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The physics behind MRI safety, including static magnetic fields, radiofrequency fields, and gradient magnetic fields

Kolokolo Hannington[1], Shema Innocent[2] , Kanyana Ruth[3],Kibirige David[4],Opolot Samuel Otekat[5], Wodidi Jonah[6],Senyonjo Timothy[7],Kwesiga Dominic[8] ,Kalule Mugagga[9], Tigasitwa Fred[10],

Ernest Cook Ultrasound Research and Education Institute (ECUREI)
Department of Engineering and biomedical sciences
hanningtonkolokolo@gmail.com[1],shemablast10@gmail.com[2], kanyanaruth@gmail.com[3] ,semkibirige@gmail.com[4] ,Samueloso63@gmail.com[5],wodidijona@gmail.com [6], timothysenyonjo387@gmail.com[7] ,kabsdominique@gmail.com[8], Vicamugagga@gmail.com[9] ,ftigasitwa@gmail.com[10]
U/23030029/MBE[1], U/23030022/MBE[2], U/23030023/MBE[3], U/23030031/MBE[4], U/23030034/MBE[5], U/23030041/MBE[6], U/23030044/MBE[7], U/23030047/MBE[8] U/23030045/MBE[9], U/23030049/MBE[10]

Abstract: *Magnetic Resonance Imaging (MRI), invented in 1969, is a widely used imaging modality that offers excellent soft tissue contrast and does not involve ionizing radiation. However, the strong magnetic fields and radiofrequency pulses used in MRI can pose potential safety risks to patients and healthcare workers. This review aims to provide an overview of the physics behind MRI safety, including static magnetic fields, radiofrequency fields, and gradient magnetic fields. Additionally, it discusses safety considerations, such as the risks associated with ferromagnetic objects, thermal effects, acoustic noise, and the potential for biological effects. Finally, this review highlights the importance of adherence to safety guidelines and the continuous development of safety protocols to ensure safe MRI practice.*

Keywords: *Magnetic Resonance Imaging, radiofrequency, magnetic field*

1. INTRODUCTION

Magnetic Resonance Imaging (MRI) is a non-invasive medical imaging technique that utilizes strong magnetic fields, radiofrequency (RF) pulses, and gradient magnetic fields to generate detailed anatomical and functional images of the human body. While MRI offers numerous diagnostic benefits, it is crucial to understand the physics and associated safety concerns to ensure patient and staff well-being during MRI procedures [1].

Objective

To improve Magnetic Resonance Imaging Safety by identifying and suggesting improvements to fill identified gaps in the current MRI safety guidelines.

Methodology

Research work has been conducted by reading Magnetic Resonance Imaging Safety literature, searching electronic sources, and discussions with colleagues.

The three unique Magnetic fields

The static magnetic field Bo causes the atoms of the body to align in the same direction, the time–varying Radiofrequency Magnetic field B1 moves the atoms out of their original positions, and the time-varying gradient magnetic field (dB/dt) which is the changing magnetic field as the radio waves are turned off, making the atoms to return to their original position, thereby sending back radio signals which are interpreted to generate an image [2].

THE MRI SCANNER

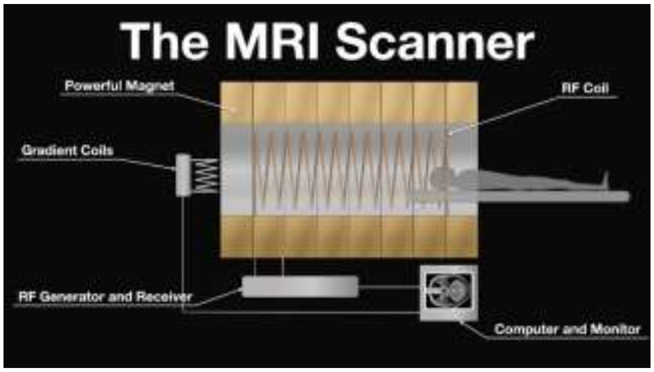

Figure 1: The MRI Scanner

Time-Varying Radiofrequency (RF) Magnetic Field and Safety Considerations

Polarized spins aligned with the static magnetic field are modulated using RF magnetic field pulses tuned to or near the resonant (Larmor) frequency for signal generation and contrast manipulation in MRI.

Primary safety concerns at the resonance frequencies (64 MHz and 128 MHz for 1.5 T and 3.0 T respectively) are whole-body and localized heating from the absorption of applied RF energy. Dielectric properties of the medium determine the conversion of the applied RF field into currents, resulting in local tissue heating. Safety concerns include heat stress from sustained whole-body temperature increases and potential tissue damage from localized high-temperature exposures [3].

Magnetically Induced Torque and Safety Limits

In asymmetric magnetic objects, a strong net dipole moment may exist, not aligned with the static magnetic field. The torque (L) generated is proportional to the cross-product between the dipole moment (m) and magnetic field (B). Total torque depends on the magnetized material volume (V), induced magnetization (M), and field strength (B). The fringe field of an MR imaging suite shows the 5-G (0.5 mT) limit. Access control is required in all areas containing the 5-G line, including above and below the unit. This safety limit is attributed to medical implants (e.g., pacemakers), necessitating personnel screening before entering. The 30-G (3 mT) zone represents the limit for significant kinetic forces exerted on ferromagnetic objects [4].

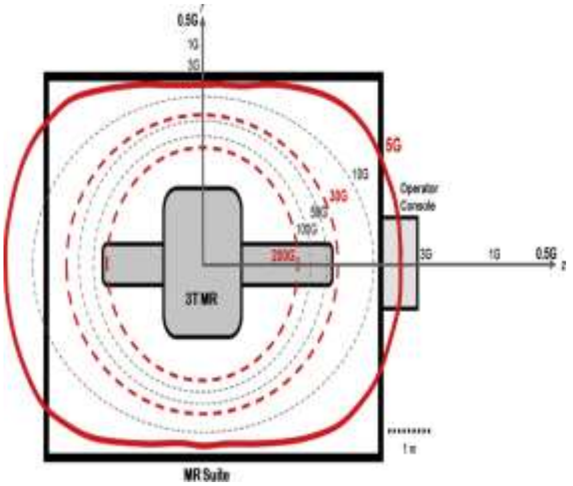

Figure 2: Fringe field of a typical MR imaging suite showing the 5-G limit. All areas containing the 5-G line, including above and below the unit, must be access-controlled. Because this safety limit is attributed to medical implants (eg, pacemakers), screening of personnel is required before entering. The 30-G zone is the limit for significant kinetic forces to be exerted on ferromagnetic objects. Refer to Table 1 for a summary of relevant isofield regions and distances from the magnet. Units: 1 G 5 0.1 mT.

Cryogen Concerns in MR Imaging

1. Liquid Helium Concerns: Superconducting magnets in MR systems use liquid helium for cooling the coils. Helium is a colorless and odorless gas that, if leaked, can displace oxygen and pose a risk of asphyxiation. A substantial amount of liquid helium is used, and a leak can lead to the release of helium gas into the room [5].
2. Quench Events: MR systems are at risk of experiencing a quench, which is a sudden loss of superconductivity in the magnet. A quench occurs when the cooling system fails to maintain the required superconducting state. This results in the generation of substantial heat due to increased resistance in the coils [2].

Heating causes the liquid helium to boil off as an extremely cold gas, leading to a significant volume expansion. The gas is expelled from the room via a quench pipe and emergency procedures should be in place to address the situation. Failure of the quench pipe may allow cold helium gas to enter the examination room, posing risks such as hypothermia or asphyxiation [6].

Active Implantable Medical Devices (AIMDs)

Electronically powered or magnetically programmed AIMDs may experience displacement forces, torques, and B0-field-induced device malfunction. Magnetic field impact on reed switches of certain AIMDs, like CIEDs, can cause fatal incidents. Areas with fringe static magnetic fields of 0.5 mT (5 G) or higher must be controlled, marked, and screened for implanted devices. Fringe fields can extend above, below, and around the MR system, potentially affecting adjacent spaces and equipment [7].

Safety Considerations

The primary safety risk from the static magnetic field is the potential for ferromagnetic objects to be pulled violently into the magnet (missile effect). Strong displacement forces and torques can pose hazards to patients with ferromagnetic implants, especially near the bore entrance and magnet isocenter. Fringe fields can damage or disrupt AIMDs, such as pacemakers, even at a distance from the magnet isocenter. Full assessment of magnet fringe fields is important, and modern scanners incorporate shielding to minimize their range. Cryogens used for cooling superconducting coils pose safety concerns, including the risk of helium leaks and magnet quenches.

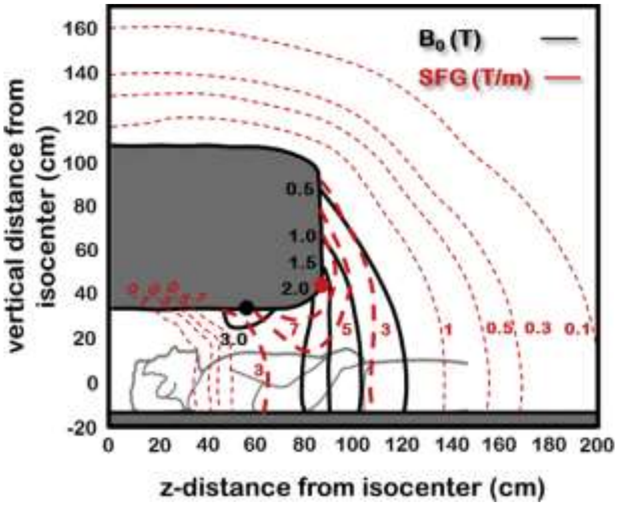

Figure 3: The approximate location and magnitude of B0 isofield lines (black) in units of Tesla and spatial field gradient (SFG) lines (red) in units of T/m as a patient enters a 3 T

scanner. The maximum field (black circle) is within the bore and is approximately 3.5 T, whereas the maximum SFG (red circle) is located at the bore opening and is approximately 10 T/m. The region of extremely high spatial gradient–generated displacement force that may be a hazard to patients with ferromagnetic medical implants is emphasized using bold SFG lines (_3 T/m) and begins at the bore opening. Further inside the bore, magnetic torque forces become stronger and are the dominant consideration as the spatial gradients weaken near the magnet isocenter. Vendors often quote the maximum SFG exposure within a cylindrical region so that users can understand the maximum SFG that might be experienced by a particular device or implant on the patient. Units: 1 T/m 5 100 G/cm.

RF Pulse Modulation

Polarized spins aligned with the static magnetic field are modulated using RF magnetic field pulses. RF pulses are tuned to or near the resonant (Larmor) frequency of imaged nuclei (protons).

Resonance frequency = gyromagnetic ratio (g) × static field strength (B0).

Safety concerns at resonance frequencies primarily include whole-body and localized heating from absorbed RF energy. Understanding and controlling this heating is crucial to prevent thermal injuries.

Specific Absorption Rate (SAR)

SAR measures RF power absorbed in tissue and serves as a surrogate for managing temperature effects. Whole-body and localized heating are the primary concerns during RF power absorption. Thermoregulatory system helps counteract thermal stress through heat radiation, evaporation, convection, and conduction. Patients may experience heat sensations, increased perspiration, and elevated pulse rate. Maximum temperatures for localized regions: Head (≤38°C), Trunk (≤39°C), Limbs (≤40°C) [2].

Radiofrequency-Induced Focal Heating

RF field can induce higher-caliber currents leading to focal resistive heating in tissue. Focal areas of high resistance can cause resistive heating. Medical implants, sharp corners, disconnects, or close proximity to other conductors can result in high electric fields and resistive heating in adjacent tissue [8].

Conducting Loops and Antenna Effect

Conducting loops formed by conductors nearly perpendicular to the applied field can generate large currents and heating. Areas of high resistance in loops may generate hotspots of substantial heating. Human skin contact and skin-to-skin contact can form large-diameter conducting loops and cause rapid heating. Long, cylindrical conductors such as needles or leads may experience the antenna effect, leading to high heating at specific locations.

Tissue Heating and SAR Control

RF currents are distributed over the patient volume, resulting in diffuse heating. Body core temperature is regulated by monitoring specific absorption rate (SAR) and patient during exposure. Patient may require breaks and time to cool off during long exposures. At-risk patients may need additional medical supervision and monitoring, such as ECG monitoring for cardiovascular stress.

Focal Heating and Thermal Events

Induced current density can concentrate in regions of higher resistance, leading to focal heating which is the leading cause of reported injuries in the MR environment. Proper patient screening for conducting objects and implants is crucial to avoid thermal events. Insulation and avoidance of contact between conducting surfaces and patient are important. Focal heating considerations include patient positioning, insulation, and avoiding exposure to high B1 hotspots.

Peripheral Nerve Stimulation (PNS)

Time-varying gradients can result in peripheral nerve stimulation (PNS). PNS limits have been developed to prevent patient discomfort and movement that may compromise examination efficacy. PNS thresholds are below cardiac stimulation thresholds, which could pose additional risks [9].

Acoustic Noise

Current-carrying coils experience mechanical forces in a static magnetic field, leading to acoustic noise during gradient slewing. Vendors aim to minimize acoustic noise through gradient design. Acoustic noise characteristics include frequency spectrum, intensity, and duration of exposure. Peak sound pressure level (SPL) is measured and referenced against a threshold value (p0), such as the threshold for human hearing [10].

Suggested Improvement

Liquid Helium: The use of liquid helium in superconducting magnets raises safety concerns due to its potential leakage. Helium leaks can lead to oxygen displacement, asphyxiation risks, and potential fire hazards. Therefore, the implementation of advanced helium leakage detection systems is essential. Utilizing sensitive mass spectrometers or infrared cameras capable of detecting minute helium concentrations improves leakage detection efficiency. These systems should be regularly calibrated and integrated into the MRI's safety protocols [11].

Contrast Agents: Gadolinium-based contrast agents (GBCAs) are commonly used in MRI to enhance image quality. However, there have been concerns about the potential accumulation of gadolinium in the brain and other organs, particularly among patients with impaired kidney function. The American College of Radiology (ACR) and the European Medicines Agency (EMA) have provided guidelines to ensure appropriate use and monitoring of GBCAs [12]. However, efforts are underway to develop non-contrast imaging techniques that reduce the reliance on contrast agents. This development aims to eliminate the associated risks, such as nephrogenic systemic fibrosis, for patients with impaired kidney function. Techniques such as arterial spin labeling and diffusion-weighted imaging show promise in providing high-quality non-contrast MRI. Patient experience: Improving patient experience during MRI examinations is vital. There is a need to reduce scan times, optimize protocols to minimize discomfort and develop immersive environments to reduce anxiety. The use of virtual reality and audiovisual distractions can lead to improvement in patient comfort and satisfaction [13].

Addition of Artificial Intelligence into the MRI for safety monitoring: AI algorithms have the potential to improve MRI safety by continuously monitoring patients during scanning. These algorithms can detect potential risks in real time and alert healthcare professionals. AI-based safety monitoring systems can provide an additional layer of safety during MRI procedures [14].

Acoustic Noise: MRI scanners produce loud noise during scanning, which can cause discomfort and anxiety in patients. Efforts to reduce noise levels include advancements in gradient and acoustic design, as well as providing ear protection for patients [10].

Improved Compatibility with Implants: Advancements in MRI technology aim to improve compatibility with metallic implants. Research focuses on reducing artifacts caused by implants and minimizing RF heating risks. Novel RF coil designs and sequence optimization techniques are being investigated to improve imaging quality in patients with implants [15].

Conclusion

Understanding the physics behind MRI safety is crucial for healthcare professionals to minimize potential risks associated with MRI examinations. Current safety measures address concerns related to magnetic field hazards, RF heating, contrast agents, and acoustic noise. This review suggests for better MRI safety by improving compatibility with implants, AI-based safety monitoring, non-contrast imaging techniques, and enhanced patient experience. These advancements, backed by ongoing research and technological innovation, will continue to improve the safety and efficacy of Magnetic Resonance Imaging.

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