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Review Article

Applications, limitations and advancements of ultra-low-field magnetic resonance imaging: A scoping review

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ABSTRACT

Background: Ultra-low-field magnetic resonance imaging (ULF-MRI) has emerged as an alternative with several portable clinical applications. This review aims to comprehensively explore its applications, potential limitations, technological advancements, and expert recommendations.

Methods: A review of the literature was conducted across medical databases to identify relevant studies. Articles on clinical usage of ULF-MRI were included, and data regarding applications, limitations, and advancements were extracted. A total of 25 articles were included for qualitative analysis.

Results: The review reveals ULF-MRI efficacy in intensive care settings and intraoperatively. Technological strides are evident through innovative reconstruction techniques and integration with machine learning approaches. Additional advantages include features such as portability, cost-effectiveness, reduced power requirements, and improved patient comfort. However, alongside these strengths, certain limitations of ULF-MRI were identified, including low signal-to-noise ratio, limited resolution and length of scanning sequences, as well as variety and absence of regulatory-approved contrast-enhanced imaging. Recommendations from experts emphasize optimizing imaging quality, including addressing signal-to-noise ratio (SNR) and resolution, decreasing the length of scan time, and expanding point-of-care magnetic resonance imaging availability.

Conclusion: This review summarizes the potential of ULF-MRI. The technology's adaptability in intensive care unit settings and its diverse clinical and surgical applications, while accounting for SNR and resolution limitations, highlight its significance, especially in resource-limited settings. Technological advancements, alongside expert recommendations, pave the way for refining and expanding ULF-MRI's utility. However, adequate training is crucial for widespread utilization.

Keywords: Global health, Healthcare innovation, Medical imaging, Technology, Ultra-low-field magnetic resonance imaging

INTRODUCTION

The development of low-cost magnetic resonance imaging (MRI) technologies at ultra-low-field (ULF) strengths, that is, <0.1 T, has received attention recently.[29] In the realm of modern healthcare, medical imaging has emerged as an indispensable tool, particularly in the fast-paced and high-stakes environment of critical care settings, where split-second decisions can mean the difference between life and death, and the importance of accurate and timely diagnostics cannot be overstated.[44]

Across the globe, the accessibility and availability of imaging technologies paint a diverse landscape, starkly contrasting between well-resourced nations and those striving to overcome developmental hurdles.[9] By one estimate, around 66% of the world's population lacks access to MRI scanners.[15,16] In another illustration, in low- and middle-income countries (LMICs), the ratio of computed tomography (CT) scanners to the population is <1 per million, in stark contrast to the nearly 40 per million found in high-income countries (HICs).[19,21,35] This disparity is further magnified for MRI and nuclear medicine devices, which translates to a scanner density of only 1.12 MRI units per million population (pmp) in LMICs compared to 26.53 MRI units per pmp in HICs.[22] This divide underscores the critical need for equitable healthcare resources and highlights the challenges faced by LMICs or developing regions in delivering optimal patient care.[9]

At the heart of this imaging mosaic lies MRI, a stalwart in medical diagnostics, which largely replaced CT mainly due to its enhanced sensitivity, lack of radiation exposure, and superior soft-tissue contrast, facilitating the detection of varied pathologies, including small infarcts.[30,39,45] Its applications span a wide spectrum, illuminating the intricacies of neural pathways, detecting brain and musculoskeletal injuries,[4] unraveling the mysteries of neuropathologies, including strokes and hemorrhages[30], and even peering into pediatric imaging.[10]

As technology advances, so does the pursuit for more refined and accessible diagnostic tools. This quest gave birth to ULF MRI, an innovative approach that resonates with the core principles of imaging while carving a unique niche in the medical landscape. Despite improving accessibility to magnetic resonance, ULF strengths are still progressing toward sufficient imaging quality for clinical applications.[29]

The potential benefits of ULF-MRI include its footprint, affordability, and ease of transportation to the patient's location. In contrast, conventional MRI offers its own merits, such as the ability to perform contrast examinations and a low signal-to-noise ratio (SNR), but it has limitations, such as its large size, high cost, and the requirement for patients to remain immobile in a confined space, which can cause discomfort or even claustrophobia for some patients.[36,41,48] In addition, unlike traditional MRI, ULF-MRI does not require the presence of highly trained technicians, potentially reducing the disparity in quality of diagnosis that arises due to a lack of trained technicians in LMICs.[36,41,48] ULF-MRI holds the promise of affordable, convenient, and accessible diagnostic capabilities, presenting an opportunity to redefine the standards of care for patients with complex medical histories and demographics.

ULF-MRI, with its potential to address some of the limitations of traditional MRIs, has garnered attention for its possible role in revolutionizing diagnostic imaging. As with any pioneering technology, the literature surrounding ULF-MRI is still in its nascent stages. However, a comprehensive assessment of its advantages and limitations has not been conducted for clinicians. Therefore, this scoping review aims to explore existing evidence and identify knowledge gaps for ULF-MRI to provide a singular source with the latest information. A noticeable gap exists in comprehensively understanding its full potential, applications, and comparative efficacy in various clinical scenarios. Bridging this gap is crucial to harnessing the full capabilities of ULF-MRI and translating them into tangible improvements in patient care, which is one of the objectives of this review.

MATERIALS AND METHODS

Operational definitions

The definition of "low-field" is not consistent; it is sometimes used for values below 1.5T and other times confined to the range of 0.01T–0.1T.[4] In this review, we adhere to the provided categorizations. Although evolving classifications may arise to enhance clarity, we can alleviate confusion by outlining our terminology as follows.

- ULF: ≤0.1T
- Low field (LF): ≤0.1T and ≤0.3T
- High field (HF): >1.0T and ≤3T
- Ultra-HF: ≥7T

This review has been designed to overview existing evidence, identify gaps in knowledge, and pave the way for future research. Our review adhered to the guidelines laid out by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRIMA-ScR).[32]

Search strategy

A comprehensive and systematic literature search was performed using multiple databases, including PubMed, CINAHL, and Scopus, from inception to May 31, 2023. The search included the Medical Subject Headings database and utilized the following keywords: "Ultra-Low Field MRI," "Portable MRI," or "Hyperfine MRI." Searches were limited to abstract, title, and keywords. Backward reference searches (examining references of found articles) and reference snowballing (using citations to identify additional papers) were also performed to obtain the maximum number of articles. There was no restriction on language or date to ensure that the most current and relevant data were included in the study. The search also included ResearchGate and Google Scholar and recognized repositories of Gray Literature to capture unpublished studies on this topic.

Study selection

This review considered cross-sectional and cohort studies, both randomized and nonrandomized trials, case series, case reports, and technical reports that discussed ULF-MRI. We excluded review articles, editorials, letters to the editor, meeting abstracts, book chapters, guidelines, animal studies, and studies lacking full text. Search results were imported into Mendeley to remove duplicates, and two reviewers (AA and MS) independently screened titles and abstracts based on the inclusion criteria. A third reviewer was consulted (HAI) to discuss disagreements. After title and abstract screening, the full text was screened independently, with conflicts resolved by discussion with a third reviewer (HAI).

Data extraction

For each study that met the inclusion criteria, relevant data were extracted, including study design, sample size, study setting, applications, limitations, recommendations, and adverse events related to ULF-MRI. Two reviewers (SA and UK) independently extracted per the column headings using a predefined sheet. Any disagreements on the placement of information in the headings between the reviewers were resolved by consulting an additional reviewer (HAI). Missing data were systematically handled; studies with incomplete data were still included, and attempts were made to contact authors for clarification. However, the analysis relied on available data, with any implications of missing data acknowledged within review limitations.

Data analysis

The analysis in this review was conducted through a systematic approach. Extracted data from selected studies were collated and synthesized to identify patterns, themes, and key findings. A qualitative content analysis was used to categorize and group information, allowing for an overview of the landscape while highlighting trends, gaps, and insights related to ULF-MRI applications, limitations, and recommendations across the studies.

RESULTS

A total of 25 articles were included after the title, abstract, and full-text screening. The flow diagram for article screening and selection is depicted in Figure 1. The studies reviewed originated from the USA (n = 20), Pakistan (n = 2), China (n = 1), UK (n = 1), and Sub-Saharan Africa-USA (n = 1), as shown in Figure 2. The distribution of study designs is illustrated in Figure 3, while the distribution of publication dates is depicted in Figure 4.

The analysis of the included studies revealed several distinct themes showcasing diverse applications of ULF-MRI in the field of medical imaging. First, ULF-MRI proves to be an effective tool in intensive care units (ICUs). It is particularly useful for patients who exhibit neurological alterations, experience seizures, have unexplained encephalopathy, or show abnormal head CT scans.[27,41,45] Furthermore, its relevance also extends to ICUs dealing with COVID-19 and pediatrics.[1,10,34,43] Second, the integration of ULF-MRI into remote neuroimaging settings, such as community centers, has significantly improved the patient experience during bedside scanning.[11,12] In addition, ULF-MRI demonstrates remarkable versatility in various clinical applications, from epilepsy and multiple sclerosis (MS) to ischemic stroke, intracranial hemorrhage, and even intraoperative confirmation of pituitary adenoma removal.[1,5-8,12,30,42,47,48] Mapping brain tissue and exploring connections have been facilitated through ULF-MRI, including neonatal brain tissue mapping and investigating the links between brain morphometry and verbal memory performance.[11,34] Technological advancements are evident, with studies delving into high-quality scan production through various reconstruction methods and the integration of machine learning techniques.[3,13,17,23,49] Furthermore, ULF-MRI holds promise in timely diagnosis and safety assurance for neuropathological conditions, distinguishing it from conventional MRI systems.[27,36,41,45] Ethical considerations underscore the importance of community engagement, and recommendations are made for overcoming identified limitations.[40] The technology's dynamic assessment of pathology changes over time, and its contribution to volumetric growth curves and lesion detection further emphasizes its significance.[5,10,30,42] ULF-MRI's role in high-quality imaging, its portability, and its innovative imaging techniques also stand out, along with its potential in cognitive data collection and connectivity studies.[2,6,8,11,12,17,47,48] These themes collectively shed light on the wide-ranging implications of ULF-MRI in advancing medical imaging and patient care, as shown in Table 1.

Some of the studies have identified and highlighted inherent limitations of ULF-MRI technology. These limitations encompass various aspects of the technology's functionality. These include challenges such as a low SNR,[5,40,43,48] poor resolution,[5] and its as-yet-unexplored ability to perform regulatory-approved contrast-enhanced MRIs.[13,45] Moreover, the limitations extend to the inability

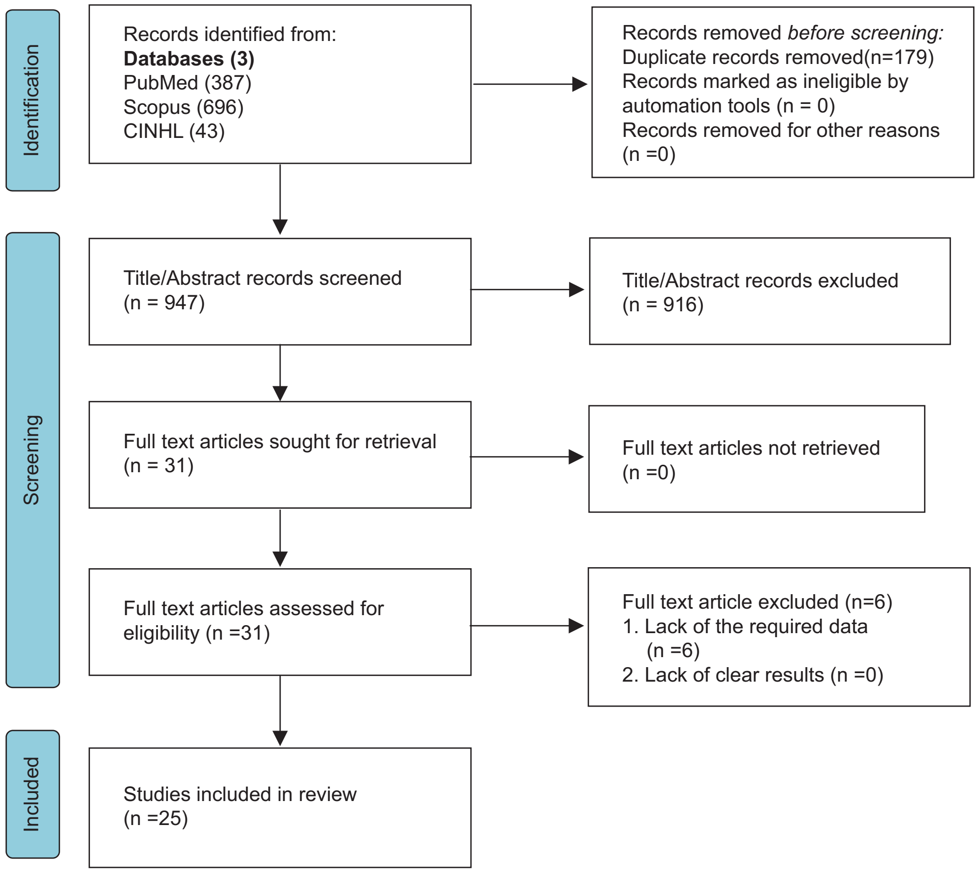

Figure 1: Preferred reporting items for systematic reviews and meta-analyses flow diagram.

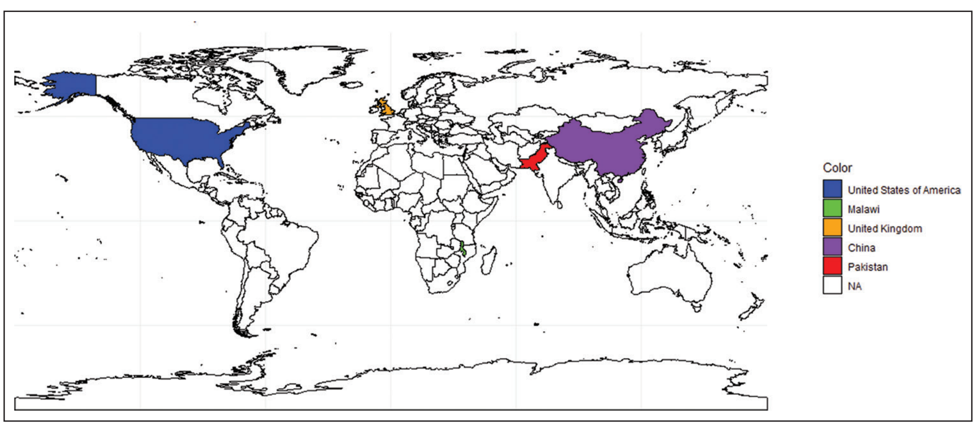

Figure 2: Countries on a world map where the studies were published.

to image anatomy beyond the brain and foot,[45] prolonged acquisition times,[36] and a reduced ability to detect ischemic penumbras and large-vessel occlusions when compared to traditional MRI systems.[42] Additional constraints entail limited tissue detection due to short relaxation times and attenuation of magnetization during transportation [17], as well as a capacity to execute solely specific standard sequences (T1, T2, fluid-attenuated inversion recovery, and diffusion-weighted Imaging).[2] Challenges are further noted in terms of accounting for changes in lesion-to-background tissue contrast,[3] the absence of functional, perfusion, and metabolic imaging on certain systems,[12] and there are insufficient validation studies to confirm the reliability and effectiveness of ULF-MRIs for their widespread use in new medical facilities.[30] The detailed limitations are outlined in Table 1.

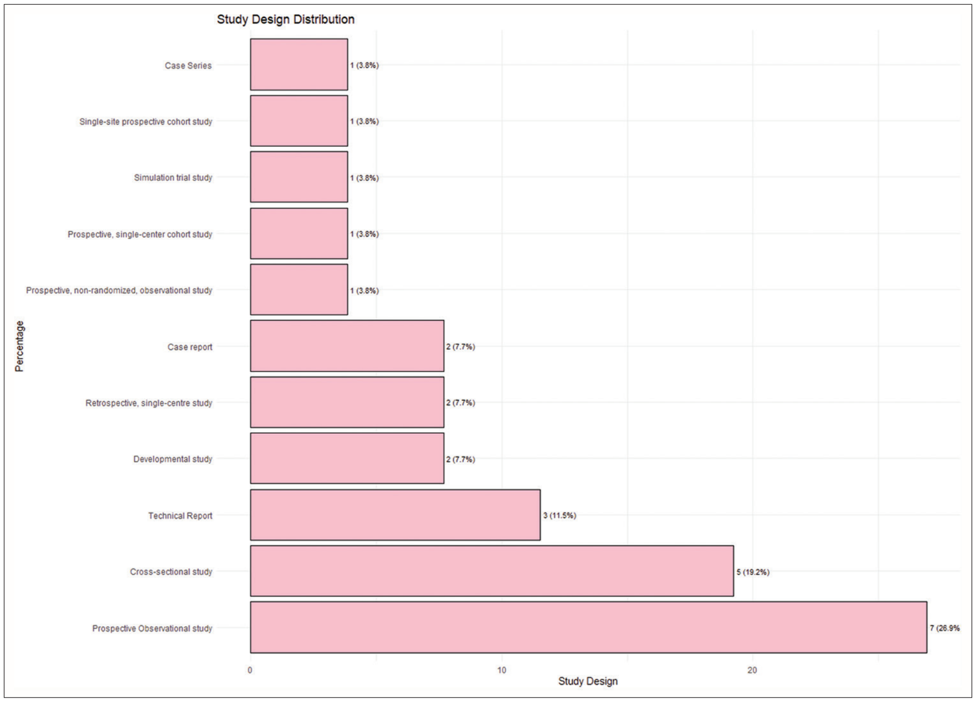

Figure 3: Study Designs included in the review.

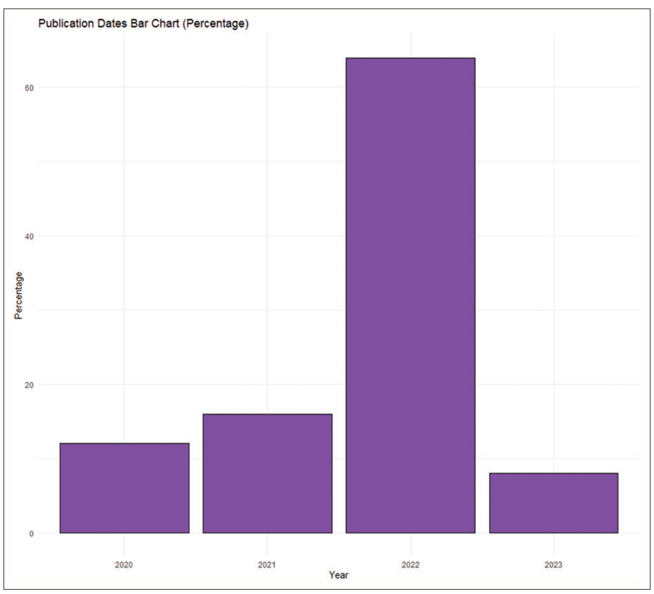

Figure 4: Publication dates of included studies.

A notable theme surfaces through valuable recommendations by experts to improve ULF-MRI functionality. Stemming from comprehensive analysis, these tailored recommendations address identified limitations, driving advancements in ULF-MRI. Improvements encompass imaging acquisition and quality, introducing novel sequences, and AI-driven improvements.[5,45,48] Clinical implementation gains momentum with proposals for expanded point-of-care MRI availability, aiding temporal profiling and interventional studies,[41] and telemedicine integration for remote accessibility.[2] Addressing challenges involves electroencephalography/near-infrared spectroscopy inclusion for image fidelity, along with thorough roadmap review and preparedness.[7,12] Rigorous validation emerges through prospective multicenter studies focusing on hypoxic-ischemic brain injury.[6] Prospects spotlight advanced techniques such as interchangeable dual-domain self-supervised networks, innovative image restoration, dual-domain reconstruction,[49] and AI-driven resolution augmentation.[1] The details of the recommendations are shown in Table 1.

DISCUSSION

This review discusses the applications, limitations, technological advancements, and recommendations associated with ULF-MRI. The findings underscore the substantial impact of ULF-MRI in various clinical settings, such as pediatrics and adult ICU, particularly to challenges posed by the COVID-19 pandemic and even resource-constrained settings. Notably, ULF-MRI showcased its proficiency in improving bedside scanning experiences and offering diverse clinical applications spanning epilepsy, MS, and ischemic stroke. Technological progress is evident through innovative reconstruction methods and integration with machine learning techniques. In addition, the review identified vital recommendations for further refining and expanding the potential of ULF-MRI.

Table 1: Provides an overview of studies involving ULF-MRI applications, limitations, and recommendations.

Author and Year	Study design	Country	ULF-MRI (T)	Sample size (*n*)	Setting	Applications	Limitations	Recommendations	ULF-MRI (adverse event)
1. Turpin *et al.* 2020.[45]	Prospective, nonrandomized, observational study	USA	0.064-T	19	ICU	• Used for neuroimaging of ICU patients. • Timely diagnosis of CNS pathologies, diagnosis of restricted diffusion, and hemorrhages.	• Inability to do contrasted MRIs. • The device is capable of imaging only the brain and the foot. • Low SNR challenge.	• Optimize and improve acquisition and post-processed images (e.g., ADC) • Addition of newer sequences • Perform scans with contrast agents.	None
2. Sheth *et al.* 2020.[41]	Prospective, single-center cohort study	USA	0.064-T	50	Neuroscience or COVID-19 ICUs	• Used in COVID-19 and NICUs. • Pathologies: Diagnosis of ischemic stroke, hemorrhagic stroke, subarachnoid hemorrhage, traumatic brain injury, brain tumor, and COVID-19 and altered mental status.	• NR	• Increased availability of bedside POC MRIs for better temporal profiles and intervention design.	None
3.Prabhat *et al.* 2021.[36]	Observational study	USA	0.064T	ULF-MRI	ICU or ED	• Obese/elevated BMI patients, ventilated patients, patients on dialysis, COVID-19 patients, post thrombolysis or mechanical thrombectomy, patients with cervical spine precautions, and claustrophobic/distressed patients. • Demonstrated the safety and feasibility of obtaining POC MRI in a wide variety of patients who presented with various neuropathologies.	• The total acquisition time is longer compared to conventional MRI, requiring the patient to stay inside the scanner for longer (~30 min) when integrating FLAIR, T2, T1, and DWI with the ADC map. • The resolution is lower compared with 1.5 T or 3T MRI	• Work is needed to incorporate pMRIs in a larger variety of clinical settings.	NR
4. Shen *et al.* 2021.[40]	Observational analysis study	USA	ULF-MRI	18 (Survey)	NR	• Study brain disorders in data-limited communities (e.g., stroke, hydrocephalus, and Alzheimer's). • Assess low-cost MRI's clinical impact (e.g., neonatal asphyxia screening and other perinatal complications in full-term and preterm infants). • Investigate the impact of adversities (nutrition, environment, psychosocial) on brain development, for example, COVID-19's effects on neural function in marginalized communities.	• Low SNR	• Engage communities and experts for robust pMRI research. • Update MRI guidelines with community input. • Align ethics guidelines for global MRI research. • Collaborate for ELSI guidance across portable imaging. • Analyze ELSI for diverse clinical pMRI use.	NR
5. Mazurek *et al.* 2021.[30]	Observational study of a single-center cohort	USA	0.064T	144	NICU and ED	• Diagnosis of strokes (ICH and ischemic heart disease) • Evaluation of ICH and ischemic heart disease- the differential is crucial for thrombolytic therapy and may be used to understand dynamic changes in ICH pathology over time. • pMRI is a safe and feasible neuroimaging.	• Motion artifacts and degraded images. • Low SNR.	• Further validation/studies are required before installation in prospective multicenter/multi-care settings.	None
6. Deoni *et al.* 2021.[10]	Cross-sectional study	USA	0.064T	42	Lab setting	• Pediatric neuroimaging. • Tracking neurodevelopmental trajectories • Volumetric growth curves for WM, GM, and ICBV were obtained.	• Low SNR.	• Further studies are required before pMRIs can be incorporated into large-scale settings.	NR
7. Deoni *et al.* 2022.[13]	Technical development study	USA	0.064T	In vivo imaging data (5 healthy female volunteers) Phantom imaging data (CaliberMRI phantom)	NR	• Reconstruction of high-resolution isotropic T2-weighted images from low- resolution anisotropic images. • Low-resolution to high-resolution reconstruction performed in 12 min which is clinically manageable and can allow much better anatomical visualization.	• Low SNR of the calculated T2 map. • Commercial LF strength devices are limited in the range of available image contrasts and acquisition methods.	• Further research can help in improving the diagnostic capability of these devices.	NR
8. Yuen *et al.* 2022.[48]	Prospective, observational study	USA	0.064T	50 patients with ischemic stroke	NICU, ED, and COVID-19 ICU	• Bedside intracranial imaging of patients with ischemic stroke. • The portability of the device enables ischemic stroke patients to be monitored over time and, hence a complete temporal profile to be developed.	• Low SNR. • Low magnetic field, which fails to detect small foci of restricted diffusion.	• Improvements in pMRI imaging quality are required	None
9. Arnold *et al.* 2022.[5]	Prospective, cross-sectional study	USA	0.064T	33 MS patients	NR (Only sites A and B reported)	• Neuroimaging of MS patients. • Detection of the volume of MS lesions.	• Low SNR and resolution • Smaller WM lesions can be missed.	• Resolution can be increased through (i) Longer scan times and (ii) More acquisitions with averaging.	NR
10. Sheth *et al.* 2022.[42]	Prospective, observational study	USA	0.064T	109	NICU	• Neuroimaging to detect intracranial MLSs developed as a result of cerebral edema. • Bedside multimodal imaging of MLS patients.	• The LF pMRI device does not currently have MR angiography or perfusion-weighted imaging, which means that it has a reduced ability to detect ischemic penumbras and large-vessel occlusions.	• Further research is required to explore the strengths and limitations of pMRI for different time points of brain injury, patient populations, and medical environments. • Validation of pMRI's sensitivity and specificity for other intracranial pathologies like ischemic stroke and hemorrhage.	None
11. Arnold *et al.* 2022.[3]	Simulation trial study.	USA	0.064T	6 adult patients with known or suspected hydrocephalus. 10 adult patients with (MS). Open access data (high field MRI 3T): HGG (n=259); LGG (n=76), stroke (n=28), and MS (n=20)	NR	• Virtual evaluation of novel imaging devices using machine learning and open-access datasets. • Quantitative assessment of image quality using gradient entropy; image quality of real and simulated images compared.	• The simulated image generation technique does not account for possible changes in LF lesion to background tissue contrast.	NR	NR

(Contd...)

Table 1: *(Continued).*

Author and Year	Study design	Country	ULF-MRI (T)	Sample size (*n*)	Setting	Applications	Limitations	Recommendations	ULF-MRI (adverse event)
12. Deoni *et al.* 2022.[12]	Developmental study.	USA	0.064T	12	Mobile van (Scan-a-van, Cargo van) and laboratory-based static scanners	• Remote neuroimaging at home or a community location. • Demonstrated the ability to acquire quality structural neuro-MRI data in a mobile platform.	• Functional, perfusion and metabolic imaging are currently unavailable in the hyperfine system.	• Include incorporation of EEG or NIRS enabling lesser image distortion.	NR
13. Chetcuti *et al.* 2022.[7]	Report	Sub-Saharan Africa (Mawali)	0.0625T	NR	Hospital setting	• Experiencing the implementation of pMRI in a hospital in Malawi- a resource-limited setting. • Various hurdles were faced during the year-long usage of LF pMRI and later overcame with solutions.	1. Challenge: Equipment delivery and receipt logistics. 2. Challenge: Equipment roadmap 3. Challenge: Equipment storage 4. Challenge: Equipment operation 5. Challenge: Equipment utilities	1. Solutions: • Reliable transportation route assessment. • Trusted carrier with tracking. • Adequate insurance coverage. • Prereceipt uncrating/setup training. • Tools for setup readiness. • Thorough container gauge inspection. 2. Solutions: • Assess portable routes. • Construct smooth, low-incline ramps. 3. Solutions: • Evaluate temperature/humidity conditions. 4. Solutions: • Train end users comprehensively. 5. Solutions: • Assess electricity/Internet capacity. • Obtain the recommended surge protector.	NR
14. Cho *et al.* 2022.[8]	Prospective, observational, ongoing study.	USA	0.064T	3	ICU (ECMO patients)	• Detecting the severity of ABI in ECMO patients, using pMRI. • fMRI scans completed without SAEs, having good image quality where pathologies were easily detectable.	• Multiple sequences increase exam duration mainly when the clinical intervention of ABI is time-dependent in ECMO patients.	• Further work and research are needed.	None
15. Beekman *et al.* 2022.[6]	Retrospective, single-center study.	USA	0.064T	19 (Resuscitated from CA)	ICU	• To describe the imaging characteristics of patients postCA to evaluate brain injury using pMRI. • HIBI was found to be most easily recorded in the FLAIR sequence.	• A limited number of patients who too subjected to selection bias are included.	• Prospective, multicenter studies with defined measures on HIBI are recommended.	None
16. Sien *et al.* 2023.[43]	Single-site prospective cohort study.	USA	0.064T	14 (Neonates)	Neonatal ICU	• Using pMRI imaging in a neonatal ICU setting. • Mild artifacts were noticed without affecting the actual diagnosis. The rest were completed smoothly, and overall a success.	• Small investigation site, with limited space for the length of lines and tubes. • Poor diagnostic accuracy assessment, with Inter-rater differences. • Low signal-to-noise within the pMRIs. • The majority of infants did not qualify for screening, as per the device's instructions.	• A larger dataset of pMRI could be useful in a neonate's brain screening test to broaden the criteria, especially if they are too weak to transport or pathology exams were poorly imaged.	None
17. Zhou *et al.* 2022.[49]	Developmental study.	USA	0.064T	Simulated data: 505 T1 and 125 T2 3D brain MRI from the HCP. Real world non-Cartesian data: 119 FLAIR and 125 FSE-T2w 3D brain MRI (Hyperfine SwoopTM pMRI system	NR	• A novel DDSS supervision helps enhance reconstruction learning without any fully sampled data. • The successfully reconstructed real data from pMRI of the suggested framework and no fully sampled data available outperformed previous methods.	• DDSS performance currently lacks full supervision, and only image and k-space self-supervised losses are imposed on the final results of the non-Cartesian reconstruction network.	• Improving performance through density-compensated primal-dual networks, data consistency operation, and deep supervision. A flexible DDSS backbone facilitates diverse image restoration networks. Combining deep learning coil sensitivity prediction, varied sampling patterns, and higher acceleration factors could yield further gains.	NR
18. Kuoy *et al.* 2022.[27]	Single-center, Retrospective study.	USA	0.064T	35	ICU and ED	• Using POC MRI in ED and ICU where time is the number one priority. • Reduced turn-around time calculated in ICU patients compared to fixed MRI. No significant difference in ED patients.	• A small, single-center study with the possibility of selection bias. Not every patient went through follow-ups with fixed MRIs.	• Further research is required to understand the strengths and weaknesses of pMRI technology.	None

(Contd...)

Table 1: *(Continued).*

Author and Year	Study design	Country	ULF-MRI (T)	Sample size (*n*)	Setting	Applications	Limitations	Recommendations	ULF-MRI (adverse event)
19. Iglesias *et al.* 2023.[23]	Prospective, observational study.	USA	0.064T	11	NR	• A machine learning super-resolution is used to improve the high spatial image resolution of pMRI scans. • The duo of pMRI and the machine learning algorithm provided highly correlated brain morphometric measurements to actual high-resolution images.	NR	NR	NR
20. Deoni *et al.* 2023.[11]	Cross-sectional study.	USA	0.064T	67	Scan-Van	• Feasibility of remote MRI and cognitive data collection in adults • Correlating brain volumes with cognitive performance using PAL assessment • Mindcrowd proved to be an important tool in cognitive assessment data collection when paired with pMRI for scanning at homes.	NR	• To firmly build its utility in neurocognitive research and study, further work and improvement are required.	NR
21. Padormo *et al.* 2023.[34]	Cross-sectional, observational study.	UK	0.064T	28 neonates	NR	• Using LF pMRI technology for T1 mapping of brain tissue in neonates as a potential biomarker for brain development. • ULF MRI scans presented with shorter T1 in scans compared to high-field, proposing T1 to be reducing postmenstrual age due to changes in brain tissue compositions.	• The motion was presented by neonates during the scanning procedure.	• Methods acquiring data for clinical use when time is limited or protocols that optimize efficient metrics are proposed for future work in more premature neonates for T1 imaging.	NR
22. Wilcox *et al.* 2022.[47]	Case Series	USA	0.064T	3 adult ECMO patients supported with IABP	ICU	• Bedside LF POC brain MRI in ICU safely detects ABI in adult ECMO patients with IABP support, enabling timely intervention.	• Lack of available safety data on the current use of IABP, large body habitus of patients, significant artifacts on images, or relevant head motion caused were the setbacks faced during scanning.	• Improving clinical management to minimize risks of ABI in a previously ignored patient population, using pMRI.	None
23. Guo *et al.* 2020.[17]	Technical Report.	China	ULF MRI	NR	NR	• To detect MR signals at a microtesla field using a superconducting quantum interference device detector, reconstructing images with the back projection method. • Three (2D) images of the phantom reconstructed, at the same acquisition rate but at different times, easily distinguishable.	• The attenuation of magnetization while transporting procedure limits tissue detection due to short relaxation time. With eddy currents generating large magnetic fields in a shielded space, setbacks occur, too.	• The pMRI systems are proposed in airport security, emergency rooms, and field hospitals, along with MEG for imaging and back projection methods to simplify the imaging pulse sequence and extend by applying a slice selection gradient pulse.	NR
24. Altaf *et al.* 2023.[2]	Case report.	Pakistan	0.064T	1	Hospital (Surgical Ward)	• Detecting neuropathology using ULF MRI and its comparison with high-field MRI results. • Both low and high-field scans revealed similar right frontal intra-axial lesions, i.e., a low-grade Glioma.	• The patient's head needs to be adjusted during scanning to avoid causing claustrophobia. • pMRI only performs certain standard sequences (T1, T2, FLAIR, DWI, and ADC)	• Telemedicine, including recent software and video communications, be made a reliable part of procedures along with pMRI to provide remote access to low-facilitated places.	None
25. Altaf *et al.* 2023.[1]	Case report.	Pakistan	0.064T	1	Operating Room	• pMRI scanning as an intraoperative imaging modality to determine any residual tumor. • The imaging confirmed the intended resection of pituitary adenoma during operation, to be successful.	• Increase in the operating room time is expected. • Limited data sets are available to set up the algorithm for the pMRI scanner, which also produces low-quality images.	• The resolution of images needs to be enhanced using AI. • More data sets are required to set up the algorithm for pMRI usage.	None

NR: Not reported, ELSI: Ethical, legal, and social issues, NICU: Neuroscience intensive care unit, MLS: Midline shift, MS: Multiple sclerosis, MRI: Magnetic resonance imaging, pMRI: Portable magnetic resonance imaging, ECMO: Extracorporeal membrane oxygenation, CA: Cardiac arrest, HIBI: Hypoxic-ischemic brain injury, DDSS: Dual-domain self-supervised, HCP: Human connectome project, ED: Emergency departments, ICU: Intensive care unit, ULF-MRI: Ultra-low field magnetic resonance imaging, PAL: Paired-associate learning, ABI: Acute brain injury, IABP: Intra-aortic balloon pump, MEG: Magnetoencephalography, WM: Whole-brain white matter, GM: Gray matter, ICBV: Intracranial brain volume, CNS: Central nervous system, ADC: Apparent diffusion coefficient, POC: Point-of-care, BMI: Body mass index, DWI: Diffusion-weighted imaging, FLAIR: Fluid-attenuated inversion recovery , ICH: Intracerebral hemorrhage, SNR: Signal-to-noise ratio, LF: Low field, EEG: Electroencephalography, NIRS: Near-infrared spectroscopy, SAEs: Serious adverse effects, FSE-T2W: Fast spin echo T2-weighted, MR: Magnetic resonance, HGG: High Grade Glioma, LGG: Low Grade Glioma

Among applications, portable imaging technologies offer a range of benefits in ICU settings that traditional MRIs do not. For example, ULF MRI enables more frequent monitoring, facilitating real-time observation of changes and the adjustment of treatment plans.[1] In addition, this technology does not use ionizing radiation, unlike X-rays or CT scans, crucially safeguarding the health of the compromised patients.[36]

ULF MRI's adaptability facilitates its smooth integration into a range of ICU settings, ensuring patient-centric care. The minimization of disturbances is noteworthy, as portable imaging helps in developing settings that are conducive to patients' recovery.[36] In addition, it enables overall patient care in the ICU setting by enabling the maintenance of appropriate staffing levels while at the same time safeguarding the patient undergoing imaging by eliminating potentially deleterious transport. Nevertheless, in the ICU setting, patients can be rerouted from fixed CT and MRI to portable MRIs, which is especially crucial to combat long wait times.[24] Rapid imaging is pivotal to critical care and would work to improve patient long-term outcomes.[31]

Early detection and diagnosis are improved through these technologies, enabling quick interventions and, hence, better patient outcomes.[5] A fundamental advantage lies in its cost-effectiveness; portable ULF-MRI systems are not only more accessible but also economically viable for populations that might otherwise experience delayed diagnoses due to financial barriers.[45]

Figure 5 exemplifies the concept of portable devices in a clinical setting. Such portable devices can be conveniently introduced into healthcare facilities within patients' reach, reducing the need for costly travel. This not only benefits patients financially but also increases the likelihood of individuals seeking timely medical attention thus, aligning with the principle of enhancing health-care accessibility.[14]

Traditional MRI machines require specialized facilities, trained technicians, and high maintenance costs.[6] However, for any trained technicians, formal operator training programs and certifications are needed. This is of special importance from a legal perspective and in unionized environments. Our review did not find any mention of planned programs that would distinguish the role of health-care providers and operators, leaving gray areas for the assigned roles associated with ULF-MRI use. Hence, discussions among medical societies on planning out the implementation of such modalities are required.

Portable neuroimaging devices often have lower maintenance requirements and can be operated with simpler infrastructure with no need to be kept in protected rooms due to their lower magnetic field strength.[40] Low-resource hospitals in LMICs would benefit from reduced

Figure 5: The Swoop® Portable Magnetic Resonance Imaging (MRI) System™ (Hyperfine, Inc., Guilford, CT, USA). This illustration showcases the practical utilization of the Hyperfine Swoop, a portable MRI scanner with low magnetic field strength, within a clinical context. The system's mobility allows it to be transported to a patient's bedside, where it can be connected to a standard wall outlet for power. The operation of the scanner is managed through a wireless tablet. The system boasts a field strength of 0.064T, employs a permanent magnet, and carries a weight of approximately 1400 pounds. On the Left: Connected to a power outlet and used through a wireless tablet. On the Right (Top and Bottom): Use of the system in a practical setting.

maintenance costs, making it more sustainable for them to offer imaging services. Portable neuroimaging devices can be transported to various healthcare settings, including remote areas or makeshift clinics.[12] This flexibility ensures that underserved populations in rural or remote regions can receive essential imaging services without the need to travel long distances.[12,48] Portable neuroimaging devices can be integrated with telemedicine solutions, allowing experts from urban centers or specialized institutions to provide remote guidance and consultations.[2] This enhances the diagnostic capabilities of low-resource hospitals and clinics.

Portable neuroimaging devices typically consume less power compared to their traditional counterparts.[41] This is particularly advantageous for hospitals in regions with unstable or limited power supply, as it helps minimize energy costs and dependence on continuous electricity.[41] Traditional MRI machines have complex components that may require specialized technical expertise for maintenance and repairs. Training personnel to operate and maintain traditional MRI machines can be resource-intensive and require specialized training.[48] Portable neuroimaging devices often have fewer intricate components, leading to simpler maintenance procedures that local technicians or engineers can perform.[40] Portable devices are designed to be user-friendly and may require less training for hospital staff, making it easier to maintain and operate the equipment effectively.[42] The design of portable neuroimaging devices could potentially result in lower long-term maintenance costs.[10]

ULF-MRI operates at significantly lower magnetic field strengths compared to traditional HF MRI machines.[45]

This can reduce the potential risks associated with stronger magnetic fields, making it safer[41] for all patients, especially infants and younger children. Especially in pediatric patients, the open and less confining design of ULF-MRI systems can help reduce anxiety and improve comfort during imaging procedures.[48] Children are more susceptible to feelings of claustrophobia in confined scanner environments compared to adults.[5,18] ULF-MRI makes it easier for pediatric patients to complete scans without requiring sedation. Anxiety decreases the comfort level of young patients and, studies have noted claustrophobia to be a drawback to ULF-MRI use.[36,37] The more open and less restrictive nature of ULF MRI can reduce the feelings of confinement, along with the potential of caregivers to remain at the patient's side and talk with them during the exam, making it easier for pediatric patients to undergo the procedure without sedation.[25,36] ULF-MRI systems may provide overall faster imaging sessions, helping to capture images before children become restless.[12] ULF-MRI can be particularly useful for pediatric neuroimaging, which includes brain imaging. It enables the assessment of brain development, abnormalities, and conditions affecting the pediatric population with improved spatial and temporal resolution.[40] Improved image quality, shortened scan times, and reduced sensitivity to subject motion have further allowed these methods to be adopted for use in pediatric populations and, more recently, even *in utero* fetal imaging.[10]

In addition, it is crucial to discuss the limitations of ULF-MRI. The limitations largely arise from the imaging performance of this modality. Low spatial resolution, a high degree of noise and artifacts in the images, and a lengthy scan time (particularly when various orientations of the images are required) are examples of these shortcomings. SNR, which is used for the assessment of noise and signal quality by comparing the actual image data (signal) to the background noise in the system, uses weak magnetic fields of <1T to produce less SNR, resulting in compromised imaging resolution.[38] The restricting size and setup of such systems that allow the patients to be placed within a limited range, causing a low SNR and lesser image quality, has forced the experts in the field to be concerned about the effects that it would cause on the scanning credibility in the long run. LF strengths result in a lower average of nuclear spins. With fewer polarized spins, sensitivity declines, necessitating longer scans for comparable quality. In a high-paced environment of medicine, this poses barriers to timely diagnosis where expedience is critical.[38] While faster protocols using under-sampling are employed, resolution suffers, potentially omitting subtle yet vital diagnostic details. In addition, it has been stated that low SNR has presented motion artifacts, especially when used with longer imaging times, causing frequent changes in volumetric measurements.[4] However, it is important to note that field strength alone does not determine image quality – advancements in radiofrequency (RF) coils, pulse sequences, and reconstruction have dramatically improved 1.5T MRI over decades without requiring stronger magnets.

Nevertheless, a significant watershed moment in ULF-MRI systems arose from the incorporation of artificial intelligence (AI) and deep learning in image reconstruction. The implementation of SNR-efficient data acquisition and reconstruction algorithms, including parallel imaging, compressed sensing, and machine learning-based image reconstruction methods, have allowed ULF-MRI to be clinically useful.[33] Essentially, a repository of MRI images spanning both low and high noise spectra was developed. Leveraging this, AI algorithms adeptly discerned the nuances of a low-noise dataset, even when presented with a noisier counterpart. Employing an array of mathematical and computer vision-driven modalities, this technique not only enhances image quality but, in theory, holds the potential to drastically truncate acquisition times. In addition, scientists are now working toward SNR-optimization techniques to address low-quality and basic imaging concerns, even if the timely diagnostic approaches of LF strength have worked out so far in critical patient care. One way to do that is using modified, specially designed magnets with more homogeneous fields, which improves SNR by reducing dephasing. For example, open magnets with B0 fields of 0.1–0.2T can offer more uniformity and less distortion in the system.[46] In addition, more efficient sequences such as long spiral readouts, turbo spin echo with full 180° refocusing pulses, or balanced steady-state free precession sequences may increase SNR per unit time.[46] Signal averaging is another strategy for increasing SNR as it increases by the square root of the number of averages, though at the cost of longer scan times.[38] Recent work further suggests that SNR depends not just on B0 strength but also on coil design and sample properties, providing opportunities for optimization independent of field strength.[33]

Proponents argue that ULF-MRI expands access with simpler, low-cost systems in underserved regions. However, meaningful access mandates reliable diagnosis. A case report regarding a suspected stroke MRI conducted on the same day in the same patient using both 3T and 0.064T stated that even though the patient's movement caused low-quality scanned images and lacked diagnostic precision needed, the results were still reliable and concordant with that of HF 3T MRI scanner.[20]

Machine learning has shown promise for improving ULF-MRI technology. Be it in the form of image reconstruction, artifact minimization, contrast enhancement, or predictive modeling. One group developed an active electromagnetic interference cancellation system using analytical and deep learning models that eliminated the need for traditional RF shielding in a low-cost 0.55T ULF-MRI system.[29] Lau *et al.* have helped visualize the idea of the dual-acquisition 3D super-resolution brain imaging model through deep-learning of HF brain data in LF, cost-friendly, and RF shielding-free MRI scanners to get democratized in resource-limited settings.[28] Public MRI datasets have also been leveraged to generate synthetic ULF training data, which reduces manual labor and opens access for various patient populations.[3] Deep learning reconstruction techniques like the AUTOMAP framework have been applied to enhance image quality from low SNR ULF data by suppressing artifacts.[26] While challenges remain, these initial advances demonstrate the machine and deep learning's potential to address limitations in ULF-MRI sensitivity, artifacts, and the need for physical infrastructure – improving accessibility in resource-limited regions.

Recommendations

Further work is needed to incorporate ULF MRIs in a larger variety of clinical settings and to improve the diagnostic capability of these devices. Although ULF-MRI offers several advantages over traditional MRI scanners, such as lower cost, reduced power requirements, and improved patient comfort, the findings of this review suggest several important areas for future investigation based on the current limitations identified. First, it is recommended that future researchers focus on longitudinal studies to understand better the long-term feasibility and safety effects associated with the use of ULF-MRI. In addition, the studies that have been performed previously were mainly cross-sectional, cohort study designs, and case reports. There is a need for more randomized controlled trials to establish causality and determine the effectiveness of the new technology in a wide variety of use cases – some of which would not be possible with an HF MRI scanner. Furthermore, researchers are encouraged to explore diverse populations and settings and, therefore, enhance the generalizability of findings. It is also advised to employ rigorous research designs, utilize standardized measurement tools, and employ robust statistical analyses to increase the validity and reliability of research outcomes. These recommendations may serve as a guide for future researchers, enabling them to build on the existing knowledge base and contribute to the advancement of ULF MRIs.

Limitations

Limitations of this scoping review include variations in the study methodologies of the included studies, potential biases from selected literature, and the qualitative nature of the data synthesis. Moreover, despite the steps taken, the data synthesis is subjective and restricted to predefined headings. In addition, the sample sizes of included studies were generally small (<100), and therefore, the use of larger cohorts in the future is crucial for increased generalizability. Potential confounders, such as the status of the patients and their comorbidities within each study, were also not considered. These factors, while considered, could impact the depth and scope of the findings presented.

CONCLUSION

This review has unveiled the remarkable potential of ULF MRI across a spectrum of clinical applications. The findings underscore its significant role in enhancing patient experiences in ICU settings, its diverse clinical utility spanning various medical and surgical conditions, and its integration with innovative reconstruction methods and machine learning techniques. ULF-MRI can be particularly useful in resource-limited settings to bridge the gap in diagnostic modalities. Future work should address its limitations in imaging quality and further facilitate its clinical adoption.

Ethical approval

The Institutional Review Board approval is not required.

Declaration of patient consent

Patient's consent was not required as there are no patients in this study.

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Conflicts of interest

Edmond Knopp is the Vice President of Medical Affairs at Hyperfine Inc. Chip Truwit is the Vice President of Scientific Affairs at Hyperfine Inc. Khan Siddiqui is the Chief Medical Officer at Hyperfine Inc.

Use of artificial intelligence (AI)-assisted technology for manuscript preparation

The authors confirm that there was no use of artificial intelligence (AI)-assisted technology for assisting in the writing or editing of the manuscript and no images were manipulated using AI.

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