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Sustainable Low-Field Cardiovascular Magnetic Resonance in Changing Healthcare Systems—An Update

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ABSTRACT

Cardiovascular magnetic resonance (CMR) is the gold standard imaging modality for evaluating cardiac structure, function, and myocardial tissue characteristics, yet its widespread adoption remains limited by cost, technological complexity, and infrastructure barriers—especially in low- and middle-income countries (LMICs). Recent advances in low-field (LF) CMR, particularly around 0.55 Tesla, demonstrate that strong diagnostic performance can be achieved despite reduced signal-to-noise ratios. Optimized hardware, including advanced gradient coils and radiofrequency systems, as well as AI-driven image reconstruction techniques, has greatly enhanced image quality. LF magnets offer notable advantages that reduce infrastructure demands and simplify protocols—both critical for lower resource settings. Clinical applications in cardiac function, tissue characterization, flow quantification, and even interventional procedures have expanded through sequences adapted to LFs, including novel approaches to myocardial mapping and real-time imaging. Concurrently, cryogen-free magnet designs and smaller system footprints have simplified installation and lowered operational costs. These developments bolster the feasibility of scaling CMR in environments where high-field scanners are prohibitively expensive or challenging to maintain. Moreover, greater accessibility to LF CMR could help bridge global disparities in cardiovascular diagnostics, enabling earlier detection of cardiomyopathies and ischemic heart disease in underserved regions. Although challenges remain—such as reduced signal-to-noise ratio, slower acquisition times, and limited availability of cardiac-specific hardware—ongoing innovations and collaborative global initiatives position LF CMR as a transformative, sustainable solution for modern cardiovascular care worldwide.

Muhammad Umair and Ahmed Marey are co-first authors.

1 | Introduction

Over the past four decades, cardiovascular magnetic resonance (CMR) has undergone significant technical advancements, establishing itself as the gold standard for assessing cardiac structure, function, and myocardial tissue characteristics, including inflammation and fibrosis [1]. Through innovations in magnetic resonance imaging (MRI) hardware, data acquisition and reconstruction techniques, image processing, and artificial intelligence algorithms, CMR has expanded its clinical utility, particularly in evaluating right ventricular function, valvular diseases, and congenital heart conditions [2, 3]. CMR uniquely offers velocity-encoded imaging for hemodynamic assessments and tissue characterization through late gadolinium enhancement (LGE) and advanced techniques, such as T1, T2, T2*, and extracellular volume (ECV) mapping [4]. CMR techniques are invaluable for diagnosis, risk stratification, and prognostication for a variety of cardiomyopathies and ischemic heart disease and have been widely incorporated into cardiovascular imaging guidelines by major societies such as the European Society of Cardiology and the American Heart Association/American College of Cardiology [5, 6].

Despite this progress, CMR is underutilized globally, with a large disparity in its availability and affordability between high-income countries (HICs) and low- and middle-income countries (LMICs). The use of CMR, based on predominantly standard MRI systems (1.5 or 3 T), is largely confined to academic centers, large hospitals, and urban facilities in HICs for several reasons, including the complexity of cardiac imaging protocols, the need for highly specialized trained personnel, and unfavorable reimbursement rates compared to other modalities like echocardiography and single-photon emission computed tomography (SPECT) [7]. Additionally, practical challenges such as MRI compatibility for patients with cardiac implanted electronic devices (CIEDs) and difficulties in scanning severely obese or claustrophobic patients hinder the routine use of CMR, which accounts for less than 5% of all MRI scans and an even smaller fraction of overall noninvasive cardiovascular imaging.

These challenges are even more pronounced in LMICs, which bear a disproportionate share of the global cardiovascular disease (CVD) burden [8]. The steep costs of acquisition, operation, and maintenance of standard MRI systems render them prohibitive and consequently unsustainable for healthcare systems in these regions [9–11]. Additionally, the lack of adequate infrastructure, appropriately trained personnel, and scarcity of training programs for CMR further limit its use, exacerbating gaps in cardiovascular diagnostics and early intervention capabilities [12]. Addressing these barriers through cost-effective solutions, such as low-field (LF) CMR, is therefore essential to improving global cardiovascular health outcomes.

Recent evolutions in LF CMR (0.3–1.0 T) offer a promising solution to many of these challenges. Technological advances in LF MRI have broadened its clinical applicability beyond traditional cardiac imaging. Commercial low-field systems are now being utilized for comprehensive body imaging, including lung, musculoskeletal, and abdominal assessments [13], making this a versatile and cost-effective technology and therefore improving accessibility to advanced diagnostics in underresourced healthcare settings, such as LMICs [14]. Moreover, LF MRI has been identified as a promising tool for screening high-risk populations—such as women with a familial or genetic predisposition to breast cancer—where both cost and accessibility are primary concerns [15]. For example, MR mammography is known to be more sensitive than standard x-ray mammography, especially for women with dense breast tissue. But it is often limited to women who are at high risk because of the expense and restricted availability of conventional MRI. Recent interest in shorter ("abbreviated") MRI protocols has opened avenues for applying LF MRI more broadly, potentially reducing costs and making regular screening feasible for women who might otherwise be unable to access advanced imaging. LF systems also hold potential for simple treatment monitoring in conditions like liver disease, where frequent follow-up scans may be necessary but are often constrained by financial and infrastructure barriers [16–18].

Low-field CMR using systems operating at 0.55 T is particularly attractive. Emerging evidence from head-to-head and same-patient studies indicates that for core CMR tasks—including cine volumetry and wall-motion analysis, phase-contrast flow, and quantitative T1/ECV mapping—diagnostic performance at 0.55 T can closely approximate 1.5 T when modern acquisition and reconstruction strategies are used. However, formal outcome-level "clinical yield" data and large comparative trials remain limited, and some advanced applications (e.g., first-pass perfusion, highly detailed fibrosis assessment) still require further validation at low field. A commercial 0.55-T system is available but has not yet received regulatory clearance for cardiac imaging. These developments position LF CMR as a potential, cost-effective alternative to standard systems, particularly in resource-limited settings, as supported by comparative data on capital expenditure, operational costs, and sustainability factors summarized in Tables 1 and 2. As research continues to refine these innovations and the number of clinical adopters and end users grows, LF CMR is poised to play a central role in the global expansion of cardiovascular diagnostics, offering a scalable solution for both developed and developing healthcare systems.

Modern LF systems leverage advanced magnetic field gradient coils, radiofrequency (RF) technology, and AI-driven image reconstruction to overcome challenges associated with lower signal strength. A simplified infrastructure employing sealed magnets that require only minimal helium markedly reduces the need for specialized cooling systems, lowering both cost and complexity in clinical settings. Table 1 summarizes the key differences between standard and LF MRI.

In this review, we build upon our 2022 publication [7] by highlighting recent technological advancements and emerging clinical applications of LF CMR in cardiovascular care [14, 19–31]. By incorporating the latest evidence, we aim to provide a comprehensive update on how LF CMR can help address the growing global burden of CVD and improve access to high-quality diagnostic imaging.

TABLE 1 | Comparative overview of high-field versus low-field CMR.

Parameter	High-field CMR	Low-field CMR	Clinical/operational implications
Field strength	Typically 1.5 or 3 T; higher magnetization translates to inherently higher SNR and more advanced imaging capabilities (e.g., perfusion, high-resolution mapping)	Ranges from 0.3 to ~1.5 T; offers lower initial magnetization and thus inherently lower SNR, although AI-driven denoising and advanced sequences can compensate	Higher SNR at 1.5–3 T aids detailed tissue characterization, but low-field systems still provide diagnostic-quality images with cost and safety advantages, particularly beneficial in resource-limited settings
Helium requirement	Traditional 1.5-T magnets contain hundreds of liters of liquid helium; unless zero-boil-off, they lose ~1%–4% per month, requiring periodic refills (e.g., ~€34 k for 864 L). Newer 1.5-T models with sealed magnets reduce this cost. 3 T: Similar cryogen burden as 1.5 T or more; most 3 T are also superconducting. Some newer 3 T designs (Philips, etc.) aim to use less helium (~7 L sealed), but conventional 3 T requires large helium fills.	Often cryogen-free (e.g., permanent magnets or superconducting magnets with minimal helium) or use advanced cryocoolers	High helium dependence increases both installation and operational costs; cryogen-free low-field solutions lower maintenance and mitigate helium supply volatility
Signal-to-noise (SNR)	Generally high SNR, allowing shorter acquisition times and improved spatial resolution	Intrinsically lower SNR; can be mitigated by optimized hardware (high-performance gradients, RF coils) and reconstruction methods (compressed sensing, AI)	Lower SNR at low field can lead to longer scan times or reduced resolution; however, emerging techniques enable clinically sufficient image quality
Specific absorption rate (SAR) constraints	Higher RF power deposition → more restrictive SAR limits, especially at 3 T	Lower global SAR at low field may reduce overall RF power deposition; however, local RF-induced heating depends on device-specific resonance effects and cannot be assumed to be reduced. Safety must be evaluated on a case-by-case basis, particularly for elongated conductive structures.	At high field, SAR often constrains certain pulse sequences; low-field scanners allow safer scans for at-risk populations (e.g., those with metallic implants or limited thermoregulatory capacity)
Bore size and design	Standard cylindrical bores, typically narrower; can lead to patient discomfort or claustrophobia	Often feature open or wider bores (some permanent magnet designs); reduced acoustic noise	Open/compact designs improve patient comfort, facilitate scanning obese or claustrophobic patients, and potentially reduce sedation requirements
Fringe field	Large fringe fields require specialized shielding and facility siting (RF-shielded rooms and reinforced floors)	Smaller fringe fields ease siting requirements (lighter weight, potentially no need for dedicated RF-shielded rooms)	Reduced facility costs and simpler installation make low-field MRI more feasible in outpatient, mobile, or rural/remote settings

(Continues)

TABLE 1 | (Continued)

Parameter	High-field CMR	Low-field CMR	Clinical/operational implications
Susceptibility artifacts	Strong susceptibility effects lead to larger artifacts near metal implants or air–tissue boundaries	Reduced susceptibility effects; improved imaging near metallic implants and fewer off-resonance distortions	Beneficial in postsurgical imaging or in patients with pacemakers/defibrillators
Purchase cost	**$1–$1.5+ million** typical for a new 1.5-T scanner (can exceed $1 M after adding site prep and options). **$2–$3 million** for a high-end 3-T system is common (approximately $1 M per Tesla scaling; can approach $3 M with all features). Largest upfront cost among routine clinical MRI.	Lower capital cost compared to conventional 1.5-T systems, although variability is substantial depending on system architecture (portable vs. superconducting) and configuration; reported reductions should be interpreted cautiously and are context-dependent.	Cost benefits are particularly significant for low- and middle-income countries (LMICs), or smaller clinics where budget constraints and maintenance overhead are pivotal.
Cost per scan	For 1.5 T: Highly variable; depends on utilization. At full capacity, equipment amortization might be ~$100+ per scan. For example, one hospital found ≈€180 total cost per MRI (general) exam, of which ~€90 was equipment-related. Per-scan cost can be high if utilization is low, but 3 T can scan faster or with higher resolution, potentially increasing throughput. In practice, cost per scan often slightly higher than 1.5 T due to higher capital and maintenance—unless fully booked.	Lower expected cost per scan due to reduced capital and running costs (exact $/scan varies by volume; potentially ~30%–50% lower than 1.5 T on equipment/service portion).	
Maintenance needs	Requires specialized service teams, periodic helium refills, and higher infrastructural support Substantial annual service contracts (often ~$100 k/year).	Less complex hardware maintenance, often minimal or no helium use. Portable and ultralow-field systems are more amenable to deployment in resource-limited environments; however, clinical low-field superconducting systems (e.g., 0.55 T) still require dedicated infrastructure and specialized maintenance.	Lower maintenance burden and simpler repair cycles enable wider deployment and fewer downtimes, especially in regions with limited technical support

Note: Low-field MRI systems encompass heterogeneous technologies with distinct infrastructure and economic profiles. Statements regarding power requirements, cost, and deployment feasibility vary substantially between ultralow-field portable systems and clinical low-field superconducting scanners (e.g., 0.55 T).
Abbreviations: CMR, cardiovascular magnetic resonance; LMICs, low- and middle-income countries; SAR, specific absorption rate; SNR, signal-to-noise ratio.

TABLE 2 | Low-field vs. high-field MRI according to SCMR sustainability recommendations.

Sustainability factor	LF-CMR	Conventional CMR	SCMR sustainability recommendations
Energy consumption	Energy consumption is lower compared to higher field systems. However, infrastructure requirements vary significantly by system type. Ultralow-field portable systems may operate on standard electrical supply with minimal infrastructure. In contrast, clinical low-field superconducting systems (e.g., 0.55 T) require dedicated installation, three-phase power supply, and appropriate cooling and support systems. **Installation** cost up to 70% less (lighter magnet, no quench pipe)	1.5 T: Higher—needs dedicated power supply and cooling. An MRI can draw tens of kW; even idle, a unit may use ~35–47 MWh/year in electricity (≈$8–10 k/year) just for cooling systems. Active scans add to HVAC load and power use. 3 T: Highest energy usage among these: stronger gradients and cooling mean greater power draw. Requires robust cooling (chiller) and electrical infrastructure. The annual electricity cost for a 3 T can be significant (likely somewhat above 1.5T's ~35–47 MWh, depending on usage).	Reduce scanner idle power and optimize protocols
Helium use	Minimal or cryogen-free	Helium usage depends on magnet design. Modern high-field scanners (1.5 and 3 T) increasingly adopt sealed magnet technology with minimal helium requirements (< 10 L), eliminating the need for refilling.	Transition to low-helium systems
Weight and siting	Lighter, simpler installation	Heavy, requires reinforced floors	Improve redeployment and recycling
Equipment recycling	Easier redeployment	Harder to recycle due to infrastructure needs	Extend scanner lifespans and optimize disposal
Scan time	Slightly longer for some applications	Faster for high-res imaging	Optimize protocols to reduce scan time
SNR and resolution	Lower than 1.5 T+	Higher diagnostic detail	Use AI and reconstruction to close the gap

Note: Low-field MRI systems encompass heterogeneous technologies with distinct infrastructure and economic profiles. Statements regarding power requirements, cost, and deployment feasibility vary substantially between ultralow-field portable systems and clinical low-field superconducting scanners (e.g., 0.55 T).

1.1 | Classification of Low-Field CMR Systems

Low-field CMR encompasses a spectrum of MRI systems with distinct hardware architectures, which differ substantially in terms of infrastructure requirements, clinical capabilities, and deployment models. Broadly, these systems can be categorized into two main groups: (1) ultralow-field portable systems and (2) clinical low-field superconducting systems.

Ultralow-field systems (typically < 0.1 T) are commonly based on permanent magnet designs and are optimized for portability, low power consumption, and point-of-care applications. These systems can often operate using standard electrical infrastructure and require minimal site preparation, making them particularly attractive for use in resource-limited settings and bedside imaging scenarios. However, their lower field strength is associated with reduced signal-to-noise ratio (SNR) and limited spatial resolution, constraining their application primarily to targeted use cases such as neuroimaging or screening [9].

In contrast, clinical low-field systems operating at intermediate field strengths (e.g., 0.55 T) are typically based on superconducting magnet technology. Although these systems offer significantly improved image quality and support a broader range of cardiovascular applications—including cine imaging, flow quantification, and myocardial tissue characterization—they retain many of the infrastructural requirements of conventional MRI systems. These include dedicated installation, specialized power supply (often three-phase), and manufacturer-supported maintenance [32].

Recognizing these distinctions is essential when evaluating the clinical and operational potential of low-field CMR, as the advantages related to accessibility, portability, and cost are not uniformly applicable across all system types.

1.2 | Technological Advances in Low-Field CMR

The escalating demand for accessible, cost-effective CMR has fueled significant progress in LF MRI. These advances not only target the cost and infrastructure barriers inherent to standard systems but also broaden the clinical capabilities of LF imaging for cardiovascular care. This section outlines key developments in LF hardware, gradients, RF systems, real-time imaging techniques, cryogen-free technology, and sustainability strategies [32–35]. Figure 1 summarizes some of the technological advances in low-field MRI.

1.2.1 | Low-Field Hardware Concepts

LF CMR typically refers to systems operating below 1.0 T [32]. These scanners have gained traction due to reduced cost, simpler siting requirements, and cryogen-free magnet technologies. At lower fields, MRI magnets can be specifically designed superconductors requiring minimal helium, permanent magnets, or resistive electromagnets. Such designs reduce both the infrastructure and the high maintenance costs of conventional high-field machines [17–36]. For example, cryogen-free superconducting coils and magnet designs cooled by Gifford–McMahon cryocoolers can mitigate the global helium supply dependence [37, 38], leading to more sustainable installation and operations, especially in resource-limited environments [32].

In permanent magnet designs (e.g., Halbach arrays), no external cryogens are necessary, thereby reducing installation overhead [39, 40]. These relatively lightweight systems are also useful in mobile units and outpatient clinics, facilitating point-of-care imaging [18]. Resistive electromagnets, cooled by water or air, further expand this concept by allowing flexible field strengths [40, 41]. The key advantage of all these LF approaches is their smaller fringe fields and lighter weight, significantly easing siting requirements, often eliminating the need for reinforced floors or elaborate RF-shielded rooms [17, 34]. Table 3 summarizes the different LF MRI magnet technologies.

Although gradient strengths in LF scanners are typically lower than in standard 1.5- or 3-T devices, modern electronics and RF coil designs compensate for reduced SNR. Although only a handful of 0.55-T systems currently employ high-performance gradients, they demonstrate that advanced pulse sequences and precise spatial encoding are still achievable at LFs [42]. Simultaneously, the radiofrequency (RF) wavelength at 0.55 T is longer, lowering energy deposition [32] and allowing higher flip angles without exceeding specific absorption rate (SAR) limits [43, 44].

1.2.2 | Advantages in Patient Safety, Device Compatibility, and Comfort

LF MRI introduces several important clinical benefits. At lower magnetic field strengths, magnetohydrodynamic (MHD) effects are diminished, improving the stability of ECG triggering/gating used for the synchronization of the data acquisition with cardiac motion [33]. The longer RF wavelength in tissue reduces the risk of tissue heating, making it safer for patients with metallic implants such as pacemakers or abandoned leads [34, 45–47]. Low-field MRI systems are associated with reduced global SAR; however, this does not inherently eliminate the risk of RF-induced heating. RF-induced heating is a localized phenomenon driven by electromagnetic coupling and resonance effects, which are strongly influenced by device

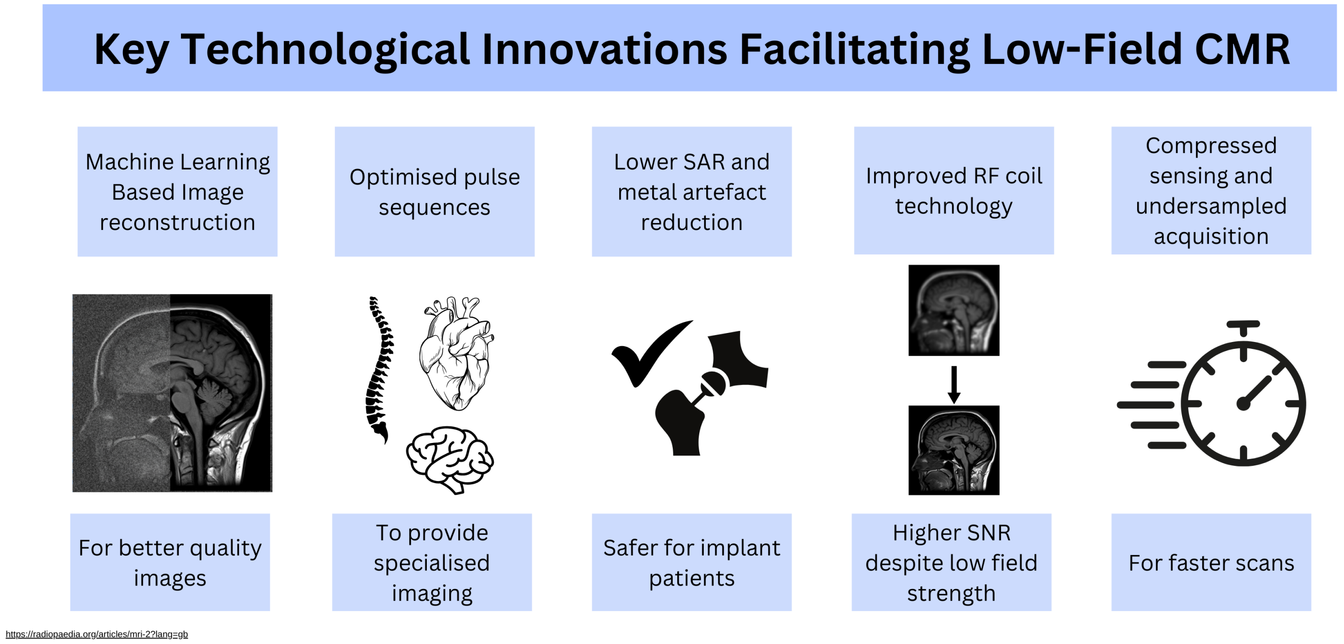

FIGURE 1 | Technological advances enabling low-field CMR.

TABLE 3 | Summary of key low-field MRI magnet technologies.

Magnet Type	Typical Field Strength Range	Cooling Method	Advantages	Disadvantages	Representative Commercial Example
Ramped-down conventional superconducting magnet	~0.55 T (adapted from 1.5 T)	Helium-based (comparable to standard 1.5-T MRI), albeit run at a lower field	- Uses established high-field magnet design, ensuring good field homogeneity. - Retains modern gradient and coil hardware.—Familiar workflow and service paths for experienced MRI centers.	- Still relies on superconducting technology, requiring helium and specialized service.—Overall scanner size, weight, and siting needs comparable to full 1.5-T systems.—Partial magnet ramp-down reduces field but not the infrastructure burden.	*Older 1.5-T systems ramped down to 0.55 T for research/clinical adaptation.*
Specifically designed low-field superconducting magnet	~0.5–1.0 T	Minimal/cryogen-free helium use (e.g., conduction cooling or MgB_2 wires)	- Reduced helium dependence lowers long-term costs and carbon footprint.—High magnet homogeneity for body-wide imaging - Maintains many advanced CMR capabilities (spiral, bSSFP, and mapping sequences)	- Still more expensive than permanent magnets due to superconducting components. - May need specialized parts (cryocoolers, advanced quench safety protocols) - Typically heavier and larger than permanent or resistive magnet designs	- 0.55 T **Siemens MAGNETOM Free. Max** - 0.5 T **Paramed MROpen** - 0.5 T **Synaptive Evry**
Permanent magnet (e.g., Halbach arrays, C-shaped magnets)	~0.06–0.7 T (commonly 0.3–0.5 T)	None (no cryogens needed)	- No liquid helium; low maintenance needs - Often lighter total system weight (especially smaller bores) - Lower fringe fields and simpler facility siting - Safer scanning for device-bearing patients (reduced susceptibility artifacts)	- Heavier for midrange fields (some designs weigh thousands of kg) - Limited to lower fields (≥ 1.0 T is rare) - Field strength sensitive to temperature changes; passive shimming may be needed. - SNR shortfalls can require extended scan times or advanced recon.	- 0.064 T **Hyperfine Swoop** (head-only) - 58–74 mT **Promaxo** (prostate imaging)

(Continues)

TABLE 3 | (Continued)

Magnet Type	Typical Field Strength Range	Cooling Method	Advantages	Disadvantages	Representative Commercial Example
Resistive electromagnet	~0.02–0.6 T (prepolarization magnets can briefly reach ~0.6 T)	Water or air cooled	- Adjusting coil current can vary magnetic field strength. - Affordable upfront costs vs. superconductors. - Potentially easier on-site construction with coil winding and steel return paths	- Requires continuous power to maintain the field, raising energy consumption - Heat buildup demands water cooling and carefully managed power supplies. - Field homogeneity can be modest, requiring frequent calibration or specialized gradient strategies.	- Custom-built neonatal systems (~0.02–0.2 T) - Research prototypes (prepolarization ~0.6 T; readout ~20–30 mT)

Abbreviations: bSSFP, balanced steady-state free precession; CMR, cardiovascular magnetic resonance; MgB_2, magnesium diboride; MRI, magnetic resonance imaging; SNR, signal-to-noise ratio.

geometry, orientation, and insertion trajectory. Recent studies have demonstrated that RF heating at low field may be comparable to, or in some cases exceed, that observed at higher field strengths when conductive structures approach resonance conditions [48]. Therefore, RF safety at low field requires rigorous, device-specific evaluation and cannot be generalized based on field strength alone.

Reducing off-resonance artifacts near device hardware is a well-documented advantage of low-field MRI, aiding in postsurgical cardiac imaging [39, 49, 50]. It is important to distinguish between reduced susceptibility artifacts—which primarily improve image quality—and broader safety considerations, as reduced artifact burden does not directly translate to reduced RF-induced heating risk. Additionally, the wider bore design and the lower acoustic noise in low-field systems enhance patient comfort, addressing issues of claustrophobia and anxiety [35]. Notably, the risk of MRI-induced vertigo has been shown to increase with field strength; low-field systems may reduce this effect, which can otherwise compromise patient tolerance or even cause falls [51, 52]. These patient-centric advantages expand the pool of eligible subjects, particularly those who cannot tolerate conventional high-field exams or those whose implanted devices pose challenges in 1.5- or 3-T environments [34, 45, 53]. In a cohort study comparing standard 1.5 T and low-field scanners, most patients reported no claustrophobia during scanning on either 1.5 T (91.9%) or 0.55 T (90.1%) systems. Among those examined on both scanners, most perceived no difference, though a significant proportion favored the low-field system. These data suggest that although overall claustrophobia prevalence is low, patients with direct comparative experience preferred the low-field environment [54].

1.2.3 | Technological Approaches to Enhance LF Image Quality

In parallel with hardware simplifications, LF CMR systems exploit a range of modern imaging computational techniques. The net magnetization—and thus SNR—decreases with field strength, following a nonlinear relationship ($SNR \sim B_0^{1.65}$) [55]. So, hardware improvements at 0.55 T are increasingly paired with modern reconstruction strategies—such as compressed sensing, simultaneous multislice (SMS), and AI-based denoising. Although these techniques are widely applied at 1.5 and 3 T as well, and do not alter the fundamental SNR limitations of low-field systems, they help to mitigate the practical impact of lower signal by reducing scan times, stabilizing image quality, and improving perceived diagnostic confidence. In this way, they make clinically feasible acquisitions possible at 0.55 T despite reduced intrinsic magnetization [56, 57]. In many cases, sequences such as balanced steady-state free precession (bSSFP) remain reliable at 0.55 T for cine imaging, with only mild increases in scan time or adjustments to flip angles [14, 58]. The broad consensus now is that these refinements can produce diagnostic-quality images of cardiac function and blood flow at LF strengths [32, 43]. For clarity, representative parameters used in same-patient and feasibility studies are summarized in Table 4. At 0.55 T, cine bSSFP typically employs higher flip angles (120°–160°) permitted by lower SAR, with slightly coarser in-plane resolution (~1.6–2.0 mm). Temporal resolution remains in the clinically acceptable range (35–45 ms).

TABLE 4 | Representative imaging parameters for cardiac cine bSSFP at 0.55 versus 1.5 T.

Parameter	0.55 T (typical)	1.5 T (typical)	Notes/references
Sequence	Balanced SSFP, high flip angle (120°–160°)	Balanced SSFP, flip angle 45°–60°	Higher flip feasible at low-field due to reduced SAR
Spatial resolution	1.6–2.0 × 1.6–2.0 mm^2 in-plane; slice 6–8 mm	1.4–1.8 × 1.4–1.8 mm^2 in-plane; slice 6–8 mm	Slightly coarser in-plane res at 0.55 T
Temporal resolution	35–45 ms	30–40 ms	Minor differences; both clinically acceptable
Typical TR/TE	TR ~3.0–3.5 ms; TE ~1.5–1.7 ms	TR ~2.8–3.0 ms; TE ~1.3–1.5 ms	Similar ranges; slightly longer TR at 0.55 T
Flip angle	120°–160°	45°–60°	SAR constraints looser at 0.55 T
Number of phases	25–30	25–30	Comparable
SNR (relative)	~25%–30% lower than 1.5 T	Reference (59%)	SNR loss mitigated by reconstruction (CS/AI)
Scan time (per slice stack)	12–18-s breath-hold (standard); 1–2-min free-breathing with CS	8–12-s breath-hold	Slightly longer at 0.55 T; real-time CS can reduce
Qualitative IQ	Diagnostic, good blood-myocardium contrast; slightly higher noise floor	High, with sharper borders	Agreement shown in same-patient studies

Scan times at 0.55 T are modestly longer than at 1.5 T for several routine CMR applications. For example, cine bSSFP stacks typically require ~12–18 s per slice at 0.55 T compared with ~8–12 s at 1.5 T, or ~1–2 min for free-breathing accelerated cine. Similarly, LGE acquisitions are ~15%–20% longer at 0.55 T due to reduced intrinsic SNR. Despite these differences, diagnostic image quality is preserved. Ongoing advances—such as compressed sensing, SMS imaging, and AI-based reconstructions—are already demonstrating substantial time savings, with free-breathing whole-heart cine and joint T1/T2 mapping at 0.55 T achievable in clinically practical durations. Thus, although scan time remains a current limitation, technological innovations continue to narrow the gap with high-field CMR.

For instance, compressed sensing (CS) reconstructions dramatically reduce acquisition times by reconstructing undersampled data with high fidelity [56]. SMS imaging acquires multiple slices concurrently, shortening scans and reducing breath-hold demands [56]. At 0.55 T, relatively high flip angles (90°–110°) can be used in bSSFP sequences to facilitate superior blood–myocardium contrast [59, 60]. Moreover, advanced gradient waveforms such as spiral sampling further improve sampling efficiency and mitigate motion artifacts, enabling free-breathing acquisitions in challenging cardiac cases [56].

An emerging trend is the integration of machine learning for both reconstruction and postprocessing (Figure 2). Deep learning models reduce noise while preserving fine structure [59], enabling diagnostic-quality images even under lower SNR conditions. Free-breathing 3D bSSFP sequences, combined with inline motion correction algorithms, are particularly promising, as they maintain temporal and spatial resolution without heavy reliance on breath-holds [57].

Although all of these approaches may also be used at higher field, the impact is greatest at low field, where an image can go from unusable to diagnostic on an accessible scanner.

1.2.4 | Novel Cardiac Applications

At 0.55 T, high-quality imaging of the lung parenchyma is possible due to the longer T2*, thereby creating new opportunities for cardiopulmonary assessment. For example, real-time imaging of lung water density and cardiopulmonary dynamics has been successfully achieved using ultrashort echo time (UTE) techniques [61]. These sequences, combined with automated inline image processing, provide quantitative assessments of lung water redistribution in heart failure patients, offering a novel noninvasive method to monitor disease progression [62, 63]. Another new opportunity is in fetal imaging, where low-field offers lower acoustic noise, less susceptibility artifacts, and wider bore. Dynamic imaging techniques have been applied to fetal cardiac imaging, where optimized bSSFP sequences at 0.55 T have enabled the successful visualization of fetal heart structures and blood flow [20]. These innovations demonstrate the versatility and expanded capability of LF systems in tackling a range of dynamic imaging challenges, from fetal monitoring to pulmonary assessments.

1.2.5 | Sustainability and Global Accessibility

The shift toward environmentally sustainable CMR is a critical focus in modern imaging, as highlighted by the Society for Cardiovascular Magnetic Resonance (SCMR) [64]. Compared to standard systems, LF CMR presents significant advantages in

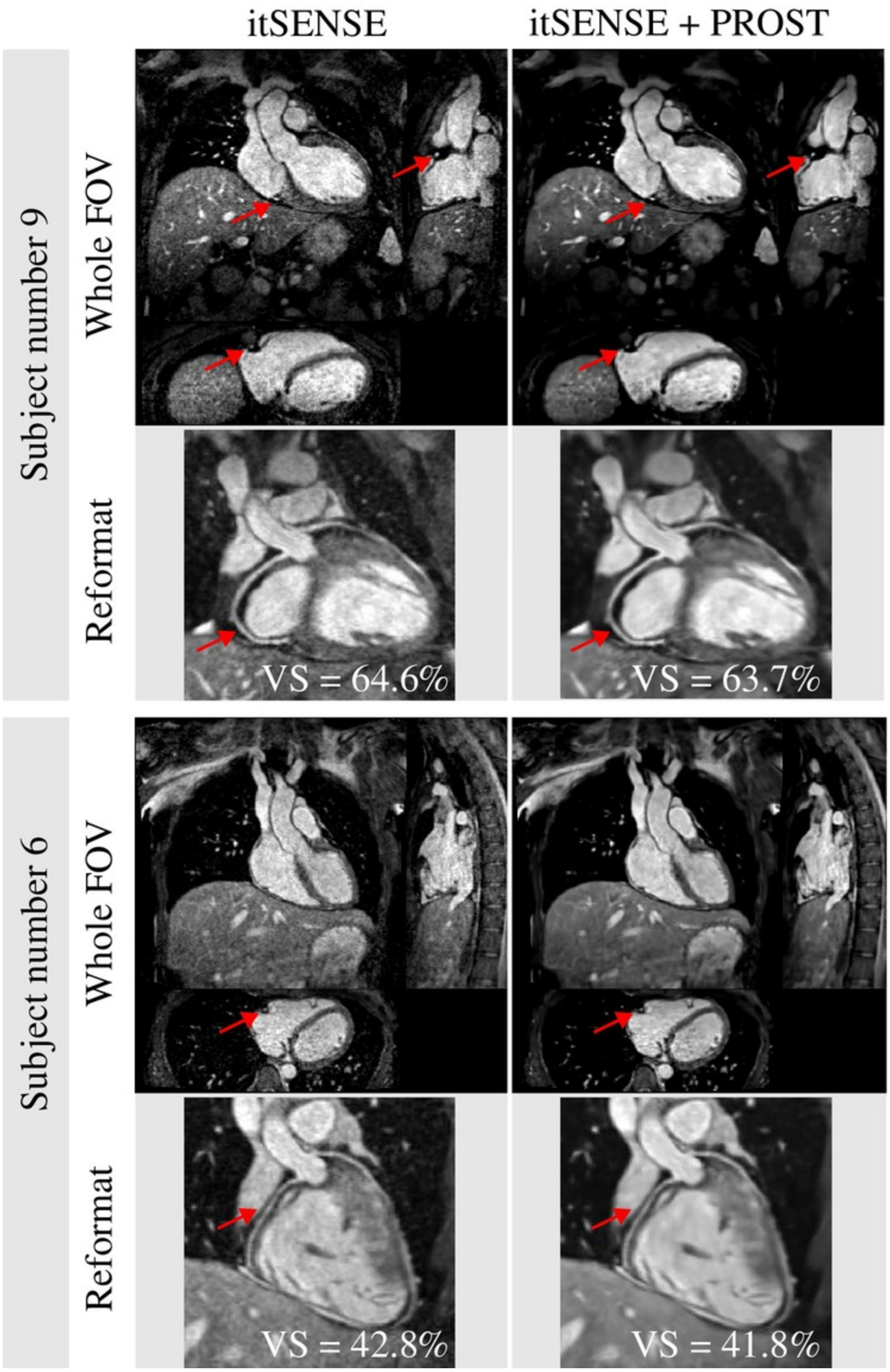

FIGURE 2 | Effect of AI-based PROST denoising on 0.55-T whole-heart coronary MRA. Images reconstructed with conventional iterative SENSE (itSENSE, left) show increased noise compared with those reconstructed with PROST denoising (right). Denoising improved overall image quality but was associated with a slight reduction in vessel sharpness (mean vessel sharpness: 51.4% ± 10.8% for itSENSE versus 50.3% ± 9.8% for itSENSE + PROST; $p = 0.054$) (Adopted from Ref [28]).

reducing energy consumption, minimizing helium dependency, lowering waste, and improving accessibility, all of which align with sustainability objectives. Table 4 summarizes the benchmarking of low-field versus standard MRI against the sustainability recommendations of SCMR.

1.2.5.1 | Energy Consumption and Carbon Footprint. One of the primary sustainability concerns with conventional MRI scanners is their high energy demand. A standard 1.5-T system consumes about 13 kW in idle mode and up to 31 kW when actively scanning, whereas a 3-T scanner can reach 55 kW. By contrast, some low-field designs—particularly those with reduced gradient performance—draw less power during scans (e.g., around 20 kW at peak for a 0.55-T system), which can translate to meaningful energy savings in high-use settings [65]. However, idle power may not be dramatically lower if sealed superconducting magnets still require cryogen pumps, so the overall carbon footprint reduction depends on both scan volume and system design. Even with these caveats, lowering peak power demands can offer tangible operational efficiencies and improved sustainability in resource-constrained environments [66].

1.2.5.2 | Helium and Rare Earth Metal Dependence. The SCMR report underscores the scarcity of helium and other finite resources, such as niobium and titanium, which are extensively used in MRI magnet construction. Conventional 1.5-T scanners require approximately 1000 L of helium over their lifespan, whereas helium-reduced models still consume around 70 L [64]. In contrast, LF scanners, particularly those with cryogen-free designs, eliminate helium usage entirely or reduce it to minimal levels (< 1 L in some cases). Permanent and electromagnet-based LF systems require no helium at all, making them exceptionally sustainable. However, cryogen-reduction and cryogen-free technologies represent a broader evolution in MRI magnet design across field strengths, rather than a feature unique to low-field systems. Advances such as sealed magnet architectures and microcooling technologies have enabled both low-field and high-field MRI systems to significantly reduce or eliminate helium dependence [67].

By minimizing helium and material usage for superconducting wire, floor reinforcement, and shielding, LF-CMR systems contribute to long-term environmental sustainability and reduce the risks associated with resource depletion and supply chain disruptions, and improve local sovereignty.

1.2.5.3 | Equipment Longevity and Recycling Potential. Sustainability in MRI is not just about energy efficiency but also about equipment life cycle management. The SCMR highlights the significant environmental cost associated with manufacturing, transporting, and decommissioning high-field MRI scanners, which are often large, heavy, and require specialized infrastructure [64].

In contrast, LF-CMR systems—particularly cryogen-free and permanent magnet models—often have a significantly smaller physical footprint, require fewer structural modifications, and can be installed in diverse settings, including mobile units. Some newer systems no longer require full room-sized Faraday cages, due to their reduced fringe fields and RF emissions, which simplifies siting and lowers installation costs. Although permanent magnets can be heavier than superconducting alternatives, the overall system design is often less complex, improving adaptability for redeployment and easing end-of-life recycling. This flexibility enhances sustainability by reducing the need for frequent replacements and minimizing waste from decommissioned imaging systems [68, 69].

1.3 | Clinical Applications of Low-Field MRI

LF MRI systems (e.g., 0.55 T) have evolved to reliably perform the routine cardiac MRI sequences typically used at 1.5 T, proving effective for cardiac structure and function assessments even under the inherent SNR constraints of lower fields [32]. By leveraging hardware improvements and refined imaging protocols, these systems support a broad range of clinical applications in cardiology—from basic ventricular volume measurements to advanced interventions.

1.3.1 | Assessment of Cardiac Function and Ventricular Volumes

Cine imaging, crucial for quantifying chamber volumes, ventricular mass, and systolic function, has been validated extensively at LF strengths [58, 70, 71]. Comparative studies between 0.55 and 1.5 T show near-equivalent accuracy in assessing ventricular volumes and detecting regional wall-motion abnormalities, underscoring the viability of LF CMR for standard cardiac evaluations [14, 71–73]. To compensate for reduced magnetization, sequences such as bSSFP can be modified with higher flip angles and spiral-in-out acquisitions, boosting the blood-myocardium contrast and the SNR without requiring longer breath-holds [32, 74]. Figure 3 [14] shows example cine images acquired at 1.5 and 0.55 T in a 39-year-old man undergoing clinically indicated CMR for mild dilated and valvular cardiomyopathy. Two readers rated image quality as excellent at both field strengths.

1.3.2 | Myocardial Tissue Characterization

Myocardial tissue characterization forms the backbone of diagnosing myocarditis, ischemic injuries, and infiltrative cardiomyopathies. LF CMR has successfully adapted LGE and T1/T2 mapping methods, matching or closely approximating results at 1.5 T [13, 58, 75]. Although lower field strengths naturally produce reduced SNR, sequence optimizations and advanced reconstruction algorithms maintain sufficient diagnostic accuracy to evaluate myocardial fibrosis and scar burden. Notably, T1 mapping at 0.55 T correlates strongly with 1.5-T-derived ECV values, as shown in Figure 4 [75], making it valuable for diffuse pathology assessments [14, 76].

Despite promising early results, myocardial tissue characterization remains one of the most significant challenges for low-field CMR and represents a critical gap compared to higher field systems. Although techniques such as LGE and T1/T2 mapping have been adapted to 0.55 T, their diagnostic performance is still inherently influenced by reduced SNR, altered relaxation times, and lower spatial resolution [32].

These factors may limit sensitivity for detecting subtle or diffuse myocardial fibrosis, particularly in early-stage disease. Furthermore, the lack of standardized reference ranges for parametric mapping at low field remains a major barrier to clinical translation, as values are field-strength dependent and not directly comparable to established 1.5- and 3-T benchmarks [14].

From a clinical perspective, this limitation is particularly relevant when considering that echocardiography can reliably assess cardiac structure and function, especially in resource-limited settings. Therefore, the added value of LF-CMR must be justified through its ability to provide tissue-level information

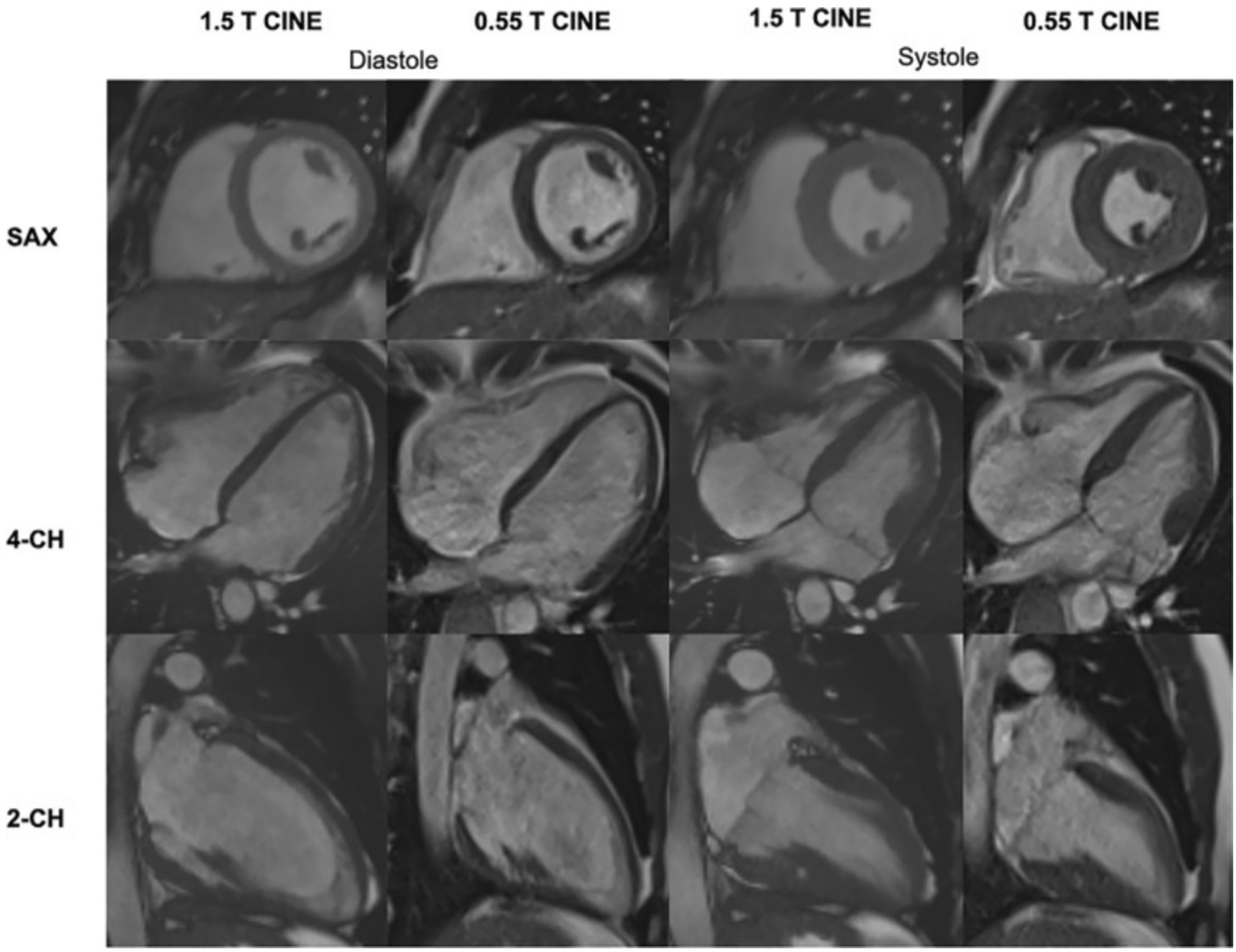

FIGURE 3 | Example cine images acquired at 1.5 and 0.55 T in a 39-year-old man undergoing clinically indicated CMR for mild dilated and valvular cardiomyopathy. Short-axis (top row), four-chamber (middle row), and two-chamber (bottom row) views are shown in end-diastolic and end-systolic phases. Two readers rated image quality as excellent at both field strengths (Adopted from Ref [14]).

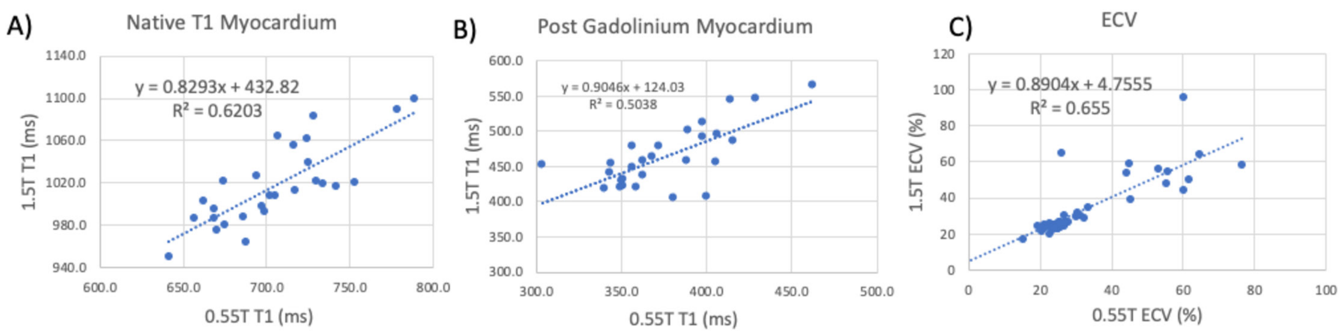

FIGURE 4 | Scatter plots showing correlation between 0.55- and 1.5-T measurements of (A) Native myocardial T1, (B) postcontrast myocardial T1 and (C) extracellular volume (ECV). Data points include both remote myocardium and chronic infarct. In Panel C, the higher ECV values (> 40%) correspond to infarcted regions (Adopted from Ref [75]).

not otherwise accessible. In this context, LF-CMR tissue characterization should currently be considered complementary rather than substitutive.

Ongoing technical advancements are expected to mitigate these limitations. Sequence optimization strategies, including high flip-angle bSSFP imaging and improved inversion recovery techniques, have shown promise in enhancing contrast and signal efficiency at low field [32]. Additionally, emerging artificial intelligence (AI)-based reconstruction and denoising techniques have demonstrated the potential to compensate for reduced SNR and improve image quality, enabling more reliable quantitative tissue assessment [19]. As these technologies continue to evolve, they are expected to play a key role in improving the robustness and clinical applicability of myocardial tissue characterization at low field.

1.3.3 | Flow Quantification and Hemodynamics

Flow quantification is another critical application of CMR, particularly in the evaluation of valvular disease, congenital heart disease, and pulmonary hypertension. LF CMR systems, using advanced phase-contrast imaging, have demonstrated robust capabilities in measuring blood flow through major vessels, with studies showing comparable results to 1.5-T systems. Specifically, phase-contrast imaging at 0.55 T has been successfully applied to quantify aortic and pulmonary artery flow, with excellent correlation to high-field measurements [77]. These capabilities extend to both pediatric and adult populations, making LF CMR a valuable tool for assessing hemodynamics in complex congenital and acquired heart diseases. Recently, bSSFP-based flow measurements have been demonstrated to further improve SNR without compromising quantification.

An additional advantage of low-field CMR is the improved robustness of imaging in regions of turbulent or complex flow. At 0.55 T, reduced susceptibility effects and longer T2* values mitigate signal loss that can occur at higher fields near stenotic valves, regurgitant jets, or prosthetic devices [78]. This translates into fewer artifacts in areas of high velocity or turbulence, potentially enhancing visualization of flow jets and quantification of valvular lesions. Same-patient studies have confirmed high correlation of aortic and pulmonary flow measurements at 0.55 versus 1.5 T, with anecdotal reports of improved artifact resistance in turbulent-flow settings.

1.3.4 | Interventional Cardiovascular Magnetic Resonance (iCMR)

The integration of real-time imaging capabilities with low-field MRI systems has opened new avenues for iCMR, including catheter ablation, MR thermometry, and MR-guided angioplasty in early feasibility studies. These applications leverage the intrinsic safety advantages of low-field (reduced RF heating and improved device compatibility) [79–81]. This approach is particularly advantageous for the following.

1.3.4.1 | MR-Guided Cardiac Ablation. Minimally invasive procedures for arrhythmias (e.g., ventricular tachycardia) can leverage real-time imaging and MR thermometry at 0.55 T to visualize and monitor lesion formation during ablation. Using proton resonance frequency shift (PRFS)–based thermometry, temperature changes in myocardial tissue can be tracked in real-time, providing indirect yet continuous feedback on lesion development. This technique has the potential to improve procedural precision and reduce recurrence rates by ensuring adequate lesion delivery without relying on ionizing radiation [82–85]. Figure 5 shows the difference in guidewire heating at 0.55 versus 1.5 T [81].

1.3.4.2 | MR Thermometry at 0.55 T. MR thermometry, based on the PRFS method, allows for real-time temperature monitoring during ablation [86]. A recent study demonstrated the feasibility of cardiac MR thermometry at 0.55 T using commercially available systems [79]. Key findings included as follows:

- Temperature stability: Achieved stability of 1.8°C ± 1.0°C, comparable to 1.5-T systems (1.5°C ± 0.4°C), demonstrating its potential for guiding ablation procedures.
- Reduced susceptibility effects: Although low-field MRI systems are associated with reduced global SAR, RF safety in interventional applications remains complex and cannot

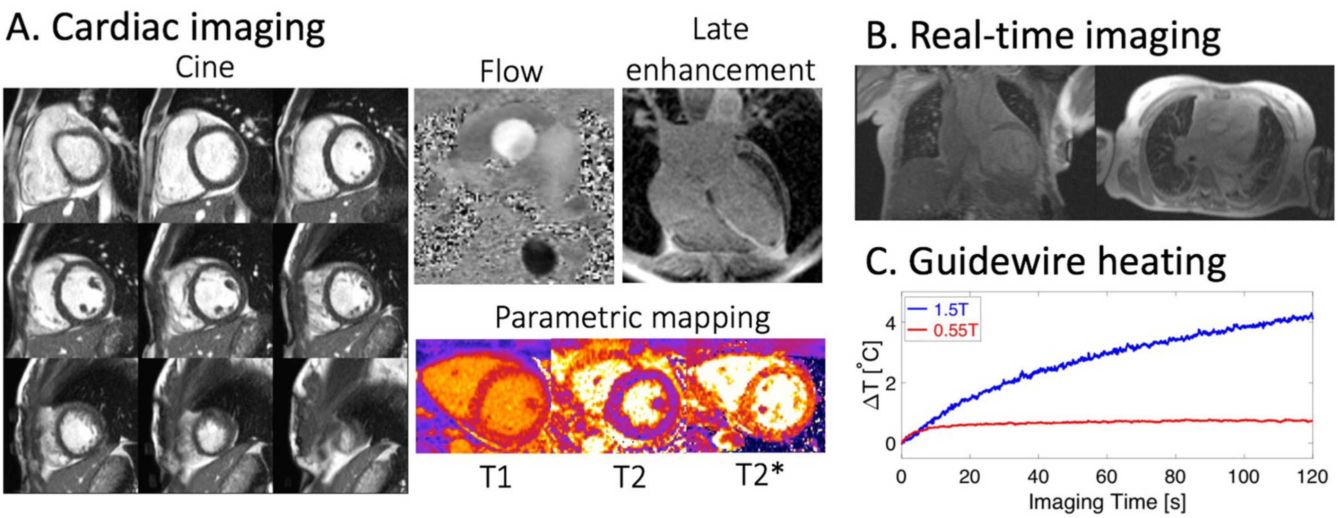

FIGURE 5 | Interventional CMR at low field. (A) Example cardiac MR images acquired using a high-performance 0.55-T imaging system illustrating the comparable image quality. (B) Real-time bSSFP imaging used for patient right heart catheterization at 0.55 T. (C) Guidewire (180 cm × 0.035″ Glidewire, Terumo, Tokyo, Japan) heating in an ASTM gel phantom measured at 1.5 T and prototype 0.55 T (both MAGNETOM Aera, Siemens Healthcare, Erlangen, Germany). *ASTM* American Society for Testing and Materials, *bSSFP* balanced steady-state free precession, *CMR* cardiovascular magnetic resonance (Adopted from Ref [81]).

be generalized. Local RF-induced heating is governed by resonance phenomena, which depend on the relationship between RF wavelength and the effective electrical length of conductive devices. At 0.55 T (Larmor frequency ~23 MHz), the longer RF wavelength in tissue shifts the half-wavelength resonance condition to physically longer dimensions. As a result, elongated conductive structures—such as guidewires, electrophysiology catheters, or extended implant leads—that may be off-resonance at higher field strengths can approach resonance at low field, potentially increasing localized RF heating [48].

- Technological innovations: Multibaseline correction of respiration-induced phase changes significantly improved temperature map accuracy, enabling robust and consistent monitoring during dynamic cardiac motion.

These developments suggest that LF MR thermometry can provide operators with real-time feedback on ablation position and lesion depth, potentially reducing recurrence rates by enabling precise and targeted therapy [79, 87].

1.3.4.3 | MRI-Guided Angioplasty and Stent Deployment. A recent preclinical study demonstrated, for the first time, the feasibility of performing real-time MRI-guided right and left heart catheterization, inferior vena cava (IVC) angioplasty, and stent deployment using a commercially available wide-bore 0.55-T CMR scanner [22]. In this study, researchers successfully used standard interventional tools—including wedge catheters, guidewires, and stainless steel stents—modified with MR-visible passive markers to carry out stenting procedures under MRI guidance.

Stainless steel stents generated only minimal susceptibility artifacts at 0.55T, enabling accurate visualization of deployment and wall apposition, whereas a platinum–iridium stent produced more significant artifacts that hindered postdeployment assessment. The wide-bore and low RF energy environment of the 0.55-T system facilitated safe and effective navigation of devices, highlighting the potential of low-field MRI as a platform for complex cardiovascular interventions. These findings underscore the expanding scope of low-field iCMR beyond ablation procedures, providing a radiation-free alternative for vascular interventions, especially in patient populations requiring repeated imaging.

However, such procedures remain confined to advanced research environments, and their translation to LMICs will require substantial investment in infrastructure, training, and device availability. In LMICs, the primary near-term value of low-field MRI lies in expanding access to core diagnostic CMR applications—cine, flow, and tissue characterization—whereas interventional uses should be viewed as a longer term opportunity. Active research targets refined respiratory compensation, advanced device design (e.g., specialized catheters), and large-scale trials to validate the safety and efficacy of LF iCMR [31, 88–90].

1.3.5 | Pediatric and Fetal Cardiac Imaging

The use of LF MRI in pediatric and fetal cardiac imaging is particularly compelling due to its safety profile, cost-effectiveness, and ability to accommodate pregnant patients more comfortably during prolonged exams [18]. Although lower SNR and reduced gradient performance at 0.55 T can present technical challenges, recent studies have nonetheless demonstrated the feasibility of visualizing major fetal cardiac structures and quantifying flow in utero [20, 91]. This represents a meaningful step forward in expanding access to fetal cardiac imaging, especially in environments where conventional MRI may not be feasible. In pediatric populations, LF CMR is emerging as a preferred option for repeated imaging, particularly in congenital heart disease [23].

In summary, LF CMR has firmly established its capability to address a range of cardiac clinical demands, from basic volumetric assessments to sophisticated interventional procedures. Combined with increasing cost-efficiency and expanding hardware options, these systems—particularly at 0.55 T—are poised for broader integration into routine and advanced cardiovascular care, offering high diagnostic confidence and greater patient tolerance in both well-resourced and low-resource settings.

1.4 | Low-Field CMR for Global Health

LF CMR offers an unprecedented opportunity to address the growing global burden of CVD, which disproportionately affects LMICs. Approximately 80% of CVD-related deaths occur in LMICs, highlighting the urgent need for diagnostic solutions that are both effective and cost-efficient [92, 93].

Early deployments of LF MRI in LMICs have demonstrated that this technology can circumvent many historical barriers to advanced imaging, such as high cost, complex infrastructure requirements, and inadequate specialist personnel. In sub-Saharan Africa, for example, work at Mbarara University of Science and Technology (MUST) in Uganda has shown how locally constructed MRI systems can succeed in environments where limited resources have traditionally hampered adoption [11, 94]. Although most current applications emphasize general diagnostic imaging, these initiatives underscore the feasibility of adapting low-field solutions to specific healthcare needs, including cardiac protocols. The International Society for Magnetic Resonance in Medicine (ISMRM) has further bolstered these efforts through a 2023 partnership with the Bill and Melinda Gates Foundation [95], focusing on augmenting MRI availability in Africa and bridging the gap in diagnostic imaging between high- and low-resource regions.

1.4.1 | Low-Field CMR in LMICs: Current Status

Despite the sparse publication of large-scale LF CMR data in LMICs, several proof of concept deployments illustrate its promise in resource-limited settings. For example, Sheth and colleagues employed a 0.064-T MRI system for bedside stroke management [96, 97], whereas Zhao et al. recently introduced a whole-body 0.05-T MRI system capable of cardiac imaging at improved field homogeneity [98], demonstrating how cryogen-free, LF technology can overcome constraints in power, helium availability, and specialized staffing—challenges shared by advanced cardiac imaging worldwide. Organizations like RAD-AID International and Imaging the World also continue to pilot low-cost imaging in sub-Saharan Africa, Southeast Asia, and

Latin America, showing rising global interest in using LF scanners across a broader array of clinical scenarios.

1.4.1.1 | Affordable Access in LMICs. Traditional MRI often remains out of reach for many LMICs due to steep acquisition and maintenance costs. LF systems counter these barriers by offering lower initial investments and easier upkeep, helping reduce the gap in advanced cardiac diagnostics. Innovations such as cryogen-free technology have further reduced the operational complexity and costs associated with LF MRI [13]. Halbach array magnets are easy to service and maintain by replacing individual magnets or rows of magnets. Open-source initiatives like OSI2 ONE enable sites to build their own scanners, and in doing so, gain expertise for maintaining equipment [99].

1.4.1.2 | Addressing Limited Resources. Regions with intermittent electricity or limited technical expertise benefit from the lower energy demands and simpler design of low-field MRI systems. This reduced complexity can make staff training more feasible, as the operational learning curve is generally less steep than for conventional high-field scanners [42, 80].

However, the increasing reliance on cloud-based image reconstruction and remote support introduces a new dependency: stable internet connectivity. In many low-resource settings, limited or inconsistent internet access may hinder the use of these cloud-enabled features. Developing local reconstruction pipelines or hybrid cloud-edge solutions may help mitigate this limitation.

Furthermore, the potential for energy independence through solar power offers a compelling solution for sites lacking reliable grid electricity. Many low-field systems operate within a 10–30-kW range, raising the possibility of powering them with appropriately sized solar arrays in conjunction with a 20-kWh battery system. Although this model of autarchy is still largely theoretical, it represents a promising avenue for delivering sustainable, off-grid diagnostic imaging in remote and underserved regions.

1.4.1.3 | Global Health Initiatives and the Future of Low-Field CMR. LF CMR aligns closely with global health priorities, such as the United Nations' Sustainable Development Goals (SDGs), particularly SDG 3 on promoting well-being for all ages [100]. As healthcare systems in LMICs evolve, LF MRI can anchor key diagnostic services, strengthening both infrastructure and clinical capability [30]. Strategic partnerships among international organizations, governments, and industry—combined with targeted investments in workforce training—will be critical to scaling up these systems and unlocking their full diagnostic potential [19]. Figure 6 illustrates a workflow for implementing low-field MRI in resource-limited settings.

In parallel with technological innovation, remote mentoring and training programs have become essential to expanding CMR capacity. Professional organizations—including the SCMR, the ISMRM, and advocacy groups such as RAD-AID International and Consortium for Advancement of MRI Education and Research in Africa (CAMERA)—now deliver structured online teaching, case interpretation workshops, and technologist training. These initiatives provide accessible pathways for radiologists, cardiologists, and MR technologists in resource-limited settings to develop CMR expertise, bridging geographic and institutional gaps.

1.5 | Benchmarking LF-CMR for Global Adoption: Standardization and Validation

1.5.1 | The Need for Standardized Benchmarking in LF-CMR

For LF CMR to achieve widespread adoption—especially in LMICs—robust validation frameworks must confirm that acquisition techniques, reconstruction methods, and postprocessing algorithms consistently meet clinical standards. The Medical Image Computing and Computer-Assisted Intervention

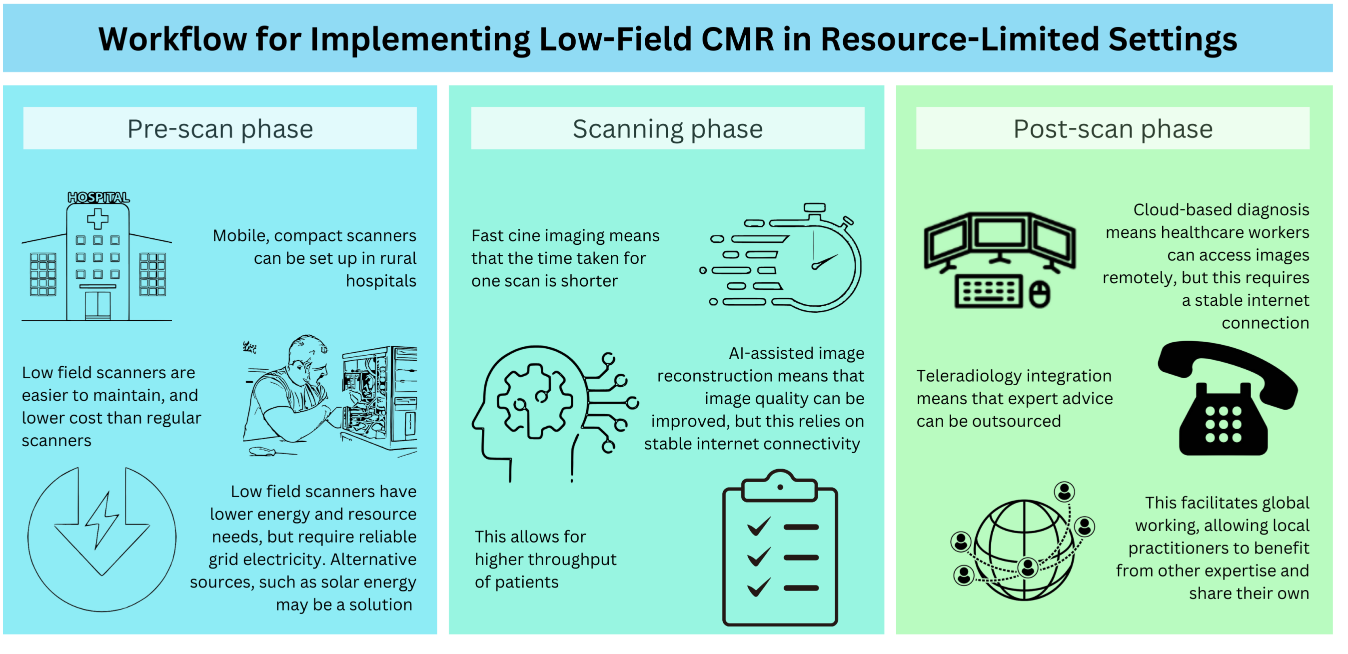

FIGURE 6 | Workflow for implementing low-field CMR in resource-limited settings.

(MICCAI) community exemplifies how global challenges can validate new imaging software and AI algorithms using standardized, harmonized datasets [100]. A similar benchmarking framework would greatly accelerate LF-CMR's clinical uptake and foster transparency:

- Reproducibility: Comparing performance across scanner manufacturers and field strengths to ensure uniform high-quality results.
- Collaboration: Encouraging synergy among academics, vendors, and clinicians to refine LF-CMR protocols.
- AI Innovation: Motivating researchers to optimize advanced reconstruction methods, reducing scan times while preserving diagnostic accuracy.
- Clinical comparisons: Benchmarking LF-CMR directly against high-field systems for critical applications like tissue characterization, perfusion, and flow quantification.

1.5.2 | Proposed Structure for a Global LF-CMR Benchmarking Initiative

- A structured global benchmarking challenge would involve.
- Curating harmonized datasets: Gather large, diverse LF-CMR data from both LMICs and HICs to capture broad patient demographics and scanner variations.
- Defining clinical metrics: Establish outcome measures that accurately gauge LF-CMR's performance in ventricular volume assessments, fibrosis detection, and quantitative myocardial mapping.
- AI-based reconstruction challenges: Facilitate contests that encourage robust deep learning or compressed sensing methods specifically tuned for LF-CMR.
- Industry and regulatory collaboration: Partner with manufacturers, policy experts, and regulatory agencies to align challenge outcomes with clinical requirements, easing the path to broader approvals.
- Economic benchmarking and cost–benefit analysis: Incorporate an economic dimension that evaluates the cost-effectiveness of LF-CMR—both for specific applications (e.g., heart failure monitoring and myocarditis diagnosis) and as a general cardiovascular diagnostic platform. This would include comparative analyses of capital and operational costs, training and infrastructure requirements, and projected clinical and societal benefits (e.g., earlier diagnosis, reduced hospitalization, and improved access in underserved regions). Such economic benchmarking is essential to inform procurement decisions, public health investments, and policy formulation, particularly in resource-limited settings.

1.6 | Beyond an Academic Discussion: LF-CMR as a Real-World Solution

Although ongoing academic investigations are vital and pioneering in the field, the eventual goal is to demonstrate LF-CMR's tangible benefits so that policymakers, hospital administrators, and patients can confidently invest in this technology. By establishing and publicizing a formal global benchmarking effort, stakeholders in LMICs can implement validated LF MRI solutions with minimal hesitation, bridging the gap between cutting-edge research and daily clinical practice. Ultimately, widespread use of LF-CMR, supported by strong standards and relevant training, can revolutionize cardiovascular care in underserved regions and propel international efforts to deliver equitable, high-quality diagnostics.

1.7 | Challenges and Future Prospects

While LF CMR has demonstrated considerable potential to transform cardiovascular diagnostics—especially in resource-constrained settings—several challenges remain. These span technical, clinical, and operational domains, all of which must be addressed to achieve widespread clinical adoption. In addition, the current body of research on LF CMR remains relatively limited compared to standard systems. More studies are needed to close knowledge gaps, validate emerging techniques, and establish robust clinical guidelines. At the same time, ongoing innovations in hardware, software, and imaging protocols present promising avenues for overcoming existing barriers, positioning low-field CMR as a pivotal tool in the future of global cardiovascular health.

1.7.1 | Technical Limitations and Image Quality

A key challenge for low-field CMR is the reduced SNR, which can impact diagnostic accuracy, particularly for advanced applications like perfusion imaging and detailed myocardial tissue characterization. Although recent advances—such as compressed sensing, variational networks, and AI-based reconstructions—have improved image quality at 0.55 T, these systems still face limitations in spatial resolution and acquisition speed compared to 1.5- and 3-T scanners [32, 57, 101]. Continued innovation in hardware and reconstruction algorithms will be essential to further narrow this gap and expand the clinical applicability of LF-CMR [13].

1.7.2 | Acquisition Time and Patient Throughput

Extended acquisition times remain a challenge in LF CMR, particularly when compared to the faster scan times achievable with higher field systems. This is a critical factor for clinical workflows, especially in busy healthcare settings where patient throughput is a key consideration. Studies have shown that although LF CMR can provide diagnostic-quality images for cardiac function and flow quantification, scan times are often doubled compared to 1.5-T systems [14, 102]. Longer acquisition times can also increase the likelihood of motion artifacts, particularly in patients with limited breath-hold capacity, further complicating the imaging process.

However, techniques like compressed sensing (CS) and radial K-space sampling offer promising solutions for accelerating image acquisition in LF CMR [103]. Compressed sensing allows for undersampling in data acquisition, significantly reducing scan times while maintaining image quality [104, 105]. This technique has been successfully applied to LF CMR, particularly in free-breathing and real-time imaging protocols, enabling faster acquisitions without compromising diagnostic accuracy [106].

Ongoing efforts to optimize techniques, particularly those designed for real-time and free-breathing acquisitions, are expected to reduce scan times and improve patient comfort. Advanced reconstruction algorithms, such as deep learning-based methods, hold promise for accelerating data acquisition without compromising image quality, which could help LF CMR achieve greater parity with high-field systems in terms of efficiency [19].

1.7.3 | Training and Expertise in Low-Field CMR

A significant nontechnical challenge to the widespread adoption of LF CMR is the training and expertise required to effectively use and interpret LF CMR images. Although LF systems are generally easier to operate than their high-field counterparts, a learning curve remains—particularly in optimizing protocols and interpreting subtle findings in lower SNR images. This challenge is amplified in many LMICs, where CMR expertise is often limited [13].

Addressing this gap requires robust, tailored training programs focused on low-field system operation, image acquisition strategies, and interpretation techniques. In parallel, incorporating automated image processing and AI-assisted diagnostic tools can support less experienced users and promote consistent results [19, 61, 107].

1.7.4 | Expanding Clinical Validation and Standardization

Although recent studies have demonstrated that LF CMR can provide reliable diagnostic information for a range of cardiovascular conditions, further clinical validation is needed. Most existing research focuses on functional assessments, such as ventricular volumes and flow measurements, but there is still a need for more robust evidence on the use of LF CMR for advanced myocardial tissue characterization, perfusion imaging, and fibrosis detection [13, 14]. Additionally, standardizing imaging protocols across different LF systems will be critical for ensuring consistent diagnostic performance and facilitating broader clinical adoption. Establishing reference ranges pertaining to the magnetic field strength at lower fields for volumetric quantifications, scar quantification, and T1 and T2 mapping is an additional challenge given the sparsity of data at the moment.

Future research should focus on conducting large-scale, multicenter clinical trials that directly compare the diagnostic accuracy of LF CMR to high-field systems across a range of cardiac pathologies. These studies will be essential for validating the clinical utility of LF CMR and developing standardized imaging protocols that can be adopted across different healthcare settings [60].

1.7.5 | Integration into Healthcare Systems and Global Health Initiatives

The successful integration of LF CMR into healthcare systems, particularly in LMICs, will require tackling several operational and logistical challenges. Although LF systems are more affordable and easier to install than standard systems, healthcare providers in resource-limited settings may still face difficulties in acquiring the necessary equipment, maintaining the systems, and ensuring a consistent supply chain for replacement parts and upgrades [13].

To overcome these barriers, global health initiatives, including public–private partnerships and funding from international organizations, will play a crucial role. Ensuring that LF CMR systems are included in national healthcare strategies, particularly in LMICs, will be critical for their widespread adoption sustainably integrated into healthcare systems over the long term [80, 108].

International collaborations and partnerships with technology developers, nongovernmental organizations, and governmental bodies will be crucial in expanding the use of LF CMR globally. Initiatives that focus on both financing the acquisition of LF systems and supporting the necessary training and infrastructure development will help ensure that these systems can be deployed in underserved regions, where they can make the greatest impact on cardiovascular health outcomes.

2 | Conclusion

Low-field CMR has emerged as a promising tool that improves accessibility and reduces costs, making it particularly attractive for resource-constrained settings. Head-to-head studies have shown feasibility and diagnostic agreement with high-field systems for key applications such as cine function, flow, and parametric mapping. However, current evidence does not yet demonstrate equivalence to 1.5 or 3 T across all domains, particularly for advanced tissue characterization, perfusion, and outcome-level diagnostic yield. Thus, low-field CMR should presently be regarded as a complementary and evolving modality, with further multicenter comparative trials and clinical outcome studies required to establish its role as a true alternative to high-field systems. With its potential to democratize access to advanced cardiovascular diagnostics and improve global health outcomes, LF CMR is well-positioned to eventually play a pivotal role in addressing the global burden of CVD.

Author Contributions

Conceptualization: S.A., M.U. *Writing – original draft preparation*: A.M., M.U. *Writing – review and editing*: U.C.A., A.E.C.-W., N.A.B.N., O.P.S., T.N., R.M., S.A. *Supervision and project adminstration*: S.A. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

No new data were generated or analyzed in support of this research. All information presented is derived from previously published studies, which are appropriately cited within the article.

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