Electromagnetic Field Mechanisms and Safety Implications in Magnetic Resonance Imaging: A Contemporary Review

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Article History: Received 1 February 2026; Revised 10 June 2026;
Accepted 15 June 2026; Published 30 June 2026

Abstract

Magnetic resonance imaging (MRI) relies on static, gradient, and radiofrequency (RF) electromagnetic fields to generate high-resolution diagnostic images. As MRI technology continues to advance, comprehensive knowledge of these fields is increasingly important for safe and effective clinical practice. However, existing evidence remains fragmented, while limited technical understanding may affect protocol selection, implant assessment, patient handling, and risk management. Therefore, this review aims to explain the principles of MRI electromagnetic fields, examine their effects on image formation, system performance, biological tissue interactions, and implanted medical devices, and synthesise current evidence on their associated safety implications. An integrative narrative review was conducted using structured literature searches, followed by narrative and matrix synthesis of 40 sources including review articles, experimental and simulation studies, clinical investigations, safety guidelines, consensus statements, and organisational studies. The findings indicate that static magnetic fields facilitate nuclear alignment but introduce projectile, vestibular, and implant-displacement hazards. Gradient magnetic fields provide spatial encoding but may induce peripheral nerve stimulation, cardiac magnetostimulation, and acoustic exposure, whereas RF fields enable proton excitation while presenting tissue-heating and implant-related thermal risks. MRI safety is influenced by multiple interacting factors, including scanner configuration, implant characteristics, patient anatomy, operating conditions, staff competency, and institutional governance. Integrating electromagnetic-field principles with evidence-based system design, rigorous safety protocols, and patient-specific risk assessment is essential for ensuring high-quality imaging while minimising patient and occupational risks.

Keywords: Electromagnetic Fields, MRI Principles, MRI Safety, Radiofrequency Fields, Risk Assessment

1.0 Introduction

Magnetic Resonance Imaging (MRI) is an essential diagnostic modality that provides detailed anatomical and functional information without ionising radiation. It is widely applied in neurological, musculoskeletal, cardiovascular, abdominal, and oncological examinations. MRI operates through interactions between electromagnetic fields and atomic nuclei within biological tissues; therefore, image quality, acquisition speed and safety depend on how these fields are generated, controlled and applied [1], [2].

MRI uses three principal electromagnetic field components: the static magnetic field (B_0), time-varying gradient magnetic fields and radiofrequency (RF) fields. B_0 aligns hydrogen nuclei and influences magnetisation and signal strength. Gradient fields produce controlled spatial variations for slice selection, frequency encoding and phase encoding. The transmit RF field (B_1^+) provides energy at the Larmor frequency to excite aligned nuclei, while receiver coils detect the resulting MR signals [3], [4], [5]. Together, these fields determine image contrast, spatial resolution, signal-to-noise ratio, scan duration and overall system performance.

Advances in MRI have introduced higher static-field strengths, faster gradients, complex RF transmission and specialised imaging protocols. Although these developments improve image quality and reduce acquisition time, they also increase electromagnetic interactions with patients, personnel, tissues and implanted devices. RF absorption may cause tissue heating and burns, rapidly switching gradients may induce peripheral nerve stimulation, and static fields may produce translational forces, torque and projectile effects involving ferromagnetic objects or implants [6], [7]. These concerns become more complex at 3 T and 7 T, where shorter RF wavelengths may produce non-uniform energy deposition and localised heating in tissues or conductive implants [8]. Portable and low-field systems also introduce distinct field distributions, shielding requirements, performance limitations and accessibility considerations [9], [10].

A practical understanding of electromagnetic-field behaviour is therefore essential for safe MRI operation. MRI personnel must understand nuclear alignment, Larmor precession, gradient-induced electric fields, RF excitation, specific absorption rate (SAR) and the root-mean-square RF magnetic field (B_1, rms^+). Insufficient knowledge may contribute to inappropriate protocol selection, incorrect placement of conductive materials, inadequate implant assessment and misinterpretation of MRI safety classifications. Reports of RF burns, peripheral nerve stimulation, implant interactions and projectile events show that safety depends on equipment performance, technical knowledge and adherence to established procedures [2], [6], [7], [9]. Surveys and incident reports have also identified training limitations and possible underreporting of electromagnetic-field-related events [9], [10].

Despite the extensive clinical use of MRI, electromagnetic-field physics, image formation, system behaviour, biological exposure and patient safety are not

Politeknik & Kolej Komuniti Journal of Engineering and Technology, Vol. 11, No. 1, 2026
eISSN 0128-2883

always examined within an integrated framework. Existing reviews have often addressed MRI safety from broad clinical or historical perspectives. Mittendorff et al. discussed safety issues associated with static, gradient and RF fields [1], [11], while other systematic reviews evaluated general MRI risks and preventive measures with less emphasis on the electromagnetic principles underlying image formation and field-related hazards [12]. Earlier foundational and topical reviews also examined biological and health effects, although many reflect previous scanner technologies and operating conditions [13], [14].

An updated synthesis is therefore required to connect fundamental electromagnetic-field principles with contemporary MRI operation and safety. This need is increasingly relevant with higher-field scanners, advanced gradient systems, parallel RF transmission, portable MRI and the growing use of active and passive implants. Accordingly, this review synthesises recent peer-reviewed evidence on the behaviour and functions of static, gradient and RF fields and their influence on image formation, system performance, biological tissues and implanted medical devices. By integrating electromagnetic theory with contemporary applications and safety considerations, the review aims to support safer, more informed and technically accurate MRI practice.

2.0 Methodology

This study adopted an integrative narrative review approach to synthesise contemporary evidence on the mechanisms of MRI electromagnetic fields, their influence on system performance, and associated safety implications. This review design was selected because it enables the integration of diverse forms of evidence, including physical, engineering, biological, clinical, and organisational perspectives, thereby providing a comprehensive understanding of electromagnetic field behaviour and its implications for safe and effective MRI practice.

Relevant publications were identified through structured literature searches using keywords related to static magnetic fields, gradient magnetic fields, RF fields, specific absorption rate, RF heating, peripheral nerve stimulation, acoustic noise, low-field MRI, ultra-high-field MRI, and implant safety. The reviewed literature comprised narrative, descriptive, and systematic reviews [1], [2], [3], [4], [8], [13], [15], [16], [21], [23], [24]; clinical and observational investigations [7], [9], [30], [31]; safety guidelines and consensus statements [10], [12], [19], [20]; human-factor and organisational safety studies [11], [18]; and experimental, simulation, phantom, ex vivo, and technical development studies [6], [14], [17], [25], [26], [27], [28], [29], [32], [33], [34], [35], [36], [37], [38], [39], [40]. Publications were screened based on their titles, abstracts and full-text content and were included if they addressed the physical mechanisms, biological interactions, system performance, or clinical safety implications of MRI electromagnetic fields. A general overview of medical imaging was consulted to establish the technological background of MRI [5], while an MRI-based artificial intelligence study was included to illustrate the broader application of MRI data in contemporary diagnostic practice [22].

Information was extracted according to the study design, electromagnetic field type, scanner configuration, exposure parameters, safety outcomes, principal findings, strengths and limitations. The extracted evidence was organised into thematic categories covering static-field safety, gradient-related physiological and acoustic effects, RF heating, electromagnetic field-tissue interactions, MRI system design, implant safety, and organisational safety management. A structured narrative and matrix synthesis were subsequently performed to compare the selected studies, identify recurring findings and methodological limitations, and highlight emerging strategies for improving MRI safety and clinical practice.

3.0 Research Gap and Issues

Despite the increasing number of studies addressing electromagnetic field effects in MRI, the available evidence remains fragmented. Most published studies focus on individual aspects of MRI safety, including RF heating, acoustic noise, peripheral nerve stimulation, implant interactions or organisational safety practices. Limited research integrates static, gradient and RF field mechanisms within a unified framework that connects MRI performance, biological exposure, implant safety and clinical risk management. This limitation is increasingly important as contemporary MRI systems adopt higher field strengths, faster gradient hardware, advanced RF transmission and more complex implanted medical devices. To identify the current state of knowledge and remaining research gaps, the reviewed literature was synthesised according to methodology category as summarised in Table 1.

Table 1: Matrix synthesis of reviewed literature on electromagnetic field behaviour and safety considerations in MRI

Methodology Category	Citation Numbers	Strengths	Limitations
Narrative, Descriptive, and Topical Reviews	[1], [2], [3], [4], [8], [13], [15], [21], [23], [24]	Coverage: Provide broad explanations of MRI electromagnetic fields, RF heating, acoustic noise, implants, and field-strength developments. Foundation: Establish the theoretical and clinical background of MRI safety.	Original Evidence: Most do not provide new experimental or clinical data. Methodological Variation: Several lack a formal search and selection protocol.
General Educational and Background Resource	[5]	Accessibility: Provides a clear introductory overview of medical imaging and MRI. Context: Supports the	Source Quality: It is not a peer-reviewed academic publication. Technical Depth: It

Methodology Category	Citation Numbers	Strengths	Limitations
		general background of MRI technology.	provides limited evidence for detailed EMF safety conclusions.
Original Experimental and Technical Studies	[6], [14], [17], [25], [26], [27], [28], [29], [32], [33], [34], [35], [36], [37], [38], [39], [40]	Technical Evidence: Provide detailed findings on induced electric fields, PNS, acoustic noise, SAR, RF heating, and implant coupling. Innovation: Introduce improved coils, simulations, monitoring sensors, and RF safety techniques.	Clinical Validation: Many rely on simulations, phantoms, or ex vivo models. Generalisation: Results are often specific to particular scanners, coils, implants, and exposure settings.
Clinical Observational and Incident Studies	[7], [9], [30], [31]	Real-World Evidence: Examine actual MRI incidents, implant displacement, and patient examinations. Clinical Relevance: Demonstrate how MRI risks and safety protocols operate in practice.	Study Design: Most are retrospective or institution specific. Rare Events: Sample sizes may not detect uncommon complications.
Safety Culture, Human Factors, and Survey Studies	[10], [11], [18]	Organisational Insight: Emphasise training, teamwork, communication, and reporting systems. Safety Improvement: Support stronger institutional safety culture and staff preparedness.	Self-Reporting: Findings may be influenced by recall or response bias. Regional Variation: Practices and resources differ across institutions and countries.
Safety Guidelines, Consensus Statements, and Position Papers	[12], [19], [20]	Clinical Guidance: Provide practical recommendations for screening, device management, monitoring, and workflow. Standardisation: Support consistent MRI safety practices across institutions.	Consensus Dependence: Some recommendations rely partly on expert opinion. Updating Needs: Guidance may change with new scanners, implants, and clinical evidence.

Methodology Category	Citation Numbers	Strengths	Limitations
Systematic Reviews and Meta-analyses	[16]	Structured Synthesis: Uses a predefined method to evaluate MRI safety evidence. Clinical Evidence: Combines findings from multiple studies involving cardiac devices and retained leads.	Heterogeneity: Included studies differ in device type, field strength, and protocol. Scope: Findings are mainly limited to cardiac devices.
Contextual MRI Application Study	[22]	Contemporary Application: Demonstrates AI-based analysis of MRI images for brain tumour detection. Implementation Insight: Highlights training, ethics, privacy, and human oversight in healthcare AI.	Indirect Relevance: Does not directly investigate MRI electromagnetic-field mechanisms. No Safety Evaluation: Does not assess SAR, RF heating, PNS, acoustic noise, or implant interaction.

As summarised in Table 1, the reviewed literature provides substantial evidence on electromagnetic field behaviour, RF heating, peripheral nerve stimulation, acoustic noise, implant coupling and MRI system design. However, many rely on simulations, phantoms, ex vivo models, or specific scanner and implant configurations, which may limit their generalisability. Clinical studies, surveys, guidelines and consensus statements provide practical evidence on patient outcomes, reporting, training, workflow and safety management, but inconsistencies in reporting, limited clinical validation, regional variation and emerging MRI technologies remain important limitations. Addressing these gaps is necessary to integrate electromagnetic field mechanisms with system performance, implant safety and contemporary clinical practice.

Overall, the existing literature demonstrates a clear need for a more integrated understanding of MRI electromagnetic fields that bridges physical mechanisms, engineering design, biological interactions, implant compatibility, and organisational safety. Addressing these gaps is essential for supporting evidence-based MRI systems design, strengthening patient-specific risk assessment, and enhancing safe clinical practice in increasingly complex MRI environments.

4.0 Analysis and Discussion

This section analyses the roles of static, gradient and radiofrequency electromagnetic fields in MRI, with emphasis on their influence on image formation, system performance, biological interaction, implant compatibility and clinical safety. Figure 1 presents an integrated overview of the functions, safety risks, mitigation strategies, implant considerations and clinical management requirements associated with these electromagnetic fields.

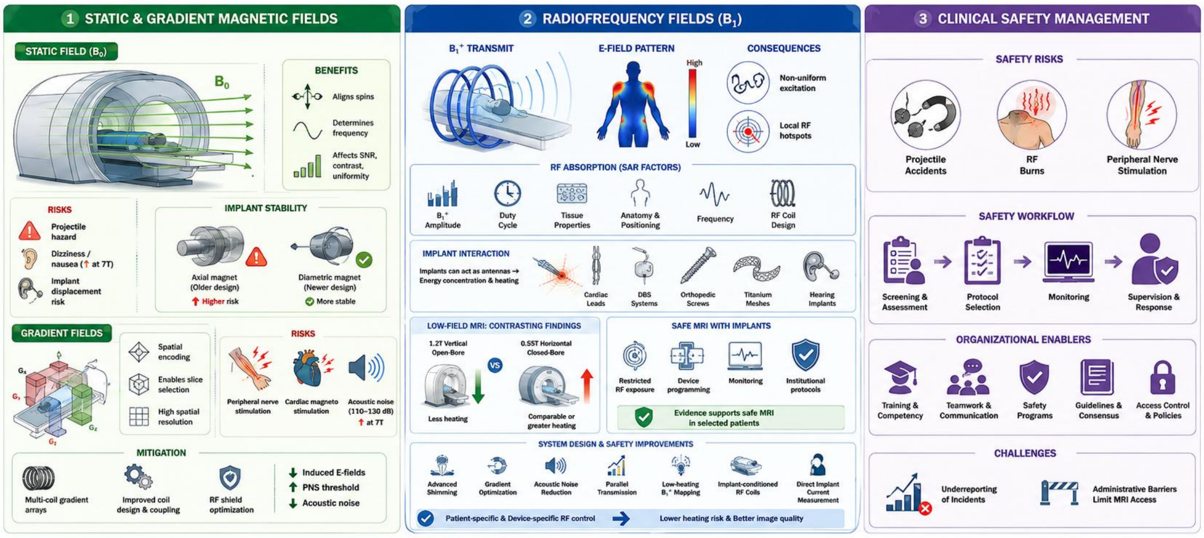

Figure 1: Integrated overview of MRI electromagnetic field mechanisms, safety risks and clinical management

Figure 1 shows that the static magnetic field supports nuclear alignment but may create projectile, vestibular and implant-displacement risks. Gradient fields provide spatial encoding but can cause peripheral nerve stimulation, cardiac magnetostimulation and acoustic noise, while RF fields enable excitation but may produce tissue heating and implant-related hotspots. The figure also highlights the importance of system optimisation, patient-specific implant assessment, monitoring, staff training and institutional safety protocols.

4.1 Static and Gradient Magnetic Field Mechanisms and Safety

The static magnetic field (B_0) is fundamental to MRI signal generation because it aligns nuclear spins and determines their precessional frequency according to the Larmor relationship ($\omega = \gamma B_0$). Its magnitude and homogeneity directly influence signal-to-noise ratio, image uniformity, tissue contrast and susceptibility artefacts. However, spatial variations in B_0 generate translational forces and torque on ferromagnetic objects. These forces are strongest near the bore entrance and may create projectile hazards, requiring strict access control and comprehensive patient and equipment screening [1].

Higher static-field strengths may also produce physiological and implant-related effects. Dizziness and nausea are reported more frequently at 7 T and are associated with Lorentz forces acting on ionic currents in the inner ear [4]. Mechanical forces on implants also increase with field strength and spatial gradients. Although low-field systems may reduce some mechanical effects, uncertainty remains when devices are scanned outside their labelled conditions [8], [23], [24]. Evidence involving cochlear implants further shows that older axial magnet designs are more susceptible to displacement, whereas newer diametric magnet configurations provide greater mechanical stability [7], [40]. These findings consistently show that B_0 contributes to both MRI signal formation and mechanical safety risk.

Gradient magnetic fields provide spatial encoding but introduce physiological and acoustic effects because of rapid field switching. According to Faraday's law ($\nabla \times E = -\frac{\partial B}{\partial t}$), changing magnetic fields induce electric fields within biological tissue. The induced field depends on gradient amplitude, slew rate, coil design, patient anatomy and positioning. High slew rates may stimulate peripheral nerves, particularly in high-performance 3 T and 7 T systems [1], [25], [26]. Computational studies similarly show that gradient configuration and patient geometry influence individual sensitivity to peripheral nerve stimulation and cardiac magnetostimulation [6], [25], [26].

Rapid gradient switching also produces acoustic noise through Lorentz forces acting on gradient-coil structures. Sound-pressure levels of approximately 110 to 130 dB have been reported during certain imaging sequences, requiring appropriate hearing protection [21], [27]. Acoustic exposure may be greater at 7 T because of stronger gradients and scanner resonance effects [17]. However, multi-coil gradient arrays have reduced induced electric fields by up to 61%, thereby increasing predicted peripheral nerve stimulation thresholds [6], [26]. Improved gradient-coil construction, mechanical coupling, and RF-shield design have also reduced acoustic noise while preserving imaging performance [27]. These findings show that higher gradient performance must be balanced against physiological stimulation and auditory exposure.

4.2 Radiofrequency Fields, Tissue Heating, Implant Interaction and System Design

Radiofrequency fields (B_1) are required for spin excitation and signal detection but represent the principal source of thermal risk in MRI. The transmitted B_1^+ field determines flip-angle accuracy, excitation uniformity and image contrast. As field strength increases, RF wavelengths become shorter within tissue, producing more complex field distributions. At 3 T and above, standing wave and interference effects may cause non-uniform excitation and localised RF hotspots [2], [34], [35].

RF absorption is commonly assessed using the specific absorption rate. SAR depends on B_1^+ amplitude, duty cycle, tissue conductivity, patient anatomy, operating frequency and RF coil configuration [28], [32], [38]. Non-uniform electric fields may produce localised heating in regions such as the shoulders and joints [2], [28]. Differences in tissue conductivity, permittivity, anatomy and positioning also contribute to patient-specific variations in RF exposure. Conductive implants may act as antennas and concentrate RF energy near lead tips or metallic structures. This effect has been reported for cardiac leads, deep brain stimulation systems, orthopaedic screws, titanium meshes and other active or passive implants [3], [28], [29], [30], [32], [36], [38], [39].

Implant heating varies with scanner field strength, bore configuration, implant length, lead trajectory, material, surrounding anatomy and RF coil design [29], [32], [36], [37], [38]. At 7 T, shorter wavelengths and complex interference patterns further complicate heating prediction and control [17], [34], [37]. Active hearing implants, titanium meshes and DBS systems may also respond differently depending on their design and placement [37], [40].

The evidence presents contrasting findings regarding low-field MRI. A vertical 1.2 T open-bore scanner produced substantially less DBS-lead heating than a conventional 1.5 T horizontal system, indicating that scanner geometry and electric-field orientation can reduce RF exposure [29]. In contrast, complete DBS configurations produced comparable or greater heating at 0.55 T than at 1.5 T under certain conditions [36]. These findings show that lower B_0 does not automatically provide lower RF-heating risk. Implant safety must instead be evaluated using the complete scanner, coil, implant and patient configuration.

Despite these risks, MRI may be performed safely in selected implant populations under controlled conditions. Experimental studies reported acceptable outcomes for specific DBS and retained-lead configurations when RF exposure and acquisition conditions were restricted [14], [30]. Clinical studies and systematic evidence also support MRI access for selected patients with cardiac implantable electronic devices or abandoned leads when appropriate device programming, monitoring and institutional protocols are applied [16], [19], [31]. Nevertheless, gradient-induced voltages may interfere with cardiac devices when MRI-appropriate operating modes are not correctly implemented [13], [30], [31].

MRI system design is therefore central to electromagnetic risk control. Active and passive shimming improve B_0 homogeneity, although susceptibility effects make field uniformity more difficult to maintain at 7 T [4]. Gradient-coil optimisation, distributed current elements and anatomically informed modelling can reduce induced electric fields while preserving gradient performance [6], [25], [26]. Acoustic noise may also be limited through structural damping, coil construction, scanner geometry and RF-shield modification [27].

RF safety may be improved through parallel transmission, low-heating B_1^+ mapping, implant-conditioned RF coils, sensor-based exposure assessment and direct measurement of implant-induced RF currents [28], [33], [35], [39]. Multi-row transmits arrays and DBS-specific RF systems have demonstrated improved SAR efficiency and substantial reductions in implant heating [34], [35]. These approaches support patient-specific and device-specific RF control rather than reliance only on global scanner-reported SAR.

Low-field MRI offers longer RF wavelengths, reduced susceptibility effects, lower infrastructure requirements, improved accessibility and potentially lower mechanical forces on implants [8], [23], [24]. However, reduced signal-to-noise ratio, longer acquisition times, reconstruction demands and persistent implant-heating risks remain important limitations [23], [24], [29], [36]. MRI performance is also increasingly extended through artificial intelligence-assisted image interpretation. Automated brain tumour detection demonstrates the wider diagnostic value of MRI data [22], although such applications remain dependent on sufficient image quality, signal stability, electromagnetic-field control and patient safety.

4.3 Clinical Safety Management and Integrated Implications

MRI safety depends not only on electromagnetic-field behaviour but also on clinical workflow, staff competency, communication and institutional governance. Projectile accidents, RF burns and peripheral nerve stimulation arise from predictable electromagnetic interactions and may be reduced through effective screening, protocol selection, monitoring and supervision [1]. However, substantial underreporting of MRI incidents limits institutional learning and the development of preventive measures [9]. Organisational studies emphasise structured training, teamwork, communication and clearly defined responsibilities [11], [18]. Formal safety programmes, controlled access zones, updated guidelines and consensus recommendations support consistent patient screening, implant assessment, device management, monitoring and incident response [10], [12], [15], [19]. However, administrative barriers and inconsistent institutional policies may continue to restrict MRI access for patients with implanted devices, even when scanning is supported under controlled conditions [20].

Overall, the reviewed evidence consistently shows that static, gradient and RF fields have both functional and safety-related effects. Static fields enable nuclear alignment but introduce projectile, vestibular and implant-displacement risks [1], [4], [7], [8], [40]. Gradient fields provide spatial encoding but may cause peripheral nerve stimulation, cardiac magnetostimulation and acoustic exposure [1], [6], [17], [21], [25], [26], [27]. RF fields determine excitation and image contrast but remain the main source of tissue heating and implant-related thermal risk [2], [3], [4], [14], [28], [32], [33], [34], [35], [36], [37], [38], [39]. Implant-related risk therefore depends on device design, material, lead trajectory, scanner architecture, field strength, patient anatomy and operating mode rather than device classification alone [3], [7], [13], [14], [16], [19], [29], [30], [31], [40]. The contrasting low-field findings further confirm that reduced field strength does not consistently eliminate RF heating [23], [24], [29], [36]. Safe MRI practice consequently requires the integration of electromagnetic-field principles, evidence-based system design, patient-specific implant assessment, controlled operating conditions, trained personnel and effective institutional safety governance [9], [10], [11], [12], [15], [18], [20].

5.0 Conclusion

This review demonstrates that electromagnetic field behaviour is fundamental to both MRI performance and clinical safety. Static magnetic fields support nuclear alignment and signal formation but may generate projectile hazards, vestibular symptoms, and implant displacement. Gradient magnetic fields enable spatial encoding. However, rapid switching can induce peripheral nerve stimulation, cardiac magnetostimulation, and acoustic noise exposure. RF fields determine excitation efficiency and image contrast but remain the main source of tissue heating and implant-related thermal risk. The reviewed evidence also shows that MRI safety cannot be determined solely by magnetic field strength or device classification. Instead, risk is influenced by the interaction of multiple factors, including scanner geometry, RF coil configuration, implant design, lead trajectory, patient anatomy, and operating conditions. In particular, contrasting findings from low-field MRI systems demonstrate that reduced magnetic field strength does not necessarily correspond to lower RF heating risk. Although advances in gradient design, RF transmission, implant-specific coils, exposure monitoring, and safety protocols have substantially improved risk management, much of the available evidence remains derived from simulations, phantom experiments, ex vivo investigations, or relatively limited clinical populations. Overall, this review integrates evidence from engineering, biological, clinical, and organisational perspectives to provide a comprehensive understanding of how electromagnetic field mechanisms influence MRI performance and safety. These findings emphasise that safe MRI practice requires the integration of electromagnetic field principles, evidence-based system design, patient-specific implant assessment, competent personnel, and robust institutional safety governance. Future research should prioritise large-scale clinical validation across diverse scanner platforms and implant technologies while advancing real-time exposure monitoring, personalised risk assessment, and adaptive electromagnetic-field control to support safer and more effective MRI practice.

Acknowledgement

The authors gratefully acknowledge the Department of Electrical Engineering, Politeknik Sultan Salahuddin Abdul Aziz Shah, for its facilities, technical support, and valuable guidance throughout this study.

Author Contributions

Wong Guan Chengg: Conceptualisation, Methodology, Investigation, Formal Analysis, Writing – Original Draft, Writing – Review & Editing; **Siti Sabariah Salihin**: Supervision, Validation, Resources, Writing – Review & Editing; **Rasha Ragheb Atallah**: Writing – Review & Editing; **Che Zawiyah Che Hasan**: Writing – Review & Editing; **Ibraheem Shayea**: Writing – Review & Editing.

Conflicts of Interest

The manuscript has not been published elsewhere and is not under consideration by any other journal. All authors have reviewed and approved the manuscript, consent to its submission, and declare that there are no conflicts of interest.

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