REVIEW ARTICLE

Small Magnets, Big Future: Low-Field MRI Technology and Clinical Utility

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Abstract

Purpose: Despite the clinical advances made in magnetic resonance imaging with high static magnetic fields (1.5T and more), open MRI with low field (0.2-0.5T) has recently attracted the attention of researchers.

Low-field MRI (LF-MRI) has both advantages and disadvantages over high-field units. It enables the scanning of anxious patients and children who cannot tolerate enclosed high-field scanners due to discomfort. The open configuration of the LF-MRI provides a spacious examination environment. It also allows the safe imaging of metallic devices owing to the lower static field and radiofrequency. While image quality is degraded compared to high-field MRI due to a lower signal-to-noise ratio, technological advances may help address this limitation.

This review aims to provide a comprehensive outline of the current applications, technical aspects, and evidence supporting the diagnostic accuracy of Low-Field MRI.

Materials and Methods: A literature search was conducted in Google Scholar and PubMed from 2021 to the oresent using the search term "low field MRI" limited to the title. Studies were excluded if only on high-field MRI, not in English, or conference abstracts without full text. After applying exclusion criteria, 32 relevant articles remained for analysis.

Results: The results showed that portable low-field MRI expanded the availability of MRI beyond fixed facilities. One study found that 0.55T MRI had an accuracy similar to 1.5T for microbleed detection, suggesting its potential as an efficient alternative for stroke diagnosis. The literature has demonstrated the utility of low-field MRI in applications such as musculoskeletal, breast, and abdominal imaging.

Conclusion: In conclusion, these studies demonstrated the potential of low-field MRI as a cost-efficient alternative to high-field MRI for several clinical applications. The reduced costs and accessibility afforded by low-field designs have positioned this technology to increase diagnostic MRI access globally. However, further validation of diagnostic performance and cost-utility analyses accounting for accuracy are still needed.

Keywords: Low Field Magnetic Resonance Imaging; Magnetic Resonance Imaging; Portable Magnetic Resonance Imaging; Image Quality; Artificial Intelligence.

DOI:

1. Introduction

Magnetic Resonance Imaging (MRI) is a pivotal medical imaging technique that utilizes Nuclear Magnetic Resonance (NMR) to generate detailed anatomical and functional images of the human body. Unlike X-rays, MRI does not require ionizing radiation. This imaging method employs a robust static magnetic field, pulsed Radiofrequency (RF) fields, and applied magnetic field gradients to spatially encode hydrogen proton signals from tissue water molecules [1, 2].

Despite their exceptional capabilities, certain challenges currently impede the broader utilization of MRI in medical diagnostics. Substantial capital and operating costs associated with superconducting magnets, RF hardware, and gradient systems have historically constrained MRI accessibility (Arnold, T. C., *et al.*, 2023). Additionally, the prolonged scan times required for imaging the complete anatomy can present limitations (Hong, C. S., *et al.*, 2023). Patients may also experience claustrophobia in enclosed scanners (Hudson, D. M., *et al.*, 2022) or encounter incompatibility issues if they have implanted metallic devices such as pacemakers, given the powerful magnetic fields of MRI (Khodarahmi *et al.*, 2022), or for individuals with certain metal implants that may be affected by the magnetic/RF fields, leading to heating or acceleration (Espiritu *et al.*, 2023). Moreover, motion artifacts stemming from physiological processes such as breathing or patient movement during scans, can further compromise the image quality (Al-masni *et al.*, 2023). However, MRI remains an indispensable medical imaging modality that has revolutionized the noninvasive assessment of soft tissue morphology and physiology [3, 4].

MRI scanners are categorized based on their magnetic field strength. Those below 0.5T are considered low-field, those ranging from 0.5-1.0T are medium-field, and those exceeding 1.0T are high-field [5]. Clinical MRI scanners conventionally operate at high static magnetic field strengths of 1.5 Tesla (T) or above [6]. However, lower-field open MRI systems with strengths between 0.2-0.5T have also been developed to address specific needs. Low-field MRI (LF-MRI) systems have several advantages over high-field units. Although image quality tends to be compromised compared to high-field MRI due to a lower signal-to-noise ratio, technological advances, such as the introduction of phased array receiver coils and parallel imaging reconstruction algorithms, have mitigated this limitation (Khodarahmi *et al.*, 2023; Lyu *et al.*, 2023) and have allowed clinically functional diagnostic imaging to be performed at field strengths as low as 0.2T [7]. In addition, LF-MRI, with its reduced susceptibility artifact, is particularly favorable for imaging certain anatomical regions such as the heart or abdomen.

Considering the evolving landscape of low-field MR systems, this paper aims to provide a comprehensive overview of the current applications, technical aspects, and evidence supporting the diagnostic accuracy of LF-MRI in several medical applications. A survey on the literature regarding LF-MRI performance across different body regions and pathologies is then presented. Additionally, the intersection of Artificial Intelligence (AI) methods to enhance low-field MR image quality has been explored. The review concludes by discussing open issues and future perspectives regarding clinical translation, and the broader adoption of low-field MRI in modern medical practice.

2. Materials and Methods

This review was performed according to PRISMA-ScR guidelines.

2.1. Search Strategy

A strategy of search of major indexing databases, including PubMed, Scopus, Embase, ISI Web of Science, and Cochrane Central, using different combinations of keywords “Low Field MRI” AND “Challenges and Applications” AND “Image Quality” AND “Artificial Intelligence” conducted to identify relevant studies published on low-field MRI from 2021 up to October 2023. Articles that were not relevant to low-field MRI were excluded from the study. Abstracts were screened for relevance to the clinical applications and outcomes of low-field MRI.

2.2. Inclusion and Exclusion Criteria

Title and abstract screening of the initially selected studies for inclusion or exclusion criteria was performed independently by the reviewers. Any disagreement between the two reviewers was resolved by either discussion or with the help of a third reviewer. Only original articles were eligible if they provided all of the following characteristics: relevance

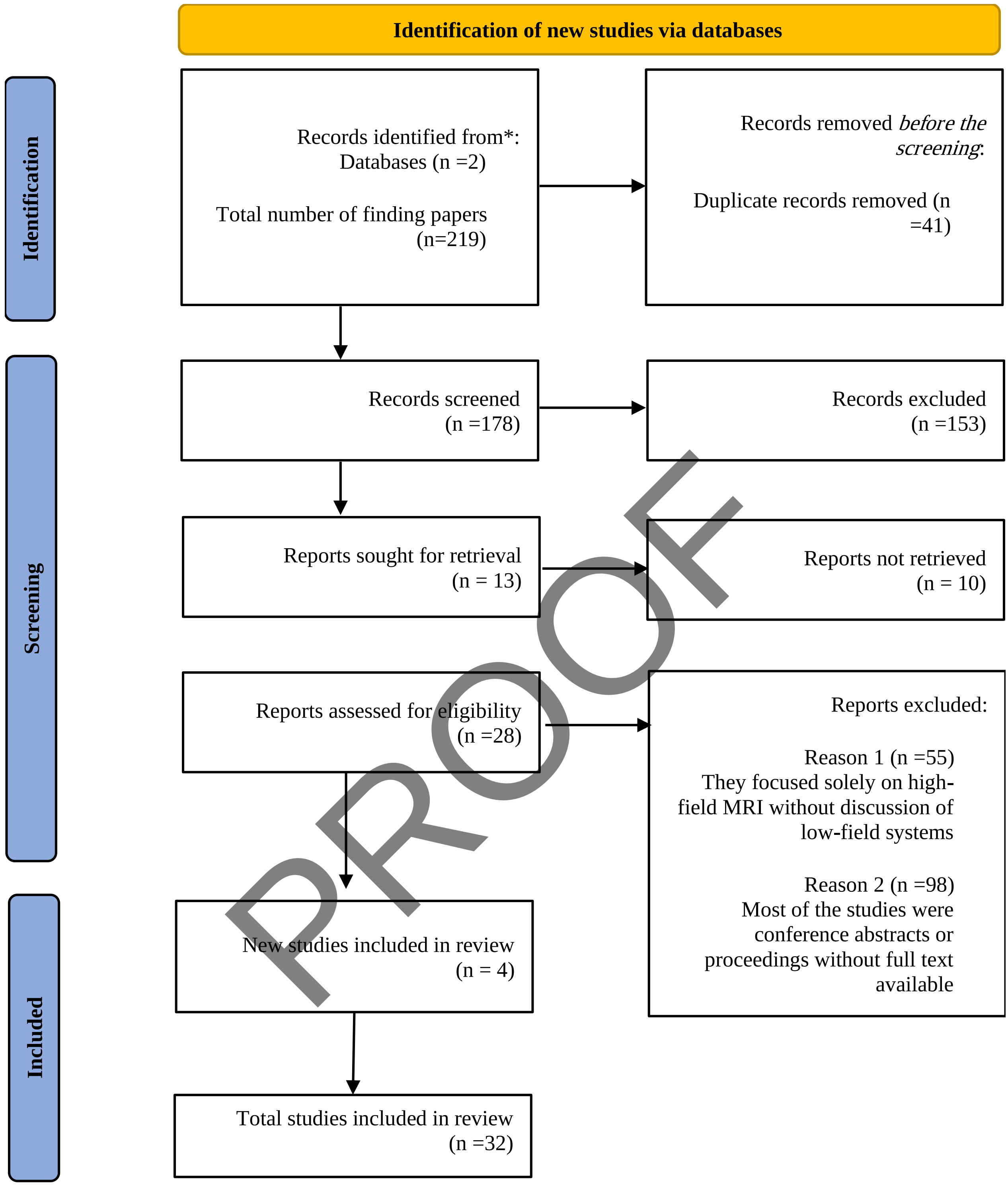

Figure 1. Displays a Prisma flow chart delineating the process of identifying and screening studies for the present research

to the topic of low-field MRI technological advances, techniques, clinical applications, and comparisons to high-field strength MRI. Studies were excluded if they focused solely on high-field MRI without discussion of low-field systems; were not published in English; or were conference abstracts or proceedings without full text available, narrative, or systematic reviews, letters to editorials, and guidelines.

2.3. Summary of Findings

This review synthesizes the current literature published in the past two years on the emerging role and capabilities of low-field-strength MRI systems.

After searching, 219 records were recognized; 178 records remained after removing duplicate records. Titles and abstracts were screened for the inclusion and exclusion criteria. Finally, 32 relevant studies were fully reviewed, based on the reasons shown in Figure 2, and included in the analysis.

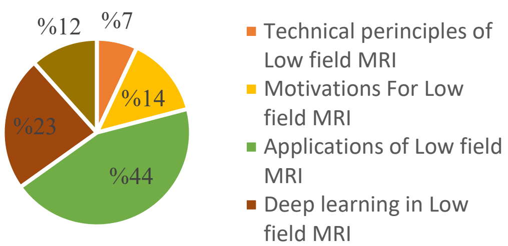

Figure 2. Distribution of the Reviewed Articles by Outlines Considered in this Review

3. Results

3.1. Technical Principles of Low-Field MRI: Magnet Design, RF Coils, and Gradient Systems

Low-field MRI operates on the same fundamental principles as conventional high-field MRI but with several key technical differences driven by the use of lower magnetic field strengths, typically below 0.5 Tesla. The lower magnetic field strengths used in low-field MRI result in a reduced nuclear spin polarization and correspondingly lower Signal-to-Noise Ratio (SNR) compared to high-field systems. This inherently limits the achievable image resolution and scan times. However, advantages like reduced magnetic field inhomogeneities can partially offset SNR limitations. Specialized gradient and Radiofrequency (RF) coil designs are tailored to the unique challenges of low magnetic fields (Figure 3). Gradient coils must be optimized for high efficiency/slew rates to compensate for SNR limitations. RF coils require larger dimensions and unique geometries to achieve uniform spin excitation across the imaging volume. MRI was originally developed in the late 1970s using low-field systems of approximately 0.05T. Commercial scanners in the 1980s used 0.5T magnets maximum. The 1.5T scanner, introduced in 1983, has become the standard, dominating high-field MRI. Early technical limitations and safety concerns led to low initial field strengths. The low-field declined in the 1990s as 1.5T SNR could not be matched. Recent advances in parallel imaging, compressed sensing, hardware, and Artificial Intelligence (AI) have enabled improving low-field image quality. Parallel imaging uses phased-array coils and fewer phase-encoding steps to reduce the scan time and improve image quality [8]. This technical improvement has driven renewed interest in clinical low-field MRI around 0.5T and point-of-care ultralow-field MRI at 0.05T, as closed magnets, emerging applications, and expanded access are

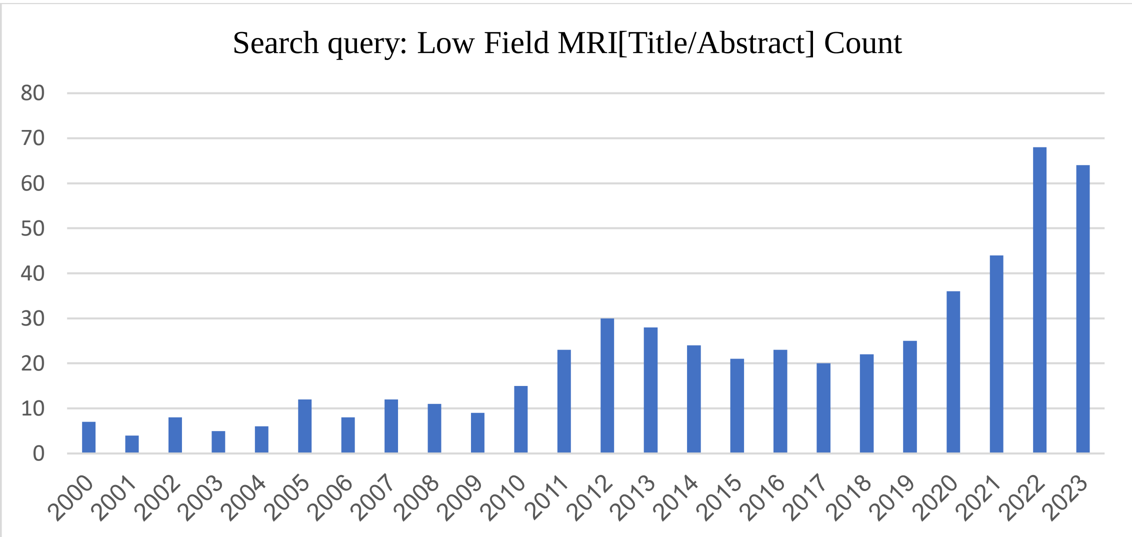

Figure 3. Number of published articles in recent years in the PubMed database about low-field MRI

motivating factors for the low-field revival [9]. Different field strengths now offer varied trade-offs and opportunities for imaging, requiring appropriate hardware optimized for the application, as a low field aims to provide diagnostic image quality without compromising exam time or accessibility.

The main components of an MRI scanner require specialized low-field designs. High-field uses superconducting magnets above 1.5 T, while low-field uses resistive electromagnets or permanent magnets below 0.5T. Permanent magnets are lightweight, but unstable over time. Resistive magnets provide better stability but use more power. RF coils operate at lower 1-10 MHz Larmor frequencies for hydrogen imaging. Large-volume coils provide a uniform excitation. Phased array coils boost the inherently low SNR through parallel reception. Gradient coils also require optimization with shorter and smaller windings for relaxed slew rates and fields, allowing lower inductance and faster switching [5].

Taken together, the scaled simplifications in the magnet, RF transmit/receive, and gradient hardware allow low-field MRI systems to achieve adequate image quality and utility for numerous clinical applications, despite compromises in intrinsic resolution and SNR relative to high-field platforms.

3.2. Motivations for Low-Field MRI Systems

Several compelling factors motivate the development and adoption of low-field MRI technology as an alternative to conventional high-field systems. Firstly, the reduced magnetic field strengths used, typically under 0.5 Tesla, dramatically lower the shielding requirements for the scanner room. Unlike high-field scanners that necessitate specialized radiofrequency shielding and controlled access zones, low-field systems can potentially be sited within standard residential buildings using limited magnetic shielding. This bypasses the need for costly construction of dedicated radiofrequency-shielded rooms, significantly reducing capital expenditures.

Secondly, low-field MRI scanners benefit from substantially reduced hardware costs compared to superconducting high-field magnets. Avoiding liquid helium and elaborate cryogenic support infrastructure enables streamlined system design and lower manufacturing/operating expenses. Permanent magnets or compact resistive electromagnets can provide the magnetic fields required. These inherent cost advantages enhance the economic viability and affordability of MRI, particularly for population health screening and lower-resource clinical settings.

A third driver is the potential for improved patient accessibility and experience. Eliminating the narrow bore tunnel geometry of high-field systems mitigates patient anxiety and claustrophobia. Open, more spacious magnet designs enable greater flexibility in patient positioning, such as weight-bearing upright or seated postures valuable for visualizing biomechanical impact on joints/spine. Reduced acoustic noise from imaging gradients also enhances comfort.

Safety represents another motivation, as low magnetic fields minimize projectile risks and permit safer scanning of patients with certain metallic implants contraindicated on high-field systems. The potential for decreased gadolinium contrast requirements could also reduce toxicity risks.

Finally, from a technical perspective, low magnetic field strengths can offer advantages in terms of reduced magnetic field inhomogeneities, chemical shift artifacts, and bulk susceptibility distortions. While trading off signal-to-noise, these effects simplify certain image reconstruction challenges compared to high-field counterparts (Cooley *et al.*, 2021, Anoardo & Rodriguez, 2023, Sarracanie & Salameh, 2020, Lau *et al.*, 2023).

3.2.1. Cost and Accessibility

One of the major motivations for the development of low-field MRI technology is the significant reduction in capital and operational costs compared to high-field systems [10]. The purchase price, installation expenses, site planning costs, and ongoing utility and maintenance fees associated with low-field MRIs are considerably lower compared to high-field ones. This increased accessibility supports the widespread dissemination of MRI, particularly in resource-constrained settings such as rural primary care facilities or hospitals in developing nations. Such locales have traditionally lacked MRI due to the prohibitively high costs of high-field scanners [11].

MRI systems provide substantial cost-benefits for community hospital adoption of this medical imaging technology [12]. Additionally, resistive electromagnets consume approximately 10 times less energy for magnetic field generation and cooling requirements than high-field systems employing liquid helium-based superconducting magnets. Likewise, maintenance contracts are cheaper given the absence of infrequent, yet expensive helium replenishment needs for permanent magnet technologies [13].

One of the reviewed papers **(**Chetcuti *et al.*, 2022**)** has described the implementation of a low-field portable MRI scanner at the Queen Elizabeth Central Hospital in Blantyre, Malawi. This record mentioned several encountered challenges, including logistics of transporting, and receiving the equipment, planning for equipment movement given terrain constraints, ensuring appropriate storage and operating conditions, training non-radiographer operators, and addressing utility issues. Solutions involved thorough pre-planning, flexibility, improvisation, and close manufacturer support. The scanner has been used to scan over 260 patients in its first year, facilitating diagnosis and management for both clinical care and research. The lessons learned can aid other resource-limited settings in implementing this technology, which has the potential to transform neuroimaging access and patient care.

3.2.2. Scanning the Subjects in Different Body Postures

Beyond the supine orientation ordinarily afforded by stationary high-field MRI systems, an advantage realized through open low-field architectures is the capability for scanning subjects beyond horizontal postures [14]. Indeed, several mobile MRI platforms have been specifically engineered to image patients in an upright, weight-bearing posture [15].

3.2.3. MR Imaging Procedure Safety

Low-field MRI provides several safety benefits over high-field systems, including reduced risks of RF-induced heating due to more uniform energy deposition across tissues and diminished interactions between the magnetic field and metallic objects, which lower the risk of accidents [16]. Many low-field designs also employ resistive magnets instead of superconducting coils, minimizing indirect patient heating from refrigeration requirements needed to maintain superconductivity. With lower static field intensities, RF power levels, and gradient switching speeds, low-field MRI reduces the RF and gradient heating of patients compared to high-field architectures, enhancing patient comfort and safety [17].

3.2.4. Low-Field MR Noise and Image Quality

Fewer implant-related artifacts are another advantage of low-field MRI systems. Breitet *et al.* [18] conducted a phantom study and visually and quantitatively evaluated susceptibility artifacts related to hip replacements at 0.55 T compared with 1.5 T and 3 T. Their results revealed that the lowest titanium artifacts occurred at 0.55 T while qualities were comparable to optimized 1.5 T and exceeded 3 T values. There is strong reliability between qualitative reader assessments and quantitative analyses. The unoptimized 0.55 T sequences and the phantom design limited the comparisons.

3.3. Applications of Low-Field MRI in the Literature

According to the findings of reviewed records, the application of low-field MRI has been demonstrated for scanning the lung, brain, spine, extremities, and different body areas, as well as guiding interventional procedures [19].

3.3.1. Low-Field MRI for Intervention

One clinical application related to the increased accessibility of low-field scanners is to guide interventions while the subject is within the scanner. In addition, a lower magnetic field typically results in lower fringe fields and less acoustic noise, both of which are advantageous when performing an intervention [20]. The synergy of accessible magnet apertures, reduction in electromagnetic and acoustic interference phenomena, and dynamic physiological road mapping favors low-field modalities for image-guided therapy. On-table navigation preserves spatiotemporal metrics that are useful for ensuring procedural safety and real-time effectiveness assessments that cannot be replicated through other guidance modalities. While X-ray fluoroscopy has limitations such as high radiation exposure for interventional cardiology [21], early investigations showed that catheters and wires could be safely used for interventions with low-field 0.55T MRI [22]. Therefore, diagnostic catheterizations are now routinely performed at some centers using a 0.55 T scanner, although additional development of pulse sequences, hardware compatibility, and software are required to fully enable clinical interventional procedures [23].

3.3.2. Low-Field MRI for Prostate Biopsy

Recently, low-field magnetic resonance imaging has been implemented to facilitate prostate biopsy procedures and enhance diagnostic precision by directing sampling toward prostatic regions exhibiting radiologically suspicious morphologic or functional characteristics on magnetic resonance images.

For example, a technical report by Satya *et al.* [24], evaluated a targeted prostate biopsy workflow using a low-field Promaxo MRI system. Patients first underwent multiparametric MRI on a 3T scanner where lesions were delineated. During the procedure in the open-bore Promaxo MRI, the urologist registers 3T images to target biopsies transperineally guided by the delineated lesions. On average, three targeted cores were obtained. This office-based low-field approach streamlines biopsies that are traditionally performed in specialized facilities. Benefits include reduced registration error through MR fusion, lower infection risk with the transperineal technique, and enhanced comfort with the open design. Preliminary results suggest that it improves biopsy accessibility, precision, and tolerability in clinical settings compared with standard techniques. However, further validation is needed to fully evaluate this targeted biopsy method using a low-field MRI system as an alternative to conventional blind biopsy protocols. A study by Sze *et al.* [25] evaluated the use of a portable low-field MRI to guide prostate biopsies, comparing it to standard ultrasound-guided biopsies in 39 men, finding that MRI-guided biopsies detected clinically significant prostate cancer in over half of cases compared to 42.5% for standard biopsies, and provided higher diagnosis upgrades in one-third versus 15% of cases; however, more research is needed, and the initial results demonstrate the feasibility of portable low-field MRI-guided biopsies and potential benefits for high BMI patients and cancers in harder to reach prostate areas.

3.3.3. Low-Field MRI for Ischemic Stroke Evaluation

Ischemic and hemorrhagic strokes require rapid differentiation to guide the subsequent treatment. Towards this end, low-field portable MRI shows potential as a point-of-care modality for stroke assessment [26]. Although CT remains competitive through its perfusion capabilities and contrast utilization, low-field MRI offers a non-ionizing alternative [27]. Specifically, the differentiation of stroke subtypes and lesion localization can often be achieved from anatomical images alone, eliminating the need for exceptional resolution provided by high-field systems [28]. Continued innovation may further support the role of low-field MRI in emergency settings. Decreasing weight and cost through innovative designs, such as Halbach arrays, could enhance deployment [29]. The open-sourcing of hardware specifications and software can galvanize a user community to accelerate such advances. Collectively, such progress positions portable low-field MRI to increasingly supplement high-field capacities, finding utility where rapid determinations are particularly time-sensitive [30].

3.3.4. Low-Field MRI for Lung Imaging

A prospective study conducted by Campbell-Washburn *et al.* [31] involved 24 patients with an average age of 59 years who underwent respiratory-triggered T2-weighted turbo spin-echo MRI at 0.55T. All patients underwent clinical CT scans. Low-field MR and CT results were compared based on their ability to detect common lung abnormalities. MRI was able to robustly detect abnormalities such as bronchiectasis, consolidative opacities, cavitary lesions, effusion, and mucus plugs, with substantial agreement with CT. The Diffuse diseases, such as ground-glass opacities and tree-in-bud nodules, were more difficult to discern on MRI. Lesion sizes measured independently on CT and MRI showed a strong correlation for nodules between 5 mm and 23 mm. This initial study indicates a high-performance of 0.55T MRI in the evaluation of common lung diseases.

Additionally, a clinical study by Hinsen *et al.* [32] evaluated the diagnostic performance of low-field MRI for pulmonary nodule detection and size assessment in 46 patients with known lung nodules who underwent same-day 0.55T MRI and multidetector CT. A blinded analysis of 964 nodules was conducted to compare nodule detection accuracy and mean diameter measurements between modalities, with CT as the reference standard. Statistical analysis showed that although modern low-field MRI demonstrates excellent precision in identifying lung nodules ≥6 mm and close alignment with CT for sizing nodules, it is not as capable as CT for detecting smaller nodules within the lungs.

3.3.5. Low-Field MRI for COVID-19

Heiss *et al.* [33] used a low-field MRI platform optimized for lung imaging and applied phase-resolved functional lung modeling to generate perfusion, ventilation, and flow maps from free-breathing scans in post-COVID patients. Machine learning identified that combining measurements of perfusion and flow correlation defect burden was a sensitive biomarker for detecting lingering respiratory symptoms and discriminating clinical status with over 70% accuracy, where individual parameters did not differ significantly. These findings suggest that quantitative low-field pulmonary MRI can discern functional deficits associated with post-viral pathology by assessing disrupted lung perfusion-ventilation interactions, demonstrating the potential for noninvasively stratifying post-COVID patients according to physiological impairment.

3.3.6. Low-Field MR Imaging for Knee

A study by Schmidt *et al.* [34] compared the quality of knee MR images of 20 volunteers, acquired using a 0.55T low-field MR system with a deep learning reconstruction option and a standard 1.5T MRI. The overall image quality at 0.55T was rated lower than that at 1.5T, with more noise, but the quality was still diagnostic. T1-weighted images showed no significant difference between 0.55T and 1.5T. The detection of meniscal and cartilage abnormalities was comparable between the two field strengths. The contrast ratios of the tissues were not significantly different between groups. While the 1.5T MR system performed better overall, the 0.55T MR system with deep learning provided diagnostic knee MRI comparable to 1.5T for basic pathologies, though with more visible noise.

3.3.7. Low-Field MR Imaging for Neonatal Studies

A study by Thiim *et al.* [35] highlighted the promising applicability of the recent lower-field MR system, Embrace 1T, as a neonatal scanner. The study revealed that this system yields an image quality comparable to that of older 1T systems. that an image quality comparable to that of the older 1T systems. While lower-field MRI has limitations in advanced imaging capabilities, the increased accessibility of this new system enables the scanning of vulnerable infants who previously had poor access. The new system allows for easier installation directly within Neonatal Intensive Care Units (NICUs), and such systems may become the primary neuroimaging modality in NICUs, although large validation studies are still needed.

Further engineering advances in ultra-low-field, portable MRI may eventually enable bedside, point-of-care neuroimaging. Overall, progress in lower-field MRI technology could significantly increase access to important neuroimaging data in critically ill newborns.

Cho *et al.* [36] assessed the safety and feasibility of point-of-care magnetic resonance imaging (POC MRI) to evaluate Acute Brain Injuries (ABI) in three adult patients receiving Extracorporeal Membrane Oxygenation (ECMO) support. These findings indicate that low-field POC MRI examinations of the brain can be conducted without any serious adverse events, demonstrating the safety and feasibility of this approach. Additionally, the results revealed that POC MRI can uncover previously undetected acute strokes, highlighting their ability to identify ABIs.

An alternative prospective study conducted by Maura *et al.* [37] assessed the use of a portable, low-field MRI system in a neonatal ICU, performing 18 exams on 14 neonates averaging 29.7 days of age with life support equipment still attached, finding 94% of exams were completed without significant artifacts. While intracranial pathology was visible, subtle abnormalities were sometimes missed compared to standard MRI, although exam reads were concordant in 59% of cases and missed significant pathology in 12%.

Another study by Murali *et al.* [38] indicated that the on-site scanner simplified workflow and reduced stress for infants, parents, and clinicians compared to transport-based MRIs. Image quality was sufficient for diagnostic needs in this vulnerable population, although it was lower than that of the conventional systems. In-NICU MRI demonstrated clinical utility and safety, indicating its potential for improving care, outcomes, and research in critically ill newborns.

3.3.8. Low-Field Portable MRI Systems for Neuroimaging

Portable MRI (pMRI) uses a low magnetic field strength that allows it to be transported to the patient's bedside, thereby addressing the risks of transporting critically ill patients to conventional MRI suites [39]. Several studies have demonstrated pMRI's ability to safely detect critical neuropathologists in the ICU, emergency department, and operating room settings, although it has a lower image quality than conventional high-field MRI [40]. pMRI holds promise for enhancing neuroimaging accessibility in underserved populations that lack conventional MRI access. It has the potential to revolutionize acute neurological care by enabling swift diagnosis and intervention in time-sensitive scenarios, such as mobile stroke units, sports arenas, and combat zones, provided they are equipped with pMRI capabilities. Leveraging machine learning approaches can further optimize low-field image analysis, particularly as pMRI training expands, thereby maximizing its value in resource-limited acute settings [41].

Sabir *et al.* [42] illustrated the feasibility and safety of employing portable bedside MRI to image the brains of critically ill pediatric patients undergoing Extracorporeal Life Support (ECLS). They conducted pMRI scans on four children with jugular ECLS cannulation and achieved successful outcomes without any adverse events. Diagnostic brain images were obtained within six minutes. This is the first documentation of pMRI application in pediatric ECLS patients with jugular cannulation, indicating that pMRI can provide bedside neuroimaging when conventional MRI is impractical. Despite its lower image quality, pMRI may serve as a valuable tool for informing time-critical neuroprotective decisions in unstable children, necessitating urgent neuroimaging, particularly in situations where transportation poses an elevated risk.

3.3.9. Low-Field MR Imaging for Temporomandibular Joint Disorders (TMDs)

Kopp *et al.* [43] conducted a comparative analysis of image quality between a 0.55T and a 1.5T MRI for assessing chronic temporomandibular joint disorders in 17 patients. The MRI protocols included Proton Density (PD)-weighted and T2-weighted sequences, involving open-and closed-mouth positions. While the median image quality was lower for the 0.55T MRI, particularly in assessing disc morphology and bone disease, it proved comparable for disc dislocation. Despite maintaining image quality at 92% for the 0.55T MRI compared to 100% for the 1.5T MRI and observing a higher prevalence of minor artifacts, the 0.55T MRI appears to be a feasible option for clinical assessment, as diagnostic confidence was adequately sustained.

3.3.10. Low-Field MR Imaging for Lumbar Spine

This study assessed the potential of a 0.55T low-field MRI system for lumbar spine imaging in comparison to a 1.5T MRI system, with and without the use of additional advanced post-processing techniques. The lumbar spines of the 14 volunteers were imaged on both MRI systems using clinical sequences. Additional sequences with simultaneous multislice acquisition and AI-based post-processing were acquired using the 0.55T system. Image quality was rated on a 5-point Likert scale by three radiologists in terms of signal/contrast, resolution, and assessment of the ability of the spinal canal and neuroforamina. While the image quality was rated lower on the 0.55T system, good overall examination quality was observed. Advanced post-processing techniques may help accelerate acquisition times at 0.55T [44].

3.4. Limitations of Low-Field MRI Compared to High-Field

The magnetic resonance signal originates from the processional magnetic moment of nuclear spins within tissues, which is directly proportional to the magnetic field strength, according to the fundamental principles of nuclear magnetic resonance physics [45]. Therefore, Low-field MRI systems, operating at levels below 0.5T, naturally experience a reduced signal-to-noise ratio compared to optimized high-field architectures exceeding 1.5T. This compels the need for either extended acquisition times or iterative phase encoding steps to obtain an adequate SNR [46]. Consequently, there is a trade-off, sacrificing temporal resolution to achieve diagnostic image quality comparable to state-of-the-art high-field instrumentation [47].

Aggarwal *et al.* (2023) evaluated the repeatability of key image quality metrics, such as SNR, uniformity, and geometric distortion, over multiple days and sessions using a 0.05T MRI scanner. Phantom images were acquired with various pulse sequences over ten days comprising three sessions daily, and image quality metrics along with temperature, humidity, and off-resonance maps were quantified. The results demonstrated high repeatability of SNR measurements and moderate repeatability of uniformity and geometric distortion metrics, indicating the potential for longitudinal low-field studies with controlled hardware and phantoms.

In addition, due to lower SNR at low field and longer acquisition, intrinsic spatial resolution of low-field MRI falls short of high-field. However, technological advances have improved it. Low field may have difficulty detecting focal calcification, iron, or hemorrhage due to proportional susceptibility artifacts. Wide adoption of high-field concentrated advanced capabilities in major hospitals, while low-field remains economical for rural/global areas where high-field is difficult. Potential limitations of contrast agents in low-field include lower baseline SNR enhancing susceptibility effects and artifacts. Susceptibility agents like iron oxides increase field inhomogeneity artifacts already more pronounced at low field. Reducing the effects of gadolinium are also less, requiring higher doses [48].

3.4.1. Reduced Signal-to-Noise Ratio

Low-field MRI suffers inherently from a 4-9 fold lower SNR compared to high-field systems operating between 1.5-3T [8]. This is directly attributable to the proportional relationship between magnetic field strength B0 and the spin polarization energy E following the Boltzmann distribution. At 0.2-0.5T versus 1.5-3T, there is a significant reduction in nuclear spin alignment and transverse magnetization generating the MR signal [1].

While parallel imaging techniques such as SENSE and GRAPPA can partially be compensated by under sampling k-space, it comes at the cost of temporal resolution [5,6]. Moreover, the SNR gap versus high field remains substantial even with such methods, limiting the ability to visualize low-contrast anatomy or pathology [6]. Prolonging scan time can improve SNR but reduces practicality. Hardware advancements in cryogen-free magnets and phased array coils have helped but not fully resolved the SNR constraint.

3.4.2. Degraded Spatial Resolution

The intrinsic spatial resolution of low-field MRI is ultimately constrained by lower SNR compared to optimized high field architectures. For example, clinical whole-body MRI scanners commonly achieve an in-plane resolution of 0.5-1mm at 1.5-3T whereas low-field is typically 1-2mm even with advances [6]. This limitation reduces the ability to visualize small lesions <5mm in size or anatomical intricacies like thin vessels or nerve tissues. While parallel imaging with GRAPPA or compressed sensing partly improves resolution by speeding acquisition, the gap relative to high-field is not fully closed.

3.4.3. Increased Susceptibility to Artifact

Low-field MRI is more prone to field inhomogeneities, chemical shift banding artifacts, and magnetic susceptibility distortions from tissues, implants, or slow-relaxing contrast agents compared to high-field strength scanners. These effects are amplified proportionally at lower B0 and introduce geometric distortion or obscuration of underlying pathology if severe. While parallel imaging and iterative shimming provide partial compensation, complete homogenization over large volumes remains challenging [18].

3.4.4. Sensitivity to Motion Artifact

Physiological motions from cardiac and respiratory cycles induce more corrupting image ghosting and blurring at the low field due to longer acquisition times needed for whole-volume imaging. While navigators and self-gating methods retrospectively correct motion-corrupted k-space segments, some residual ghosting usually persists [18-20]. Moreover, very ill or unstable patients unable to breath-hold pose difficulties for motion correction at the low field but may still be imageable at high-field using ultra-short echo time sequences [3, 4].

3.4.5. Limited Capability for Advanced Applications

Certain specialties pushing the technical and imaging contrast boundaries such as cardiac MRI, perfusion studies, molecular neuroimaging, and quantitative MRI may exceed current low-field technical capabilities and require high-field scanners. For example, late gadolinium enhancement imaging commonly used in cardiology depends on high SNR achievable only above 1.5T for robust extracellular contrast measurement [48]. Emerging applications like vessel wall imaging, microstructural neuroimaging, and even clinical 3T/7T use may continue outpacing low-field technological progress unless more novel hardware or sequence methods catch up.

3.5. Improvements in Low-Field MRI System

Wei *et al.* (2023) designed a lightweight permanent magnet for a low-field movable-head magnetic resonance imaging MRI system. To reduce weight, pole pieces, anti-eddy current plates, and shimming rings were removed and the distance between vertical yokes was shortened. Two side poles were added to the yokes to compensate for field deformation from the shortened yokes. Magnetic field distributions were simulated. Phantom and in vivo head imaging were conducted with a prototype scanner using the proposed 0.19815 T, 46 ppm homogeneous magnet weighing 654 kg. Acceptable images were acquired, showing the design promotes the development of low-field compact MRI systems by significantly reducing magnet weight versus conventional design.

Yushchenko *et al.* [49] developed and tested the first biplanar coil array for quadrature detection in low-field MRI, providing an open-access design well-suited for specialized applications needing subject positioning and access. Simulations showed the orthogonal biplanar coils generate reasonably homogeneous B1 fields over large volumes. Phantom imaging demonstrated the extended field-of-view and SNR improvement from quadrature detection. In vivo, 3D ankle and elbow imaging were achieved in under 10 minutes, enabled by the open access for positioning and the good sensitivity of the array. Although current path optimization can further improve homogeneity, this novel biplanar array extends the potential of low-field MRI for interventions and weight-bearing musculoskeletal studies requiring open-subject access [50].

Further, Shen *et al.* [51] focused on the practical design and realization of gradient coils for a 6.5 mT ultra-low-field MRI (ULF MRI) system. X, Y, and Z gradient coils were designed using the Equivalent Magnetic Dipole Method (EMDM), and the geometric parameters of size, gap, conductor pattern, and density were analyzed to understand their effect on coil performance through Finite-Element-Method (FEM) simulations. By varying the geometric parameters during the EMDM design process and evaluating the coil performance with FEM simulations, an optimal gradient coil system was arrived at. The performance of this optimal gradient coil system designed based on EMDM and geometric parameter analysis was then evaluated experimentally through both FEM simulation and magnetic field measurement.

3.5.1. A practical method for RF pulse distortion compensation using multiple square pulses for low-field MRI

Iglesias *et al.* (2022) proposed a practical method for RF pulse-distortion compensation in low-field MRI. These researchers aimed to compensate for the RF square and sync pulses in low-field MRI, where long coil recovery times can distort the applied pulses. The Q-factor of the RF coil was experimentally calculated from ring-down measurements and was used to determine the duration and amplitude of additional compensating square pulses before and after the intended pulse. For sync pulses, a series of square pulses with varying amplitudes calculated from the Q-factor was applied to approximate the continuously changing sync shape. Echo trains acquired in an inhomogeneous B0 field demonstrated that compensating the pulses successfully applied the intended excitation profiles and significantly improved the echo SNR by 61.1% for square pulses and 51.5% for sync pulses compared with uncompensated pulses, enabled by adding a pre-polarization pulse to the CPMG–Purcell (Meiboom) sequence.

3.6. Integrating Deep Learning and Machine learning approaches in Low-Field MRI

3.6.1. Denoising, Artifact Reduction, and Domain Adaption in Low-Field MRI

Deep learning has shown promise in medical image processing, including denoising and artifact removal. This is appealing for low-field MRI, which suffers from a low signal-to-noise ratio. Bhat *et al.* Bhat *et al.* (2021) simulated scanner-specific images using gradient/field encoding on public 1.5T/3T images and applied a U-Net to reduce noise and remove artifacts from low inhomogeneous fields, gradients, under-sampling, and reconstruction for a 60-67mT scanner, enhancing image quality in phantoms and subjects.

Conventional quality assurance involves manual inspection by MRI technicians; however, relying on human expertise presents accessibility issues. Jimeno *et al.* (2022) conducted a study to develop a DL-based artifact identification tool ("ArtifactID") to streamline quality control and support technicians directly at the scanner. First, ArtifactID was trained and tested to identify two common artifacts in low-field neuroimaging: wrap-around and Gibbs ringing effects. Binary classification models achieved strong performance with respect to radiologist labels. Visualization techniques additionally enable localization and model interpretability. Overall, the results of the study by Jimeno *et al.* (2022) introduced the first application of DL for low-field artifact identification and demonstrated the potential for optimizing magnetic resonance quality assurance workflows through automated, on-site validation of image quality.

Also, Koonjoo *et al.* (2021) evaluated deep learning reconstruction via AUTOMAP impacts on low-field brain and plant root MRI datasets, finding that training on paired high-quality images provided 1.3-4.5 times higher SNR for brain scans and 2-3 times for roots over traditional FFT (Fast Fourier Transform). AUTOMAP better-suppressed spike artifacts in k-space than alternatives by training on such corruptions, and jointly reduced noise while preserving features unlike simple denoising post-FFT, demonstrated through quantitative and qualitative metrics to outperform conventional methods for improving low-field MRI scan quality (Koonjoo *et al.*, 2021).

One study aimed to address the limitations of applying deep learning-based Super-Resolution (SR) methods to enhance the resolution of portable low-field MRI scans and proposed a joint domain adaptation, denoising, and SR framework to overcome issues such as domain gaps between simulated and real low-field data, as well as the lack of perfectly aligned paired low-field and high-field images for supervision. The approach consisted of denoising and SR models on simulated degraded high-resolution data using unpaired images for unsupervised domain adaptation, and finally fine-tuning the entire model end-to-end (Min *et al.*, 2022). Preliminary results on a dataset of 11 subjects show that the method enables segmentation and produces quantitative ROI volumes that correlate strongly with high-field MRI scans, indicating that it can enhance low-field MRI quality for analysis using existing tools (Laguna *et al.*, 2022).

3.6.2. Accurate Super-Resolution in Low-Field Brain MRI

Iglesias *et al.* (2022) represented a Super-Resolution (SR) method to generate high-resolution synthetic MPRAGE scans from low-field MRI acquisitions using a neural network approach. They extended their prior Synthetic SR technique to leverage paired low-field T1 and T2 scans from a portable 0.064T scanner to synthesize 1 mm MPRAGE-like images. Testing on 11 clinical subjects with paired low- and high-field data showed that direct segmentation of low-field scans failed, but segmenting the synthetic MPRAGE outputs produced volumes that strongly correlated with high-field segmentation results. They hypothesized that this approach could enhance low-field MRI quality to allow the use of existing neuroanalysis tools. Although limited by a small test set, this study demonstrates the proof-of-concept that deep learning-based reconstruction can derive clinically usable information from portable MRI scans with lower resolution and contrast than conventional scanners.

3.6.3. Increasing Signal-to-Noise Ratio (SNR) in Low-Field Brain MRI

Maximizing the information yield from the inherently low signal-to-noise profile of low-field MRI is paramount for generating diagnostically viable neurological images, and recent technological innovations in electromagnetic interference cancellation, machine learning reconstruction from sparsely sampled data, and enhanced post-processing have demonstrated the potential to partially circumvent these signal constraints (N. Koonjoo, B. Zhu, G. C. Bagnall, D. Bhutto, & M. S. Rosen, 2021b). If coupled with portable scanners that enable bedside neuroimaging, such advancements may elucidate new applications for visualizing normal brain structure/function and detecting acute/chronic pathologies in previously inaccessible scenarios. Nonetheless, continued optimization of hardware, pulse sequences, amplification algorithms, and rigorous validation across diverse clinical environments is indispensable for refining portable low-field MRI capabilities and elucidating their full utility (Ayde *et al.*, 2022).

Additionally, a study conducted by Srinivas *et al.* (Srinivas *et al.* (2022) aimed to address electromagnetic interference-induced image artifacts in point-of-care MRI using an external dynamic interference estimation and removal (called EDITER) method. EDITER method acquires simultaneous data from multiple electromagnetic interference detectors (tuned receiver coils and untuned electrodes) during the primary MR coil imaging. Time-varying impulse response functions are dynamically calculated by mapping the detector data to MRI artifacts, enabling the removal of transformed interference. EDITER was evaluated in controlled phantoms using specific introduced sources and an uncontrolled open 47.5 mT scanner, calculating structured/broadband reductions of up to 97%, 76%, and 99%, respectively. In vivo, EDITER demonstrated a nine-fold signal-to-noiseratio improvement. This flexible, robust technique could reduce the reliance on portable MRI in shielded rooms by passively removing artifacts from minimal external detectors, allowing truly ambulatory imaging without specialized infrastructure requirements.

4. Conclusion

4.1. Potential Clinical Role, Areas for Further Development

The studies reviewed highlight the promising potential of low-field MRI as a cost-effective alternative to conventional high-field systems across various clinical applications. The reduced hardware expenses and siting requirements of low-field scanners could help democratize access to advanced imaging, particularly in resource-limited settings. However, significant challenges remain before low-field MRI can be widely adopted for routine clinical use. One major hurdle is achieving quantitative comparisons that demonstrate diagnostic non-inferiority to high-field benchmarks across a comprehensive range of pathologies and anatomic regions. While early results are encouraging for certain indications, more extensive validation through larger prospective trials is needed. Additionally, comprehensive health economics analyses integrating capital/operating costs and patient outcomes are crucial to quantify the potential value proposition. Certain advanced applications requiring very high spatial or temporal resolution, such as cardiovascular imaging, may currently exceed the technical capabilities of ultralow field strengths. Ongoing engineering innovations in areas like magnetic field inhomogeneity compensation, high-performance gradient/radiofrequency coils, and reconstruction algorithms will be essential to continually enhance performance. Despite these limitations, the trajectory of low-field MRI remains promising. With each new technical advance, the gap in achievable image quality compared to high-field narrows. If this trajectory continues, low-field systems may ultimately provide a viable mainstream clinical alternative, finally realizing the decades-old vision of universal access to affordable, robust MRI capabilities worldwide. Looking ahead, larger-scale randomized controlled trials directly comparing diagnostic accuracy and clinical decision-making against high-field MRI are imperative next steps. In parallel, health economic analyses should quantify the cost-effectiveness and societal impacts of increased screening and surveillance in resource-poor populations newly acquiring access to affordable imaging. While still an emerging technology, low-field MRI is already beginning to reshape care delivery models in underserved regions historically lacking modern imaging infrastructure. With sustained multidisciplinary efforts from clinicians, scientists, and economists, these innovative systems may one day make universal access to life-saving MRI a reality for all.

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