mmol/kg of gadolinium contrast media are reported to occur in 0.07% to 2.4% (85, 87) of administrations. Side effects of gadolinium chelates are a cold or warm feeling upon injection; nausea, dizziness or headache; and pain, numbness or itching at the injection site (85-95).

Severe allergic reactions including rash hives, urticaria and bronchospasm range from 0.004% to 0.7% (89). Life-threatening reactions to gadolinium based contrast agents are very rare (0.001% to 0.01%) (89-91, 95). It is reported that, “In an accumulated series of 687,000 doses there were only 5 severe reactions” and that “fatal reactions to gadolinium chelate agents occur but are extremely rare” (85, 86, 89).

Gadolinium chelates administered to patients with acute renal failure or severe chronic kidney disease can result in a syndrome of nephrogenic systemic fibrosis (NSF) (88). There are no reports of NSF in patients with normal kidney function therefore, the U.S. Food and Drug Administration (FDA) has asked manufacturers to include a new boxed warning on the product labeling of all gadolinium-based contrast agents that patients with severe kidney insufficiency who receive gadolinium-based agents are at risk for developing (86, 89).

Claustrophobia in MR Imaging

Medical students should be aware that if their patients are not well advised about the MRI scanning procedure they may become claustrophobic and refuse to complete the exam (96, 97). Students should be informed about alternatives to traditional MRI imaging that reduce claustrophobia including larger bore sizes and “Open MRI” . Referring/Ordering physicians can significantly reduce claustrophobia events by discussing the details of the MRI procedure with the patients before their exam (98). Radiologists can also act to shorten protocols appreciably.

Evaluating the need for sedation/anesthesia

Due to the long procedure times and sensitivity to motion, non-compliant patients such as children, claustrophobic adults may require sedation or anesthesia during MRI imaging (99).

Pain management may also be necessary for patients to remain motionless during the MRI. MRI safety education for medical students should include specific risks and benefits of using sedation, anesthesia, and pain management in these patient populations (100).

Module 5: “MRI Operating Modes and the Implications”

Medical students should be aware that there are different operating modes for MRI systems. The International Electrotechnical Commission (IEC) defines the following three operating modes for MR systems (IEC 60601-2-33:2010):

1. Normal operating mode:

The normal operating mode of the MRI system is the one in which none of the outputs have a value that may cause physiological stress to patients.

The default specific absorption rate (SAR) limit is 2.0 W/kg in normal operating mode for whole body scans but might vary in different countries depending on the scanned anatomy. The body core temperature increase is limited to 0.5°C and the gradients are limited to 80% of the peripheral nerve stimulation threshold.

2. First level (Level I) controlled operating mode

The First Level (Level I) mode of operation of the MRI system is the one in which one or more outputs reach a value that may cause physiological stress to patients, which needs to be controlled by medical supervision.

The default SAR limit is 4.0 W/kg in first level controlled operating mode for whole body scans but might vary in different countries depending on the scanned anatomy. The body core temperature increase is limited to 1 °C and the gradients are limited to 100% of the peripheral nerve stimulation threshold.

3. Second level (Level II) controlled operating mode:

The Second Level (Level II) mode of operation of the MRI system is the one in which one or more outputs reach a value that may produce significant risk for patients, for which explicit approval by an institutional review board is required.

In most countries standard MRI systems are limited to a maximum SAR of 4 W/kg, so most scanning in Level II is not possible.

Medical Students should be aware of the safety risks and implications of the different operating modes of an MRI system and that patients need to be informed before the system is used in any other mode than the normal operating mode.

Module 6: “Emergency Procedures in the MR Suite”

Increasingly, non-radiologist physicians participate in MRI scanning often entering the MRI room to evaluate the patient and administer medications or interventions. Therefore, medical students need to be aware of emergency procedures in an MRI suite (72). It is often necessary to remove the patient from the MRI magnet room to resuscitate or treat the patient in emergency cases (78). It is also critical for all physicians to be trained about which objects

can be brought into the MRI zones in order to prevent fatal injuries and medical equipment failure.

Module 7: Hands-on Demonstrations to Illustrate MRI Safety Concepts

A comprehensive MRI safety module for medical students should include, in addition to the presentation of the technical and medical background of MRI safety, hands-on demonstrations of (10)

1. screening of patients with a questionnaire for ferromagnetic objects, implants, devices, body piercing, allergies to MRI contrast agents, kidney disease, pregnancy and breast feeding,
2. screening of patients that have a history of being injured by a metallic foreign body such as bullets, shrapnel, or other type of metallic fragments,
3. missile effects of ferromagnetic objects, (e.g. small ferromagnetic objects of different shapes and sizes securely fastened to a strong rope can be used to demonstrate the attractive force and torque on the object in response to the magnetic field and the varying strength of the fringe field).
4. noise of the gradient system during an MRI scan and the use of earplugs and head phones to avoid potential hearing damage,
5. videos from a quenching magnet, offered for example from the Institute for Magnetic Resonance Safety, Education, and Research <http://www.imrser.org/genpg.asp?pgname=VideoList>
6. situations in which patient positioning can lead to RF burns when limbs or other body parts are in direct contact with transmit RF coils of the MR systems or how skin-to-skin contact points can be responsible for these injuries. This demonstration can be supplemented by images of RF burns that have occurred in patients.

Comprehensive Multiple-Choice Exam

A standardized multiple-choice exam, either written or accessible through the Internet should be administered at the end of the course to evaluate the medical students proficiency in MRI safety material. The multiple-choice questions should include content from all modules in order to assess the medical students competency in each area of MRI safety. There are several pre-existing on-line proficiency exams from non-profit and full-profit organizations that have been evaluated by content experts before inclusion in the exam. This offers an excellent opportunity to objectively evaluate the effectiveness of an MRI safety education program.

Conclusion

The proposed MR safety course contains six modules that cover all critical areas of MRI safety for the general physician. These modules can be implemented as traditional didactic lectures, interactive sessions, or self-administered online (8). The goal of the course is to ensure that medical students receive a basic understanding of MR principles and safety

considerations. It prepares the medical students for optimal ordering of MR studies while emphasizing patient screening and safety. The course will help to ensure consistent quality of teaching materials and MR safety standards (10).

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References

1. Chakeres DW, de Vocht F. Static magnetic field effects on human subjects related to magnetic resonance imaging systems. *Progress in biophysics and molecular biology*. 2005; 87(2-3):255–65. [PubMed: 15556664]
2. MRI Safety Course. Available at: <http://mrisafetycourse.com>. Last accessed: December 11, 2014. [December 11, 2014]
3. AltusMedical Group, LLC MRI Safety Course. Available at: <http://altuscampus.com/mri-safety/>. Last accessed: December 11, 2014. [December 11, 2014]
4. Bracco Diagnostics Inc. e-learning center. Module: Update on MRI Safety. Available at http://bracco.theonlinelearningcenter.com/catalog/Product_cart.aspx?mid=6935. Last accessed: December 11, 2014. [December 11, 2014]
5. Falck Alford Productions MRI Safet Video. Available at <http://www.mrisafetyvideo.net>. Last accessed: December 11, 2014. [December 11, 2014]
6. ESMRMB School of MRI. Available at http://www.esmrm.org/index.php?id=en/school_of_mri.htm. Last accessed: December 11, 2014. [December 11, 2014]
7. Kanal E, Barkovich AJ, Bell C, Borgstede JP, Bradley WG Jr, et al. Expert Panel on MRS. ACR guidance document on MR safe practices: 2013. *Journal of magnetic resonance imaging : JMRI*. 2013; 37(3):501–30. [PubMed: 23345200]
8. Hipp, E.; Sammet, S.; Straus, C., editors. Proceedings of the 19th Annual Meeting of ISMRM. Melbourne, Australia: 2012. MR Safety Standards for Medical Students Nationwide.
9. Karpowicz J, Gryz K. Health risk assessment of occupational exposure to a magnetic field from magnetic resonance imaging devices. *International journal of occupational safety and ergonomics : JOSE*. 2006; 12(2):155–67. [PubMed: 16790173]
10. Sammet, S., editor. Proceedings of the 20th Annual Meeting of ISMRM. Salt Lake City: 2013. Implementation of a Comprehensive MR Safety Course for Medical Students.
11. Sammet, S., editor. Proceedings of the 22th Annual Meeting of ISMRM. Toronto, BC, Canada: 2015. Globally Applicable MR Safety Program for Medical Students.
12. Shellock, FG. Magnetic resonance procedures : health effects and safety. Boca Raton: CRC Press; 2001. p. 453
13. ASTM F2052-00 Standard Test Method for Measurement of Magnetically Induced Displacement Force on Passive Implants in the Magnetic Resonance Environment. Dec 11.2014
14. Sammet CL, Yang X, Wassenaar PA, Bourekas EC, Yuh BA, Shellock F, et al. RF-related heating assessment of extracranial neurosurgical implants at 7T. *Magnetic resonance imaging*. 2013; 31(6):1029–34. [PubMed: 23643158]
15. Hassepass F, Stabenau V, Arndt S, Beck R, Bulla S, Grauvogel T, et al. Magnet dislocation: an increasing and serious complication following MRI in patients with cochlear implants. *RoFo : Fortschritte auf dem Gebiete der Rontgenstrahlen und der Nuklearmedizin*. 2014; 186(7):680–5. [PubMed: 24497090]
16. Shellock, FG.; Kanal, E. Magnetic resonance : bioeffects, safety, and patient management. 2nd. Philadelphia: Lippincott-Raven; 1996. p. xi-342.

17. Hansson Mild K, Hand J, Hietanen M, Gowland P, Karpowicz J, Keevil S, et al. Exposure classification of MRI workers in epidemiological studies. *Bioelectromagnetics*. 2013; 34(1):81–4. [PubMed: 22532229]
18. Ghodbane S, Lahbib A, Sakly M, Abdelmelek H. Bioeffects of static magnetic fields: oxidative stress, genotoxic effects, and cancer studies. *BioMed research international*. 2013; 2013:602987. [PubMed: 24027759]
19. Hartwig V, Giovannetti G, Vanello N, Lombardi M, Landini L, Simi S. Biological effects and safety in magnetic resonance imaging: a review. *International journal of environmental research and public health*. 2009; 6(6):1778–98. [PubMed: 19578460]
20. Fuentes MA, Trakic A, Wilson SJ, Crozier S. Analysis and measurements of magnetic field exposures for healthcare workers in selected MR environments. *IEEE transactions on bio-medical engineering*. 2008; 55(4):1355–64. [PubMed: 18390326]
21. Budinger TF, Fischer H, Hentschel D, Reinfelder HE, Schmitt F. Physiological effects of fast oscillating magnetic field gradients. *Journal of computer assisted tomography*. 1991; 15(6):909–14. [PubMed: 1939767]
22. Heinrich A, Szostek A, Nees F, Meyer P, Semmler W, Flor H. Effects of static magnetic fields on cognition, vital signs, and sensory perception: a meta-analysis. *Journal of magnetic resonance imaging : JMRI*. 2011; 34(4):758–63. [PubMed: 21751291]
23. International Electrotechnical Commission (IEC), Medical Electrical Equipment, Particular requirements for the safety of magnetic resonance equipment for medical diagnosis, International Standard IEC 60601-2-33. 2002
24. Atkinson IC, Renteria L, Burd H, Pliskin NH, Thulborn KR. Safety of human MRI at static fields above the FDA 8 T guideline: sodium imaging at 9.4 T does not affect vital signs or cognitive ability. *Journal of magnetic resonance imaging : JMRI*. 2007; 26(5):1222–7. [PubMed: 17969172]
25. Brockway JP, Bream PR Jr. Does memory loss occur after MR imaging? *Journal of magnetic resonance imaging : JMRI*. 1992; 2(6):721–8. [PubMed: 1446117]
26. Cavin ID, Glover PM, Bowtell RW, Gowland PA. Thresholds for perceiving metallic taste at high magnetic field. *Journal of magnetic resonance imaging : JMRI*. 2007; 26(5):1357–61. [PubMed: 17969179]
27. de Vocht F, Stevens T, van Wendel-de-Joode B, Engels H, Kromhout H. Acute neurobehavioral effects of exposure to static magnetic fields: analyses of exposure-response relations. *Journal of magnetic resonance imaging : JMRI*. 2006; 23(3):291–7. [PubMed: 16463303]
28. Glover PM. Interaction of MRI field gradients with the human body. *Physics in medicine and biology*. 2009; 54(21):R99–R115. [PubMed: 19826206]
29. Kangarlu A, Burgess RE, Zhu H, Nakayama T, Hamlin RL, Abduljalil AM, et al. Cognitive, cardiac, and physiological safety studies in ultra high field magnetic resonance imaging. *Magnetic resonance imaging*. 1999; 17(10):1407–16. [PubMed: 10609989]
30. Kannala S, Toivo T, Alanko T, Jokela K. Occupational exposure measurements of static and pulsed gradient magnetic fields in the vicinity of MRI scanners. *Physics in medicine and biology*. 2009; 54(7):2243–57. [PubMed: 19293469]
31. Schenck JF. MR safety at high magnetic fields. *Magnetic resonance imaging clinics of North America*. 1998; 6(4):715–30. [PubMed: 9799852]
32. Schenck JF. Safety of strong, static magnetic fields. *Journal of magnetic resonance imaging : JMRI*. 2000; 12(1):2–19. [PubMed: 10931560]
33. Shellock FG, Crues JV. MR procedures: biologic effects, safety, and patient care. *Radiology*. 2004; 232(3):635–52. [PubMed: 15284433]
34. Shellock FG, Schaefer DJ, Crues JV. Exposure to a 1.5-T static magnetic field does not alter body and skin temperatures in man. *Magnetic resonance in medicine : official journal of the Society of Magnetic Resonance in Medicine / Society of Magnetic Resonance in Medicine*. 1989; 11(3):371–5.
35. Shellock FG, Schaefer DJ, Gordon CJ. Effect of a 1.5 T static magnetic field on body temperature of man. *Magnetic resonance in medicine : official journal of the Society of Magnetic Resonance in Medicine / Society of Magnetic Resonance in Medicine*. 1986; 3(4):644–7.

36. Silva AK, Silva EL, Egito ES, Carrico AS. Safety concerns related to magnetic field exposure. Radiation and environmental biophysics. 2006; 45(4):245–52. [PubMed: 17021785]
37. Valiron O, Peris L, Rikken G, Schweitzer A, Saoudi Y, Remy C, et al. Cellular disorders induced by high magnetic fields. Journal of magnetic resonance imaging : JMRI. 2005; 22(3):334–40. [PubMed: 16106367]
38. van Nierop LE, Slottje P, van Zandvoort MJ, de Vocht F, Kromhout H. Effects of magnetic stray fields from a 7 tesla MRI scanner on neurocognition: a double-blind randomised crossover study. Occupational and environmental medicine. 2012; 69(10):759–66. [PubMed: 22930737]
39. Weintraub MI, Khoury A, Cole SP. Biologic effects of 3 Tesla (T) MR imaging comparing traditional 1.5 T and 0.6 T in 1023 consecutive outpatients. Journal of neuroimaging : official journal of the American Society of Neuroimaging. 2007; 17(3):241–5. [PubMed: 17608910]
40. Yuh WT, Fisher DJ, Shields RK, Ehrhardt JC, Shellock FG. Phantom limb pain induced in amputee by strong magnetic fields. Journal of magnetic resonance imaging : JMRI. 1992; 2(2):221–3. [PubMed: 1562774]
41. Alon L, Deniz CM, Brown R, Sodickson DK, Zhu Y. Method for in situ characterization of radiofrequency heating in parallel transmit MRI. Magnetic resonance in medicine : official journal of the Society of Magnetic Resonance in Medicine / Society of Magnetic Resonance in Medicine. 2013; 69(5):1457–65.
42. Atalar E. Radiofrequency safety for interventional MRI procedures. Academic radiology. 2005; 12(9):1149–57. [PubMed: 16112515]
43. Budinger TF. Nuclear magnetic resonance (NMR) in vivo studies: known thresholds for health effects. Journal of computer assisted tomography. 1981; 5(6):800–11. [PubMed: 7033311]
44. de Greef M, Ipek O, Raaijmakers AJ, Crezee J, van den Berg CA. Specific absorption rate intersubject variability in 7T parallel transmit MRI of the head. Magnetic resonance in medicine : official journal of the Society of Magnetic Resonance in Medicine / Society of Magnetic Resonance in Medicine. 2013; 69(5):1476–85.
45. Gowland PA, De Wilde J. Temperature increase in the fetus due to radio frequency exposure during magnetic resonance scanning. Physics in medicine and biology. 2008; 53(21):L15–8. [PubMed: 18843171]
46. Hand JW, Li Y, Thomas EL, Rutherford MA, Hajnal JV. Prediction of specific absorption rate in mother and fetus associated with MRI examinations during pregnancy. Magnetic resonance in medicine : official journal of the Society of Magnetic Resonance in Medicine / Society of Magnetic Resonance in Medicine. 2006; 55(4):883–93.
47. International Commission on Non-Ionizing Radiation P. Medical magnetic resonance (MR) procedures: protection of patients. Health physics. 2004; 87(2):197–216. [PubMed: 15257220]
48. Israel M, Zaryabova V, Ivanova M. Electromagnetic field occupational exposure: non-thermal vs. thermal effects. Electromagnetic biology and medicine. 2013; 32(2):145–54. [PubMed: 23675617]
49. Kangarlu A, Shellock FG, Chakeres DW. 8.0-Tesla human MR system: temperature changes associated with radiofrequency-induced heating of a head phantom. Journal of magnetic resonance imaging : JMRI. 2003; 17(2):220–6. [PubMed: 12541230]
50. Schaefer DJ. Safety aspects of radiofrequency power deposition in magnetic resonance. Magnetic resonance imaging clinics of North America. 1998; 6(4):775–89. [PubMed: 9799855]
51. Shellock FG. Radiofrequency energy-induced heating during MR procedures: a review. Journal of magnetic resonance imaging : JMRI. 2000; 12(1):30–6. [PubMed: 10931562]
52. Shellock FG, Crues JV. Temperature, heart rate, and blood pressure changes associated with clinical MR imaging at 1.5 T. Radiology. 1987; 163(1):259–62. [PubMed: 3823445]
53. Shellock FG, Crues JV. Corneal temperature changes induced by high-field-strength MR imaging with a head coil. Radiology. 1988; 167(3):809–11. [PubMed: 3363146]
54. Shellock FG, Crues JV. Temperature changes caused by MR imaging of the brain with a head coil. AJNR American journal of neuroradiology. 1988; 9(2):287–91. [PubMed: 3128077]
55. Shellock FG, Rothman B, Sarti D. Heating of the scrotum by high-field-strength MR imaging. AJR American journal of roentgenology. 1990; 154(6):1229–32. [PubMed: 2110733]

56. Shellock FG, Schaefer DJ, Crues JV. Alterations in body and skin temperatures caused by magnetic resonance imaging: is the recommended exposure for radiofrequency radiation too conservative? *The British journal of radiology*. 1989; 62(742):904–9. [PubMed: 2819358]
57. Shellock FG, Schaefer DJ, Kanal E. Physiologic responses to an MR imaging procedure performed at a specific absorption rate of 6.0 W/kg. *Radiology*. 1994; 192(3):865–8. [PubMed: 8058962]
58. Shellock FG, Schatz CJ. Increased corneal temperature caused by MR imaging of the eye with a dedicated local coil. *Radiology*. 1992; 185(3):697–9. [PubMed: 1438747]
59. van Rhoon GC, Samaras T, Yarmolenko PS, Dewhirst MW, Neufeld E, Kuster N. CEM43 degrees C thermal dose thresholds: a potential guide for magnetic resonance radiofrequency exposure levels? *European radiology*. 2013; 23(8):2215–27. [PubMed: 23553588]
60. Wolf S, Diehl D, Gebhardt M, Mallow J, Speck O. SAR simulations for high-field MRI: how much detail, effort, and accuracy is needed? *Magnetic resonance in medicine : official journal of the Society of Magnetic Resonance in Medicine / Society of Magnetic Resonance in Medicine*. 2013; 69(4):1157–68.
61. Andreuccetti D, Contessa GM, Falsaperla R, Lodato R, Pinto R, Zoppetti N, et al. Weighted-peak assessment of occupational exposure due to MRI gradient fields and movements in a nonhomogeneous static magnetic field. *Medical physics*. 2013; 40(1):011910. [PubMed: 23298101]
62. Bourland JD, Nyenhuis JA, Schaefer DJ. Physiologic effects of intense MR imaging gradient fields. *Neuroimaging clinics of North America*. 1999; 9(2):363–77. [PubMed: 10318720]
63. Doherty JU, Whitman GJ, Robinson MD, Harken AH, Simson MB, Spear JF, et al. Changes in cardiac excitability and vulnerability in NMR fields. *Investigative radiology*. 1985; 20(2):129–35. [PubMed: 3988463]
64. Ehrhardt JC, Lin CS, Magnotta VA, Fisher DJ, Yuh WT. Peripheral nerve stimulation in a whole-body echo-planar imaging system. *Journal of magnetic resonance imaging : JMRI*. 1997; 7(2):405–9. [PubMed: 9090599]
65. Ham CL, Engels JM, van de Wiel GT, Machielsen A. Peripheral nerve stimulation during MRI: effects of high gradient amplitudes and switching rates. *Journal of magnetic resonance imaging : JMRI*. 1997; 7(5):933–7. [PubMed: 9307922]
66. Kangarlu A, Tang L, Ibrahim TS. Electric field measurements and computational modeling at ultrahigh-field MRI. *Magnetic resonance imaging*. 2007; 25(8):1222–6. [PubMed: 17368794]
67. Schaefer DJ, Bourland JD, Nyenhuis JA. Review of patient safety in time-varying gradient fields. *Journal of magnetic resonance imaging : JMRI*. 2000; 12(1):20–9. [PubMed: 10931561]
68. American College of Radiology (ACR). Manual on Contrast Media, Version 9. 2013. <http://www.acr.org/quality-safety/resources/~media/37D84428BF1D4E1B9A3A2918DA9E27A3.pdf>. Last accessed: December 11, 2014. [December 11, 2014]
69. U.S. Department of Health and Human Services, Food and Drug Administration, Center for Devices and Radiological Health, Guidance for Industry and FDA Staff. Criteria for Significant Risk Investigations of Magnetic Resonance Diagnostic Devices. Jul 14.2003
70. de Vocht F, van Drooge H, Engels H, Kromhout H. Exposure, health complaints and cognitive performance among employees of an MRI scanners manufacturing department. *Journal of magnetic resonance imaging : JMRI*. 2006; 23(2):197–204. [PubMed: 16374876]
71. U.S. Department of Health and Human Services, FDA, CDRH, Guidance for Industry and FDA Staff. Criteria for Significant Risk Investigations of Magnetic Resonance Diagnostic Devices. Jul 14.2003
72. Sammet S, Koch RM, Aguila F, Knopp MV. Residual magnetism in an MRI suite after field-rampdown: what are the issues and experiences? *Journal of magnetic resonance imaging : JMRI*. 2010; 31(5):1272–6. [PubMed: 20432367]
73. ACR MR Safety. Available at <http://www.acr.org/quality-safety/radiology-safety/mr-safety>. Last accessed: December 11, 2014. [December 11, 2014]
74. Collins CM, Wang Z. Calculation of radiofrequency electromagnetic fields and their effects in MRI of human subjects. *Magnetic resonance in medicine : official journal of the Society of Magnetic Resonance in Medicine / Society of Magnetic Resonance in Medicine*. 2011; 65(5):1470–82.

75. Machata AM, Willschke H, Kabon B, Prayer D, Marhofer P. Effect of brain magnetic resonance imaging on body core temperature in sedated infants and children. *British journal of anaesthesia*. 2009; 102(3):385–9. [PubMed: 19174372]
76. ASTM F2119-01 Standard Test Method for Evaluation of MR Image Artifacts From Passive Implants.
77. Woods TO. Standards for medical devices in MRI: present and future. *Journal of magnetic resonance imaging : JMRI*. 2007; 26(5):1186–9. [PubMed: 17969160]
78. Kanal E, Shellock FG, Talagala L. Safety considerations in MR imaging. *Radiology*. 1990; 176(3): 593–606. [PubMed: 2202008]
79. IEC 601-2-33 - Medical Electrical Equipment - Part 2: Particular requirements for the safety of magnetic resonance equipment for medical diagnosis.
80. Guidelines to Prevent Excessive Heating and Burns Associated with Magnetic Resonance Procedures developed by the Institute for Magnetic Resonance Safety, Education, and Research (IMRSE). <http://www.mrisafety.com/SafetyInfo.asp?SafetyInfoID=166>. Last accessed: December 11, 2014. [December 11, 2014]
81. Kangarlu A, Ibrahim TS, Shellock FG. Effects of coil dimensions and field polarization on RF heating inside a head phantom. *Magnetic resonance imaging*. 2005; 23(1):53–60. [PubMed: 15733788]
82. ACR_SPR Practice parameter for the safe and optimal performance of fetal magnetic resonance imaging (MRI), Amended 2014 (Resolution 39)*. <http://www.acr.org/~media/CB384A65345F402083639E6756CE513F.pdf>. Last accessed: December 11, 2014. [December 11, 2014]
83. Baker PN, Johnson IR, Harvey PR, Gowland PA, Mansfield P. A three-year follow-up of children imaged in utero with echo-planar magnetic resonance. *American journal of obstetrics and gynecology*. 1994; 170(1 Pt 1):32–3. [PubMed: 8296840]
84. Gilk T, Kanal E. Interrelating sentinel event alert #38 with the ACR guidance document on MR safe practices: 2013. An MRI accreditation safety review tool. *Journal of magnetic resonance imaging : JMRI*. 2013; 37(3):531–43. [PubMed: 23345250]
85. Thomsen, HS. Contrast media : safety issues and esur guidelines. Berlin: Springer; 2006. p. x-167.
86. Behra-Miellet J, Gressier B, Brunet C, Dine T, Luyckx M, Cazin M, et al. Free gadolinium and gadodiamide, a gadolinium chelate used in magnetic resonance imaging: evaluation of their in vitro effects on human neutrophil viability. *Methods and findings in experimental and clinical pharmacology*. 1996; 18(7):437–42. [PubMed: 8900215]
87. Mendoza FA, Artlett CM, Sandorfi N, Latinis K, Piera-Velazquez S, Jimenez SA. Description of 12 cases of nephrogenic fibrosing dermopathy and review of the literature. *Seminars in arthritis and rheumatism*. 2006; 35(4):238–49. [PubMed: 16461069]
88. The International Center for Nephrogenic Systemic Fibrosis Research (ICNSFR) by Cowper SE. Available at <http://www.icnfd.org>. Last accessed: December 11, 2014. [December 11, 2014]
89. Food and Drug Administration (FDA) Information on Gadolinium-Based Contrast Agents. 2014. <http://www.fda.gov/Drugs/DrugSafety/PostmarketDrugSafetyInformationforPatientsandProviders/ucm142882.htm>. Last accessed: December 11, 2014. [December 11, 2014]
90. Dillman JR, Ellis JH, Cohan RH, Caoili EM, Hussain HK, Campbell AD, et al. Safety of gadolinium-based contrast material in sickle cell disease. *Journal of magnetic resonance imaging : JMRI*. 2011; 34(4):917–20. [PubMed: 21769966]
91. Grobner T. Gadolinium--a specific trigger for the development of nephrogenic fibrosing dermopathy and nephrogenic systemic fibrosis? *Nephrology, dialysis, transplantation : official publication of the European Dialysis and Transplant Association - European Renal Association*. 2006; 21(4):1104–8.
92. Kanal E. An overview of electromagnetic safety considerations associated with magnetic resonance imaging. *Annals of the New York Academy of Sciences*. 1992; 649:204–24. [PubMed: 1580494]
93. Marckmann P, Skov L, Rossen K, Dupont A, Damholt MB, Heaf JG, et al. Nephrogenic systemic fibrosis: suspected causative role of gadodiamide used for contrast-enhanced magnetic resonance

- imaging. *Journal of the American Society of Nephrology : JASN*. 2006; 17(9):2359–62. [PubMed: 16885403]
94. Marckmann P, Skov L, Rossen K, Heaf JG, Thomsen HS. Case-control study of gadodiamide-related nephrogenic systemic fibrosis. *Nephrology, dialysis, transplantation : official publication of the European Dialysis and Transplant Association - European Renal Association*. 2007; 22(11): 3174–8.
95. Umans H, Haramati N, Flusser G. The diagnostic role of gadolinium enhanced MRI in distinguishing between acute medullary bone infarct and osteomyelitis. *Magnetic resonance imaging*. 2000; 18(3):255–62. [PubMed: 10745133]
96. Thorpe S, Salkovskis PM, Dittner A. Claustrophobia in MRI: the role of cognitions. *Magnetic resonance imaging*. 2008; 26(8):1081–8. [PubMed: 18524527]
97. Conquering claustrophobia during your MRI. *The Johns Hopkins medical letter health after 50*. 2002; 14(9):3.
98. Phelps LA. MRI and claustrophobia. *American family physician*. 1990; 42(4):930. [PubMed: 2220520]
99. Serafini G, Ongaro L, Mori A, Rossi C, Cavalloro F, Tagliaferri C, et al. Anesthesia for MRI in the paediatric patient. *Minerva anesthesiologica*. 2005; 71(6):361–6. [PubMed: 15886602]
100. Pilling D, Abernethy L, Wright N, Carty H. Sedation, safety and MRI. *The British journal of radiology*. 2001; 74(885):875–6. [PubMed: 11560840]