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RESEARCH ARTICLE

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Bringing MRI to low- and middle-income countries: Directions, challenges and potential solutions

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Abstract

The global disparity of magnetic resonance imaging (MRI) is a major challenge, with many low- and middle-income countries (LMICs) experiencing limited access to MRI. The reasons for limited access are technological, economic and social. With the advancement of MRI technology, we explore why these challenges still prevail, highlighting the importance of MRI as the epidemiology of disease changes in LMICs. In this paper, we establish a framework to develop MRI with these challenges in mind and discuss the different aspects of MRI development, including maximising image quality using cost-effective components, integrating local technology and infrastructure and implementing sustainable practices. We also highlight the current solutions—including teleradiology, artificial intelligence and doctor and patient education strategies—and how these might be further improved to achieve greater access to MRI.

Abbreviations: bSSFP, balanced steady-state free precession; FOV, field of view; FPGAs, field-programmable gate arrays; FSE, fast spin echo; GDP, gross domestic product; HIC, high income countries; HTS, high temperature superconducting; LMICS, low- and middle-income countries; MFI, microfinancing institutions; NdFeB, neodymium iron boron; PMP, per million population; RFPA, radiofrequency power amplifiers; SAR, specific absorption rate; SNR, signal-to-noise ratio; ULF, ultra low field.

KEYWORDS
Affordable, global health, low field, macroeconomics, microeconomics, MRI, sustainable, technology

1 | INTRODUCTION

1.1 | Current magnetic resonance imaging disparities across the world

Magnetic resonance imaging (MRI) is used worldwide to evaluate various neurovascular, oncological,[1–5] musculoskeletal[6,7] and cardiovascular conditions.[8,9] Despite this essential clinical role, it is estimated that 66% of the world does not have access to MRI scanners.[10–12] The scanner density in low- and middle-income countries (LMICs) is significantly lower than in high-income countries (HICs), with 1.12 MRI units per million population (pmp) in LMICs compared with 26.53 MRI units pmp in HICs,[13,14] as illustrated in Figure 1. The magnetic field strength of MRI systems (in T) also correlates with a country's income group, with HICs seeing a more significant proportion of high-field (HF) scanners ($B_0 \geq 3T$) compared with LMICs.[10,15] Alongside intercountry disparity there is intracountry disparity, with a higher density of MRI scanners seen in urbanised regions than in rural communities, which are often poorly serviced and require patients to travel further to reach MRI scanners.[10,16–18]

1.2 | The rationale for improving MRI access

Accessible healthcare imaging is vital to achieving universal healthcare provision.[19,20] Greater MRI access is required as LMICs undergo the 'epidemiological transition' from communicable to noncommunicable disease.[21] This transition is observed as a 'double burden' on healthcare—an increase in noncommunicable disease with the added pressures of communicable disease—discussed in previous literature.[22–24]

MRI is frequently used for the two most prevalent noncommunicable diseases: cancers and cardiovascular disease.[25–27] It is estimated that scaling up imaging could reduce 2.46 million cancer deaths worldwide.[28] For example, breast cancer affects ~7.8 million women,[29] and it is thought that advancements in rapid scanning protocols[30] could make MRI the most effective imaging tool in its diagnosis.

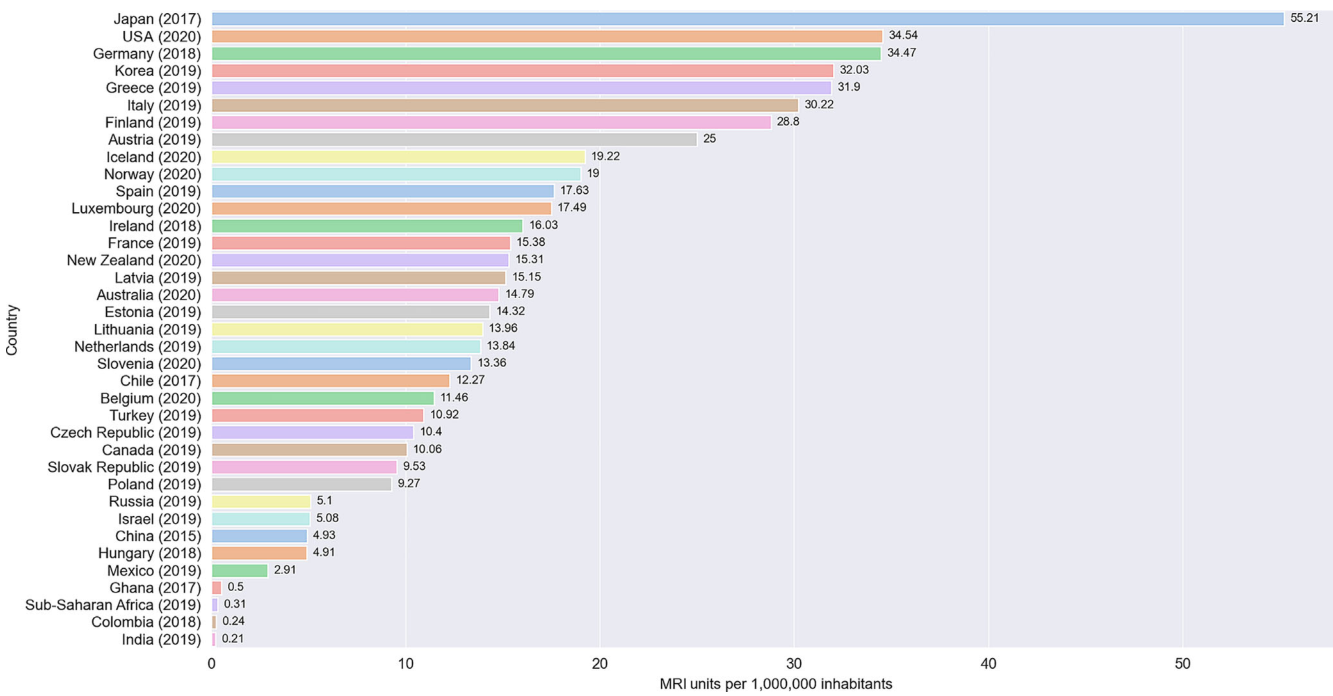

FIGURE 1 Bar chart displaying the MRI units per million population, according to the Organization for Economic Co-operation and Development. The data are organized by density, with Japan having the highest density at 55.21 units per million population. The barchart is from Qin et al.[68]

MRI possesses many advantages over other imaging modalities, such as a lack of radiation exposure compared with x-ray and computed tomography (CT), and better visualisation of soft tissue than ultrasound, CT and x-ray.[31] On the other hand, MRI is a technically challenging imaging modality, requiring significant investment to purchase and trained personnel to maintain and operate. These barriers are compounded by geographical limitations and the lack of public investment by governments in adequate infrastructure, vendor-financing programmes and a reliable energy supply.[11]

Despite current barriers and practical obstacles, technical advances allow us to postulate potential changes that could make technology more suitable for resource-poor environments. New directions include optimising affordable and sustainable MRI technology, their implementation in clinical practice and further adjustments tailored for resource-poor settings. This review outlines the current solutions and how they might be improved to better adapt MRI for the developing world.

2 | CHALLENGES OF MAKING MRI MORE AVAILABLE

2.1 | Economic

2.1.1 | Macroeconomic perspective

The acquisition and siting of MRI scanners alone can cost upwards of $1 million (for magnetic resonance [MR] instruments using superconducting whole-body magnets),[32] not to mention the construction costs as well as annual running costs and maintenance contracts. Historically, LMICs have tended to allocate a minimal budget towards healthcare; for example, in 2018, LMICs spent 5.41% of their gross domestic product (GDP) on healthcare compared with 12.46% of GDP spent by HICs.[12] Together, these factors have previously made MRI inaccessible to LMICs.

However, LMICs are experiencing a health financing transition: a phenomenon describing the shift from low governmental spending and individual out-of-pocket (OOP) expenditure to increased government spending.[33] Overall, there has been an increase in healthcare investment globally, but improvement in healthcare requires a proactive effort by governments.[12] Additionally, well-intentioned government initiatives might not yield the desired results if not properly executed and monitored. For instance, the organisation of government spending, the effectiveness of current treatments and the impact of private healthcare[12] all affect service provision.

MRI is superior in improving quality-adjusted life years and reducing the number of scans a person undertakes in many diseases,[34,35] compared with more affordable imaging modalities such as x-ray and ultrasound. However, LMICs appear reluctant to invest in sophisticated healthcare technology such as MRI, prioritising investment in x-ray and ultrasound.[36–38]

Aid dependence has also been well documented in LMICs[39–41]; however, this is an unreliable funding source, with donations making up a smaller proportion of overall global healthcare spending.[12] The question remains whether countries could provide a package of essential healthcare services to their citizens independently. Ly et al. found that achieving this goal in sub-Saharan Africa by 2035 would be difficult, especially with the prospect that economic growth over a certain threshold may exclude countries from receiving further donations.[42] Fast-growing economies still require aid to supplement their growth, receiving around 36% of the total aid.[12] More bespoke donor agreements are recommended between HICs and LMICs, so that LMICs continue to benefit from aid while undergoing economic growth.[43]

2.1.2 | Microeconomic perspective

Considerable progress has been made in government spending on healthcare. Nevertheless, 40% of healthcare spending in LMICs is still OOP expenditure.[44] Individually, healthcare is expensive, with an estimated half a trillion dollars spent annually in LMICs.[45] Figure 2 shows the average individual healthcare expenditure in different countries as a percentage of income.

From a microeconomic perspective, RAD-AID suggests incorporating microfinance institutions (MFIs) to foster radiological start-ups.[43] MFIs allow individuals to take collateral-free loans. This venture model provides entrepreneurs with initial working capital, which individuals can then pay back when their business grows to a substantial enough size to afford the repayments. However, MFIs are rarely used to fund healthcare start-ups, and are instead used to pay for healthcare.[46]

Many caveats exist with MFIs. MFIs are established on the premise that impoverished business owners will eventually make sufficient profit to be able to pay back the loan with a high level of interest.[47,48] High interest rates are utilised in order to sustain loan accessibility without asking for collateral; for example, some MFIs in Mexico issue interest rates of 40%.[47] Unfortunately, these loans have a high default rate, so MFIs hardly, if ever, see a return on investment.[47,48]

Health insurance is another avenue to help patients with healthcare expenditures. Social health insurance schemes appear most suited to LMICs but are less comprehensive (incapable of covering the chronically ill, the poor and pre-existing conditions[49]) and rely on self-reported incomes. In LMICs, many undertake nontaxable work, or current tax reporting schemes are incapable of assessing what proportion of their income

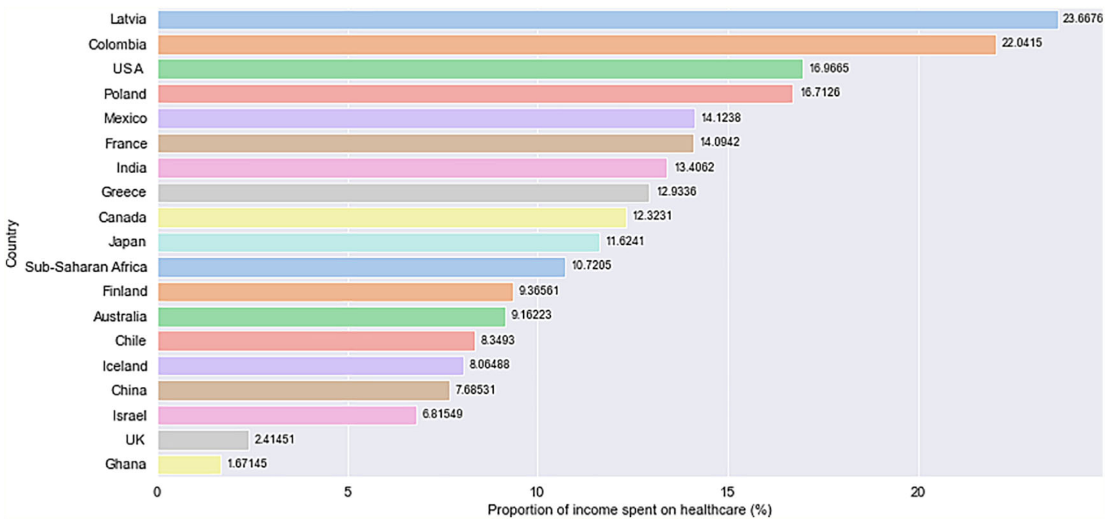

FIGURE 2 Bar chart showing the percentage, ranked by largest to smallest, of the average amount per capita spent on healthcare in each country as a percentage of overall income per capita. For many high-income countries, the proportion of money spent on healthcare is a mandatory payment, and for many countries is taken as a proportion of taxes. In many low- and middle-income countries, the largest proportion is voluntary expenditure based on the utility of healthcare services, so while the percentage is low, it is all individual cost. Additionally, some countries have poor reporting schemes that may not fully reflect the true cost of healthcare. The data used to produce this chart were taken from the Organization for Economic Co-operation and Development healthcare spending data,[223] and the average income information was taken from the worlddata.info website.[224]

people are able to afford for healthcare.[50] Private health insurance, although often comprehensive, is only available to the very wealthy. While social health insurance appears to be a step in the right direction for LMICs,[16,51] there are challenges arising with its introduction and concerns regarding the lack of equitable insurance uptake across a country's population.[12]

2.2 | Technology and infrastructure challenges

Imaging technology demands state-of-the-art hardware and software that healthcare systems in LMICs often struggle to provide. MRI software needs to be adapted to accommodate low bandwidth, poor Internet speeds and periods of Internet blackout[43,52] to prevent potential loss of data. One possible solution is to distil MRI systems to their most essential components. This could be through improving user interfaces to reduce the load on local infrastructure or by providing another means of local backup to prevent data loss. In addition, MRI scanners have specific infrastructure requirements, such as imaging rooms and safety zones, which may be challenging to implement in LMICs.[16]

Another critical component of developing healthcare technology is data protection in low-resource areas because of the lack of regulation of healthcare information and its storage.[53] Data protection can be improved by optimising system interoperability, that is, the ability of systems to communicate with one another. This would reduce the need for external communication because everything would be shared through protected channels, reducing data administration requirements, preventing data duplication and reducing workforce burden.[54]

An essential source of MRI technology and equipment for LMICs is donations from HICs.[16,20] Multiple issues pervade donations, from sourcing to delivery and usability. Current MRI donations often lack certain parts on arrival, have limited user training or cannot be accepted because of existing national policies about the age of machines.[16,37,55] In addition, there are issues surrounding the adaptation of MRI technology to the environment of LMICs.[37,55] A lack of adaptation is responsible for 14%–19% of donated medical equipment being out of service.[16] Hopefully, improvements in MRI technology developed for resource-poor locations will diminish the need for MRI donations.

2.3 | Social issues

There is a dearth of radiology training programmes in LMICs, precluding many from understanding and maximising the value of MRI. Many sub-Saharan African countries, such as Zimbabwe and Zambia, have no radiology residencies, and others, like Ethiopia, have only one.[56] Latin America also identified a similar problem, with radiology training only present in seven of 17 countries.[57] In addition, lack of knowledge of equipment maintenance is a significant obstacle, with many user manuals not printed in the country's native language.[16] Lack of access to MRI widens health disparities within and between societies and contributes to growing social and health inequities.

Healthcare illiteracy is also an issue. For many patients, visiting a doctor is a source of anxiety.[58,59] Patients often struggle to navigate public healthcare systems, instead opting for small, private healthcare facilities where they achieve faster consultation, diagnosis and treatment.[60] Some patients prefer alternative health remedies because of a distrust of modern healthcare.[60] In addition, many patients do not recognise or acknowledge worrying symptoms; for example, in South Africa, only 37% see a doctor after 2 weeks of persistent coughing.[61]

It is also worth establishing the role that MRI can play in addressing the clinical needs specific to populations based on the most prevalent diseases in that area. For example, as previously noted, LMICs struggle with the 'double burden' phenomenon, where infectious diseases occur in tandem with noninfectious conditions. Urbanisation and lifestyle changes have led to the increased emergence of noninfectious diseases in LMICs.[62] The rates of noninfectious diseases have increased in many areas, including Africa, Southeast Asia and the Western Pacific.[63,64] MRI has demonstrable clinical utility in the evaluation of noninfectious diseases; for example, it has been used to successfully identify *Plasmodium falciparum*-induced cerebral malaria, *Staphylococcus aureus*-induced osteomyelitis and *Streptococcus*-induced pneumonia.[22]

The utility of MRE in the investigation of noninfectious conditions has been demonstrated in numerous studies and it has been found to be helpful in diagnosing and monitoring treatment in musculoskeletal, neurological and cardiac disease, as well as in cancer staging.[65] MRI can be used to detect local inflammation, oedema and other manifestations of immune response. The presence of pathogens can be shown in changes in local tissue parameters, such as relaxation time, water content or diffusivity; T_2-weighted images being more sensitive to water content and the molecular composition of soft tissue makes it especially useful for recognising pathologically altered tissue.[65] The development of iron oxide particles, lanthanide chelates and fluorinated compounds has enabled the labelling of immune cells and receptors at the site of infection, the visualisation of host-response mechanisms and the severity of inflammation.[66,67] It is of the utmost importance to establish how the systems behind MRI can be altered to tailor them to local needs, such as to account for lack of software and hardware or for a minimal number of adequately trained staff in the region.

3 | FRAMEWORK FOR DEVELOPING ACCESSIBLE MRI

It is essential to discuss the adaptation of the technological aspects of MRI to improve MRI accessibility. In the authors' opinion, the ideal scanner should be suitable for imaging various body parts without excessive expenditure. This could be achieved by using inexpensive and made-to-last components that are immune to deficits in the local infrastructure. They must be easy to replace, must have adequate image quality, spatial resolution and a user-friendly interface. To facilitate these, the different components of MRI technology need to be appraised to establish where changes can be made and what frameworks can be put in place to ensure that MRI can be considered a helpful modality in these healthcare systems.

3.1 | Hardware and technology

3.2 | Signal-to-noise ratio

One of the critical diagnostic currencies of an MRI scanner is image quality, which is governed by the complementary constraints of signal-to-noise ratio (SNR), tissue contrast and spatial resolution. While previous studies have established the usefulness of low-field (LF; B_0 < 1.5 T) MRI in resource-poor settings,[68,69] current solutions still present with SNR limitations, which can be addressed by enabling technology. It is worth discussing how ultralow field (ULF; B_0 < 10 mT) and LF, and the critical components of the MR scanner, can be improved to achieve adequate and affordable image quality.

ULF- and LF-MRI cost less compared with standard field MRI. Recent ULF-MRI developments have removed the need for magnetic and radiofrequency (RF) shielding,[11,70] including portable systems such as the portable Hyperfine system,[71] and yoked or Halbach magnet designs, further increasing their suitability for resource-poor locations. Due to RF wavelength prolongation at LF and ULF, these modalities substantially reduce MRI safety concerns in the presence of passively conducting implants. Furthermore, natural tissue contrast governed by the relaxation times may help to compensate for the low SNR[72]; in this aspect, LF is slightly more advantageous. Moreover, SNR constraints can be offset by optimising pulse sequences and imaging parameters and imaging protocols.[73,74] However, these improvements must be tested in larger cohort studies.

Improvements in image quality can be achieved in many ways. Imaging protocols based on fast spin-echo (FSE) or balanced steady-state free precession (bSSFP) examinations utilised for head, body and cardiac imaging reduce the propensity to susceptibility artefacts that may cause image distortion,[75,76] therefore provide better image quality.[74,76–78] bSSFP and FSE can also benefit from RF power and specific absorption rate

(SAR) reduction at lower fields[77,78]; the SAR is proportional to the square of the magnetic field strength and describes the level of RF power deposition in tissue, which may cause tissue heating.[77,78] The International Electrotechnical Commission states that the average SAR for a 6-min scan should not exceed 4 W/kg for the whole body and 3.2 W/kg for the head when using volume transmit RF coils in the first-level control mode.[79] The UK Medicines and Healthcare products Regulatory Agency (MHRA) recommends that, in normal mode, SAR levels should be monitored to prevent a body core temperature increase of more than 0.5°C.[80]

Advances in pulse sequence development could also help to overcome some of the challenges presented by the low signal sensitivity of ULF versus LF-MRI or HF-MRI. Sarracanie et al. presented a simple, noncryogenic approach to ULF-MRI of the human brain, whereby modern undersampling strategies were combined with fully refocused dynamic spin control using steady-state free precession techniques.[73] At 6.5 mT (more than 450 times lower than clinical MRI scanners), they demonstrated $2.5 \times 3.5 \times 8.5$ mm^3 spatial resolution for human brain imaging using a simple, open-geometry biplanar electromagnet, in conjunction with three-dimensional (3D) image acquisition over the entire brain in a clinically acceptable scan time of 6 min.[73] ULF-MRI instruments showing this level of performance may allow LMICs access to MRI systems without the strict siting requirements and high costs of conventional MR systems. They could complement commercial LF-MRI systems, including rapid neuroimaging of traumatic conditions, haemorrhage, cancer and emergent and re-emergent infections.

While LF-MRI scanners improve SNR compared with ULF-MRI scanners, the SNR of LF solutions still remains a concern that must be mitigated. The most common way to try and mitigate SNR limitations lies in signal averaging over a more prolonged scan time to produce an adequate image, decreasing the efficiency of current solutions. Other ways to compensate for diminished SNR are through increasing voxel dimensions, but this comes with the caveat of reducing spatial resolution[81]; further optimisation is required to improve scanners.[82] Ideally, the aim would be to develop an MR scanner with affordable components to make it accessible to resource-poor regions to try and combat reduced image quality. To achieve this aim, a private company Voxelgrids, based in India, in partnership with Tata Trusts, released a 1.5-T MRI scanner and reported scan times that were four times faster than other commercially available products, as well as a power usage reduction of 60%.[68,83] This exemplifies that affordable, potential solutions that preserve SNR are possible.

Recent developments have demonstrated the clinical feasibility and diagnostic quality of LF-MRI for examinations of the lumbar spine,[84] bedside detection of intracranial midline shift[84] and imaging hips in the presence of hip arthroplasty implants for abdominal imaging[85] and cardiac imaging.[68] Commercial LF scanners have already been established for body extremities[86,87] and neuroimaging,[88] and are considered viable and cost-reducing alternatives compared with current standard MRI solutions (Figure 3). Neuroimaging has been utilised in LMICs, producing

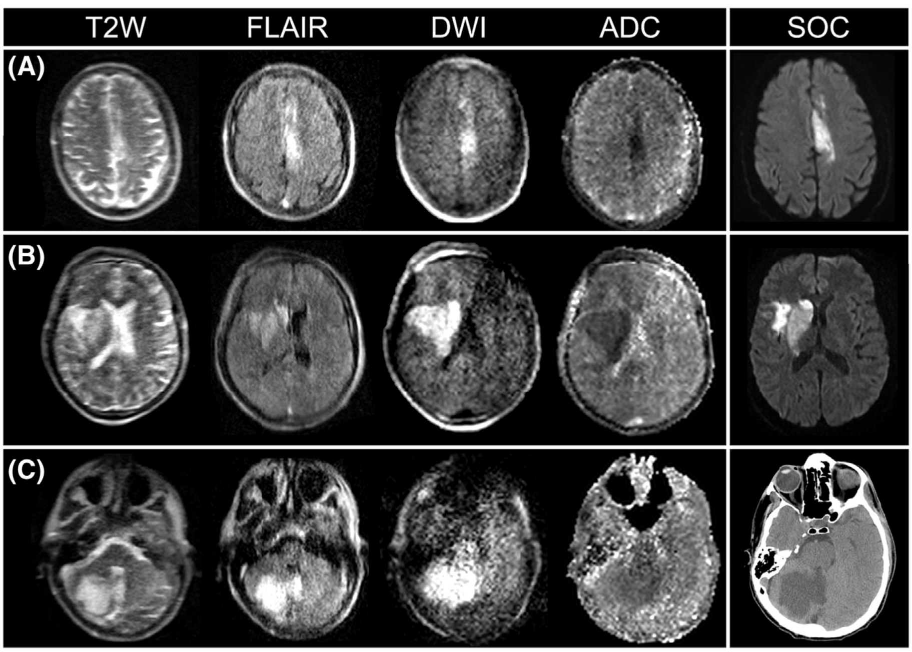

FIGURE 3 Panel of multiple images comparing low-field MRI at 0.064 T (parametric MRI [pMRI]) using Hyperfine Swoop imaging compared with standard care (SOC) capturing ischaemic infarcts in multiple brain regions. (A) The pMRI and SOC (1.5-T) images (32 and 29 h since last known normal, respectively) of a 65-year-old male with a left anterior cerebral artery stroke. (B) The pMRI and SOC (1.5-T) images (29 and 12 h since last known normal, respectively) of a 61-year-old male with a right middle cerebral artery stroke. (C) The pMRI and SOC computed tomography (CT) images (44 and 32 h since last known normal, respectively) of a 57-year-old male with a right cerebellar stroke. SOC examinations included MRI (diffusion-weighted imaging [DWI] sequence) and CT. Images are from Yuen et al.[91] T2–weighted imaging (T2W), fluid attenuated inversion recovery(FLAIR) and apparent diffusion coefficient(ADC).

repeatable and reliable images compared with standard field MRI,[89–91] and helping to confirm early diagnoses for neurological tumours.[92–94] It has previously been reported that many devices used for interventional procedures (e.g., catheters, biopsy needles) can be used at LF-MRI without costly modifications.[95,96] Table 1 demonstrates a selection of current LF scanners and their properties. The innovations in LF-MRI hardware, in conjunction with artificial intelligence (AI)-driven acquisition and image reconstruction techniques, could help enhance patient throughput and the efficiency of diagnostic LF-MRI[97] and render this technology suitable for LMICs.

3.2.1 | Magnets

The magnet is the most expensive component of an MRI scanner. Most MRI scanners use superconducting solenoid magnets because they are stable, allow for field homogeneity and produce high magnetic fields.[98] However, these magnets weigh between 3000 and 6000 kg for a whole-body 1.5-T magnet.[99] Moreover, they must be cooled to critical temperatures using helium, a costly, nonrenewable coolant.[100] Recent alternatives include using mechanical methods (e.g., a Gifford–McMahon cryocooler), which, although they require regular maintenance, are still comparatively less expensive.[98]

Permanent magnets have emerged as low-cost, point-of-care alternatives (Figure 4A). Permanent magnets have also been optimised for portability using rare earth materials like neodymium iron boron (NdFeB) to produce LF and for organising the magnets into Halbach arrays[101] (Figure 4C), overall, lowering the magnet weight and the cost of MRI.[11,101] Some issues require addressing: the poor temperature stability[102,103] and lack of B_0 homogeneity[101] of permanent magnets. Temperature regulation is vital to ensure persistent image quality and the technology's suitability in LMICs. Magnetic field inhomogeneities can be mitigated through B_0 shimming, but could also be deliberately used to create a favourable magnetic field pattern used for spatial encoding.[101,104,105]

Compared with permanent magnets, electromagnets possess improved field homogeneity and can be switched on and off[106] (Figure 4B). At LF, electromagnets may have reduced cooling and power requirements, making them better suited to LMICs, although they may have issues providing an uninterrupted power supply.[103] The scanner is operated at 23 mT with a homogeneous B_0, allowing a simple air-cooling system to be used. Similarly, Sarracanie et al. were able to image the human brain using Helmholtz coils and a 6.5-mT magnet.[73] The reduction of field strengths to ULF levels allows for expansion of the FOV and the use of resistive electromagnets with lightweight magnet permutations, essentially relying on prepolarising methods.[69,98] Prepolarising magnets allow for a weak homogenised magnetic field (B_0) combined with strong magnetic pulses (B_p) to maximise SNR. This has minimal power requirements because of the image acquisition is based on B_p and not B_0.[69]

3.2.2 | Gradient coils

Magnetic field gradients used for spatial encoding do not depend on the main magnetic field strength so there is no advantage of ULF-MRI per se. However, the fat–water shift depends on the magnetic field strength; it is approximately 146 Hz per T. This results in a fat–water shift of 220 Hz at 1.5 T and of 7.3 Hz at 0.05 T. This reduction in spectral resolution lowers the requirements on the minimum receiver bandwidth to prevent significant chemical shift artefacts from being present in the images. The receiver bandwidth governs the amplitude of the readout magnetic field gradient used for spatial encoding and should be carefully balanced against the echo time and the readout acquisition time. In conclusion, specifications for maximum gradient strengths are much lower at ULF-MRI versus clinical 1.5- or 3.0-T clinical systems.

Several methodologies are utilised in the design of gradient coils, and have been extensively reviewed in previous papers.[107–109] Several solutions have been employed in LF-MRI systems. O'Reilly et al. used a quadrupole gradient design for the Y and Z gradients, allowing a gradient efficiency of 2.2 mT/m/A.[110] The X gradient was designed using a target-field approach, which provides a gradient efficiency h of 1.4 mT/m/A. Both the Y and Z gradients were reported to have high inductance and resistance.

Lother et al. utilised biplanar gradient coils, which allow for 3D spatial encoding of an effective FOV of 140 mm, and were able to achieve slew rates of 50–150 T/m/s.[111] The gradient coil design proposed by Galante et al. for use in a ULF prototype of $B_0 \sim 9$ mT demonstrated high linearity over a FOV of 6 cm. This performance was accomplished by placing the X and Y gradient coils inside the solenoid and utilising a compensated Maxwell pair configuration for the Z coil.[112,113] It stands to reason that a constrained FOV of 6 cm is of limited relevance for human in vivo MRI, but the authors concluded 'that all the technical solutions adopted should allow scaling the device to image a human head'.

McDaniel et al. reported improving spatial encoding and overall image reconstruction by utilising a close-fitting blipped gradient coil in an 80-mT portable MRI scanner. For this purpose, an unshielded gradient coil was used for the X gradient, which then allowed for one-directional phase encoding, which was combined by rotating a Halbach magnet for encoding in the y–z plane. This combination of one-dimensional (1D) phase-encoding and rotational projection imaging permits full 3D imaging.[114] On the economic side, this approach benefits low-cost systems because it reduces the need for three gradient amplifiers to one low-budget gradient amplifier, which provides only a few amps of current to support 1D phase-encoding. This downsizing reduces expenses, eliminates extra infrastructure for water cooling and renders spatial encoding nearly silent. To eliminate gradient coils and amplifiers, the same group replaced conventional gradient encoding by using the inhomogeneous field

TABLE 1 Features of commercially available low-field scanners.

Vendor	Esaote—Gscan Brio	Esaote O scan	Paramed—OpenMR	Fonar—Upleft	AspectImaging-Embrace	Aspect Imaging—Wristview	Bazda—Polar 35
Field (T)	0.25	0.31	0.5	0.6	1	1	0.35
Type: permanent (p), superconducting (s), s cryogen-free (scf)	p	p	scf	r	p	p	p
Weight (tons)	10		22.7	111	5.5	1.05	17.5
Space (m^2)	23	9	22	21	22.3	12	25
5 Gauss line from centre (m)	1.8			Not always on and not shielded	Within cover	0.6	
Gradient (mT/m, mT/m/ms)	20, 56	20,51	20, 33.3	20, 33	150, 454	215, 1074 (limited to 650 due to PNS)	18, 60
Imaging diameter sphere (cm)	27	14	30		12 × 13 × 13	12 × 12 × 7	40
Bore size (cm)	37.5 (35.1 incl bed)		58	46	18 × 26	7.6 × 20	40.5
RF amplifier (kW)	2 × 1.5	1.5	9				5
Voltage (V)	220	220	400-480	400–480	220	220	

Source: JP Marques, FFJ Simonis and AG Webb JMRI 2019 et al.
Abbreviations: LF, low field; PNS, peripheral nerve stimulation; RF, radiofrequency.

TABLE 1 (Continued)

Vendor	Bazda—Polar 50	Neusoft—Superstar 0.35 T	ViewRa—MRIdian	Medonica—MagVue 0.33 T	Revte—GB 0.5 T	Anke—Openmark 5000, 4000 and III	Wandong—i_Open
Field (T)	0.5	0.35	0.35	0.33	0.5	0.51, 0.4, 0.3	0.5, 0.4, 0.36,0.3T
Type: permanent (p), superconducting (s), s cryogen-free (scf)	p	p	s	p	p	p	p
Weight (tons)	27	19.5			22		
Space (m^2)	30	30		30			
5 Gauss line from centre (m)				1.75			
Gradient (mT/m, mT/m/ms)	25, 75	26, 67	18, 200	20, 40			
Imaging diameter sphere (cm)	40	36	50	40			
Bore size (cm)	40.5	38	70 (diameter)	42	41		
RF amplifier (kW)	6	6		6			
Voltage (V)				220			

Source: JP Marques, FFJ Simonis and AG Webb JMRI 2019 et al.
Abbreviations: LF, low field; PNS, peripheral nerve stimulation; RF, radiofrequency.

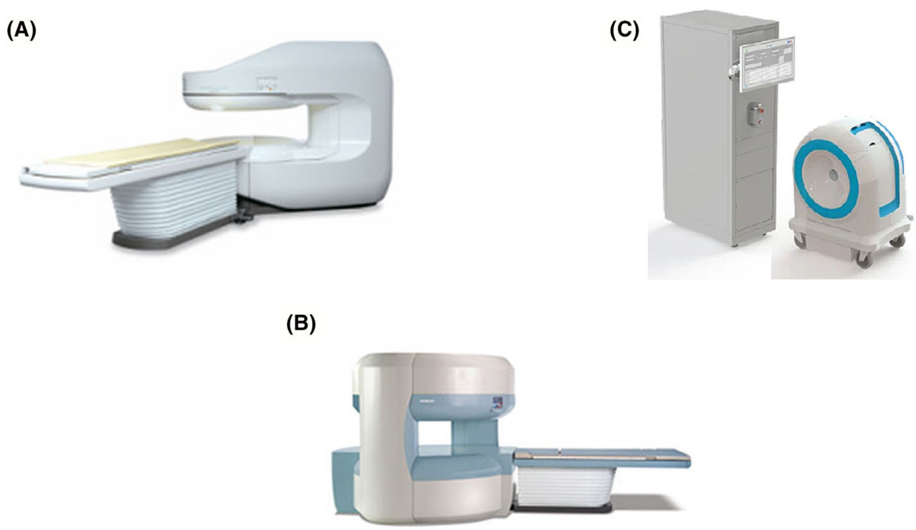

FIGURE 4 (A) An image of the Hitachi Aperto 0.4-T scanner, which utilises a permanent magnet. (B) An image of the Hitachi Oasis 1.2-T high field open (HFO) scanner, which uses an electromagnet. (C) An image of the Promaxo 0.064-T single-sided scanner, which utilises Halbach arrays. Images (A) and (B) are courtesy of Allen D. Elster, MRIquestions.com. Image (C) is from J Nasri et al, EMJ Urology 2021. et al., *EMJ Urol*. 2021;9:83-90. HFO, xxx.

pattern of the magnet as a rotating spatial encoding magnetic field to create generalised projections that encode iteratively reconstructed two-dimensional (2D) images. To summarise, these alternative encoding methods reduce the need for switchable gradient systems and reduce the need for expensive gradient power amplifiers en route to cost-effective LF-MRI systems customised for use in LMICs.

3.2.3 | RF coils

RF coils are a critical component to offset the low intrinsic sensitivity of ULF and LF-MRI. MRI at (ultra) LF introduces several requirements for RF coils because of the dominance of coil losses over body losses.[115] This distinction versus HF-MRI stresses the quality factor Q, which determines SNR. Increasing Q results in an SNR gain by a factor √Q. Q can be enhanced by increasing the inductance or lowering the resistance of an RF coil.[115,116]

One solution to lower coil resistance is cryogenic cooling of the RF receiver coil to maximise Q and SNR,[117] with temperatures of 77 K showing significant improvements in the Q factor. However, cryogenic cooling of RF coils is currently not a realistic option for rural or LMIC settings. Although conceptually appealing, the technology used for cryo-cooling RF coils is complex and prone to malfunction and failure. It requires extra maintenance, servicing and infrastructure. The enormous cost of cryogenic cooling is disproportionately large,[118] might be even more expensive than a commercial LF system and would run counter to the entire ethos of bringing affordable MRI to LMICs. These constraints deem this approach unsuitable for low-cost MRI and LMICs at the first glance. However, explorations into the development of novel high temperature superconducting (HTS) receive coils may help to overcome current obstacles governed by the technical and infrastructural complexity in exchange of a substantial gain in SNR and image quality for LF-MRI. Lee et al. reported an SNR gain of 200%–250% for MRI of the wrist, feet and brain at 0.21 T using home-built HTS surface receive RF coils.[119] A cryogenically cooled HTS coil operated at 0.17 T provided an SNR gain of 3.2 in vivo when compared with the room temperature copper coil.[120] Laistler et al. demonstrated the feasibility of a highly sensitive superconducting surface coil for microscopic MRI of human skin in vivo at 1.5 T.[121] This work showed an SNR gain of 380% for in vivo calf MRI. Recent work reported an SNR gain of up to a factor of ∼2.6 for ^{13}C brain MR at 3.0 T using a 14-channel HTS receiver RF array operating at a resonance frequency of 33.1 MHz and being cryogenically temperature cooled by liquid nitrogen.[122] For cryogenic cooling, a low-cost liquid nitrogen tank and cryostat were used. This achievement is very encouraging for implementation at lower magnetic field strengths because this technology can be conveniently adapted for ^{1}H LF-MRI; the ^{13}C resonance frequency at 3.0 T is equivalent to the ^{1}H frequency at ∼0.77 T. It stands to reason that democratisation of the development and manufacturing of HTS receive coils tailored for LF-MRI will pave the way for overcoming today's cost barriers for a broader application of cryogenically cooled RF coils. Even more, basic research has opened a trajectory into superconductors operating at room temperature, making cryogenic cooling obsolete.[123] Admittedly, this approach is at a very early development stage, but once it becomes broadly and commercially available at a reasonable cost, it may spur high Q RF coil designs for LF-MR.

Meanwhile, Litz wire-based RF coils are commonly used to lower the resistance, improve Q and provide a viable and low-cost solution for LF-MRI. Sarracanie et al. utilised a multistrand Litz wire to form a single-channel inductive coil to compensate for coil resistance.[73] Cooley et al. used a spiral helmet design for brain MRI at 80 mT using a nonuniform turn distribution wound with Litz wire on a tightly fitting helmet.[124] Similarly, Lother et al. used a solenoid coil wrapped with two strands of Litz wire to develop a prototype for neonatal brain imaging. With this set-up, an in-plane resolution of 1.6 × 1.6 mm provided an SNR of 23 in a scan time of 29 min.[111] Considering the same SNR as a clinical target, using a spatial resolution of 2.0 × 2.0 mm would reduce the scan time to ~12 min. This approach would support clinically useful LF-MRI and treatment planning in critical care conditions such as acute ischaemic stroke, infant hydrocephalus or spontaneous intracerebral haemorrhage, with the latter showing an incidence in LMICs ranging from 30 to 130 per 100,000 person-years.[125] This is in line with a recent report demonstrating the clinical applicability of a 64-mT portable, hospital bedside, LF-MR scanner for evaluating intracerebral haemorrhage.[88]

Phased RF arrays for signal reception are a proven approach to enhance SNR at HF. However, at LF, coupling between RF coils is substantial, so the concept of RF receiver arrays will not necessarily benefit SNR. Yet, we suggest that acceleration facilitated by RF receiver arrays is instrumental if not needed at LF for scan time shortening. The literature reports the use of receiver arrays for LF-MR. An array of eight loop elements was implemented in a lightweight, portable MRI system operating at ~77 mT.[126] A 12-channel RF receiver array (anterior and posterior section, each with six elements arranged in a 2 × 3 configuration) was used to assess cardiac function, blood flow and myocardial tissue mapping at 0.35 T.[127] Twenty-four channel receiver arrays were applied for cardiac and pulmonary MRI at 0.55 T.[78,95,128] Other directions of RF coil design for LF-MRI outside the brain may involve anatomically adaptive, lightweight, elastically stretchable or flexible configurations.[129–132]

3.2.4 | Gradient amplifiers

In clinical applications, gradient amplifiers are a vital component that can cause significant affordability issues. Gradient amplifiers are often extremely powerful (peak output voltage, U ~ 1000–2000 V, have a direct relation to slew rate; peak output current, I = 600–1000 A, has a direct relation to maximum gradient strength). These power requirements can be substantially relaxed at lower main magnetic fields because of less constraints on the maximum amplitude and switching time of magnetic field gradients (as outlined in section 3.2.2), which would reduce the cost of current gradient amplifier and MRI systems. Evetts and Conradi recently described a new low-power, low-cost gradient amplifier for smaller MRI systems, costing approximately $1200 compared with market-available gradient amplifiers priced at upwards of $6000.[133] This had lower amplifier capabilities, fulfilling the requirements of ±8 A and ±35 V, compared with significantly more powerful models currently available. They also described how audio units could be modified for DC coupling to create controlled voltage systems, a technique that could be suitably employed in LMICs and increase the sustainability of MRI systems. Liu et al. described a low-cost gradient amplifier currently available through Performance Controls Inc. that has capabilities of ±150 A and ±150 V, when used in an MRI system connected to an AC power outlet.[70] De Vos et al. also described how they designed a battery-operated gradient amplifier compatible with an LF-MRI system capable of ±15 A and ±15 V. To combat the variability of the battery system, they were able to adapt the bias of the amplifier relative to the power supply rails.[134] These low-cost gradient amplifiers have a maximum gradient strength and slew rate that are inferior to high-performance gradient amplifiers. Furthermore, while the spectral and spatial resolution of LF-MRI is lower than at HF, the quality of the images acquired is still arguably good enough to make meaningful clinical decisions. In addition to this benefit, one of the advantages of LF-MRI is the reduced Lorentz forces. This phenomenon benefits patient comfort because of the substantially reduced acoustic noise level at LF-MRI.

RF amplifiers

In clinical MRI, high-power RF power amplifiers (RFPAs) typically provide pulsed output power of 8–32 kW. These amplifiers are bulky and add to the cost of standard MRI machines. It is thought that RF amplifiers provided by vendors of clinical HF-MRI systems cost more than $50,000.[32] The RF absorbed power required to achieve a fixed flip angle in tissue scales with the square of the magnetic field strength if we assume a quasistatic model. This would require less power of the RF amplifier to create the same B_1^+ field at LF or ULF. In other words, it provides an optimisation and cost-reduction opportunity for RF amplifiers used in LF and ULF-MRI. To increase accessibility to MRI systems, alternatives to reduce the size and cost of RFPAs can be introduced for LF-MRI.[73,98,103] Technical solutions include compact RFPAs using laterally diffused metal oxide semiconductor (LDMOS) transistors in rugged mode. These small-size solid-state amplifiers provide a peak output power of up to 1.6 kW per channel, support excellent linearity, are affordable in low quantities and are readily available, making them an exciting candidate for low-frequency applications such as LF-MRI. An open-source effort demonstrated the feasibility of a 1-kW amplifier with material costs of approximately €2000 ($2133.33).[135] This RF amplifier uses a DC voltage input of U = 50 V for the final amplification stage and supports a frequency range of 1.8–54 MHz (B_0 = 0.04–1.2 T).[135] Using LDMOS-based RFPAs has enormous advantages in component size reduction, costs, power budget and overall reliability, which are all essential considerations for point-of-care application and employment in LMICs. Using small-size RFPAs opens a trajectory into on-RF-coil power amplifiers (PAs). Placing RFPAs close to or directly at the RF coil avoids cable losses and reduces siting and running costs.

Other low-cost and small-size solutions for RF transmission amplifiers include a bridged approach using two OPA-549 operational amplifiers for voltage amplification.[136] This configuration supports a peak current of 8 A, and when connected to a saddle-shaped RF coil (f = 180 kHz, Z = 5 Ω), it enables a 90° excitation pulse (duration: 1 ms, peak current: 1 A) with a voltage of 5 V and a peak power of 25 W, which is two to three orders of magnitude lower than the RF power used for conventional whole-body MR systems. It is a merit of this approach that the two amplifiers are supplied, each with 12 V, to provide a current of ~1 A without excessive heat dissipation. This approach comes with the extra benefit that 12-V car or tractor batteries can be employed for the power supply, which dramatically relaxes infrastructure requirements and promotes their use in LMICs.

To summarise, these improvements in systems architecture support and accelerate the move towards an affordable and even mobile MRI system for early assessment, rapid evaluation and management of stroke or other acute brain disorders in rural and remote communities or LMIC settings.

3.3 | Software

3.3.1 | Console and image storage

LMICs would benefit from establishing a simple, user-friendly interface for MRI. Several community efforts to develop suitable consoles, which are relatively inexpensive (costing between $2000 and $10,000), have been explored.[137–139] Other interfaces have been adapted to create low-cost data-acquisition systems, modified to suit MRI,[140] such as field-programmable gate arrays (FPGAs), which are lower cost and can be standardised,[141] requiring specific software and hardware to make them MRI-suitable.[142,143] For example, Jie et al. simplified commands for a 0.3-T scanner using an FPGA, allowing the pulse sequencer to control transmitter and receiver channels, enabling rapid alterations of generated RF waves and simplifying complex pulse sequences.[144] FPGAs have gained traction, such as the community open-source OCRA; however, this has yet to be applied in a clinical setting.[145] This off-shelf model costs less than $500 and is based on the STEMLab/Red Pitaya (Red Pitaya LLC, Newport News, VA, USA), allowing real-time control.[141,146]

Each MRI centre will require a form of picture archiving and communication service (PACS) to view and store images. PACS forms part of RAD-AID's Radiology Readiness Assessment.[147] RAD-AID has worked with countries in Africa, South America and the Philippines to install their Friendship PACS programme, designed explicitly for LMICs.[148] Elahi et al. described the process and challenges faced when installing PACS in Nigeria.[149] A PACS expert was available through WhatsApp in place of onsite support for initial installation and set-up. Most users struggled with the unfamiliar user interface, and the operational challenges encompassed overcoming power outages and image transfer issues. To address these challenges, technical upgrades were required, including a fibre-optic cable and disabling some antivirus and firewall protection. With these amendments, the hospital benefitted from having a complete PACS system. This study has highlighted that PACS systems can be successfully implemented with extensive technical support in LMICs, including network upgrades, more computers and better integration of PACS for reliable server-to-network connections. However, further studies are needed to explore the usability and efficiency of current PACS systems being utilised and how they can be better tailored to suit the needs of the population they serve.

3.3.2 | Maximising efficiency

Using rapid MRI protocols means that specific scan times can be shorter, allowing for greater throughput of patients. The utilisation of rapid cardiovascular MRI protocols by Menacho-Medina et al. confirmed diagnosis in 62% of 560 patients scanned during the follow-up period.[150] Diagnostic-quality images were produced in a shorter scan time. This may be beneficial to both LMICs and HICs, allowing greater throughput.[151] To improve efficiency, rapid MRI protocols could be shared via open access and internationally to increase access. This would help compensate for the lack of expertise in some countries through the development of a sharing platform that is easily accessible.

Another way of maximising efficiency is using MR fingerprinting. It, arguably, could offer the potential for high image quality at a low cost by utilising pattern recognition and multisequence image generation in one acquisition.[152–157] Similarly, synthetic MRI, which allows for the reconstruction of contrasts or other sequences from one scan, could also drastically reduce examination times.[158,159] However, this would require some simplification for it to be used in a LMIC setting or outsourced to a high-resource centre for image reconstruction.

3.3.3 | Artificial intelligence

AI, especially deep learning (DL), shows exciting potential for transforming healthcare and medical imaging, especially in light of the expansion of United States Food and Drug Administration (FDA)-approved AI algorithms and their 510k premarket notifications for diagnosis.[160,161] The FDA-approved AI-based algorithms include those for liver and lung cancer diagnosis and MRI brain interpretation.[160] AI can be used in many facets of data reconstruction, image processing and interpretation, including, but not limited to, image reconstruction, image classification, lesion detection and radiomics. With the usage of these techniques, AI has the potential to reduce the overall caseload of a sparse workforce.

The most practical example of DL-supported MR image acquisition is automated scan plane planning to ensure consistent intersubject and intrasubject scan plane prescriptions and to enhance MRI scanner usability.[162,163] The typical workflow of a scan plane set-up requires careful manual positioning and in-depth knowledge of human anatomy, and it suffers from interoperator and intraoperator variability. DL-based approaches use automated segmentation and recognition of the target organ from low spatial resolution 2D or 3D scout scans to determine the desired scan plane.[164] In-line AI-based scan planning reduces technical complexity, achieves a more straightforward and faster workflow, improves patient examination compliance and relaxes the requirements for MRI training by minimising operator dependence. All these advancements would promote and accelerate the dissemination of LF-MRI in an environment with a well-documented lack of local MR expertise.

One critical limitation of MRI in LMICs is the dearth of a skilled workforce trained for diagnostic imaging. This constraint can be offset through autonomous MRI operation, which separates the end-user interaction from the acquisition hardware.[165] The feasibility of independent MRI operation has been demonstrated for brain MRI. For scan planning and slice positioning, a neural network was used. A lookup table was employed to ensure intelligent MRI protocols that balance the complementary constraints of image contrast, SNR and scan time.[165] This approach promises to streamline the radiological workflow and the clinical efficacy of diagnostic MRI. To enhance and support local MR expertise in LMICs, AI can be of value for the efficient exploration of novel MR sequence strategies, automated pulse sequence development and imaging protocol optimisation. Supervised learning frameworks were shown to facilitate the automatic generation of MR pulse sequences and corresponding reconstruction based on the targeted clinical image contrast.[166] This concept pushes the boundaries of MRI sequence development to a new abstraction level where pulse sequence design is defined by the diagnostic image quality constraints and physical conditions rather than by providing exact timings and parameter values. This advancement can be beneficial for artefact management or the reduction of RF power deposition. AI-driven pulse sequence and protocol optimisation using a cost function that considers the hardware constraints would be instrumental in enhancing the diagnostic value and the range of clinical indications of LF-MRI in LMICs. One critical implication of AI-driven pulse sequence development and optimisation is its potential for vendor-independent MRI pulse sequence development using AI-driven generic frameworks.[167] Such an improvement would relax challenges governed by vendor-specific MR software or the pulse sequence programming environment. It would also help to loosen or eliminate vendor-specific legal requirements and hurdles that commonly impede swift pulse sequence development. AI-driven pulse sequence development also opens a trajectory into generating nonintuitive MR pulse sequences. Examples include enhanced motion suppression and correction, which would simplify the radiological workflow's complexity, lowering the training requirements for end users[168] and opening MRI to a broader clinical workforce.

AI- and DL-based reconstruction algorithms benefit ULF- and LF-MRI and outperform conventional approaches because of the enhanced immunity to noise and the reduction of reconstruction artefacts.[169,170] AI-based reconstruction helps to address some of the shortcomings of LF-MRI hardware, including compensation of magnetic field gradient nonlinearities and correction of magnetic field inhomogeneities. This advantage might help lower the technical specifications for the gradient linearity and magnetic field uniformity, promoting further cost reductions for LF-MRI hardware. Obtaining images from AI-based reconstruction with diagnostic quality in the presence of nonlinear magnetic field gradients allows for further simplification of gradient designs. This includes configurations where the switchable readout gradients are substituted by the magnet's built-in magnetic field variation for spatial encoding in the x dimension.[171] This simplification facilitates power supply through standard wall outlets and is relevant for lowering the power requirements, power budget and running costs. Unlike the readout gradient, switchable phase-encoding gradients along the y- and z-direction operate at lower duty cycles and require lower maximum gradient strengths, peak currents and rise times. A recent report demonstrated the feasibility of a two-gradient amplifier set-up (50 W power consumption, 10 A into 2 Ω for each coil) to drive LF systems tailored for neurovascular MRI.[124]

To speed up MRI examinations, a broad spectrum of undersampling reconstruction techniques has been established. These approaches rely on acquiring less k-space data than needed and recovering the complete data using prior information.[172] Pioneering examples include parallel imaging and compressed sensing (CS) techniques, facilitating substantial undersampling and scan time accelerations.[173,174] The performance of parallel imaging and CS-based reconstruction techniques depends on the choice of the sparsity representation and the tuning of the corresponding reconstruction parameters, especially in the low signal-to-noise regime. Deep neural networks are used to learn the image reconstruction process and automated reconstruction parameter setting from existing datasets. This provides fast computational times and efficient reconstruction and eliminates user interaction.

The usage of DL primarily allows for noise-corrupted images taken with lower-powered scanners to be improved. A recent DL-based denoising example demonstrated advances in image reconstruction methods to enhance the image quality in LF-MRI.[175] For this purpose, an end-to-end deep neural network approach (AUTOMAP) was implemented to improve the image quality of highly noise-corrupted LF-MRI data. The authors reported SNR gains above Fourier reconstruction by factors of 1.5–4.5 for brain MRI at 6.5 mT and demonstrated that the DL-based approach outperformed two contemporary image-based denoising algorithms. This advancement addresses the low SNR challenges of LF-MRI and facilitates enhancements in diagnostic image quality in highly noise-corrupted imaging regimes. DL-based approaches enable automated image quality assessment by identifying artefacts in LF-MRI.[176] LF-MRI is prone to folding artefacts and Gibbs ringing because of the gradient coil design and the use of a low spatial resolution.[176] These artefacts may compromise diagnostic quality and may be mistaken as pathology. Recognising this challenge, a recent study trained individual binary classification models to identify through-plane wrap-around, in-plane wrap-around and Gibbs ringing.[176] For this purpose, T_1-weighted pathological brain MRI datasets obtained at 0.36 T and more than 500 publicly available T_1-weighted brain MRI datasets were used. The validation of the models provided good agreement with the reading and labels supplied by experienced radiologists. Automated image quality assurance benefits resource-constrained settings where sophisticated LF-MRI acquisition techniques are used and where trained personnel might be scarce.

The reduced reliance on trained personnel may alternatively present another problem due to concerns about job security[177–179] in LMICs. Nonprofit organisations such as RAD-AID aim to bridge the gap through clinical radiology education, infrastructure implementation and phased AI introduction, with the aim of better integrating AI in current infrastructure.[180] More open-source resources will likely emerge in the developing market, bringing down the overall cost.[181] The most preferred clinical AI implementation strategy might be a human-supervised AI model to preserve local jobs and help reduce the workload on radiologists.

Potential problems associated with AI in less well-funded healthcare systems might manifest as insufficient data diversity and nontransparent AI algorithms.[182] There is increasing recognition of how AI models can inadvertently amplify sociocultural biases because of the dataset that the AI being trained on being inherently biased. These biases may arise from historical social and cultural prejudices within the current healthcare system, such as pre-existing notions regarding race, gender and ethnicity.[183] These biases may also arise from a general paucity of data from minority groups, meaning a lack of adequate representation of minority groups in AI training datasets.[183,184] Biases can also relate to missing data, misclassification, observational error and misapplication of AI. There is also an issue with algorithmic biases, as AI models are likely to incorrectly associate minority ethnic groups with specific outcomes because of a lack of data.[185,186] For example, some studies have found that using an AI model to allocate management resources led to unequal distribution of resources to wealthy White patients, disadvantaging poorer African-American patients.[187,188]

These issues are a well-documented problem in AI, and significant steps have already been taken to make AI a more equitable enterprise. Tackling this requires a multipronged approach and has already been acknowledged by medical device regulators. For example, the FDA, UK MHRA and Health Canada have jointly published guiding principles for Good Machine Learning Practice and specifically address this issue in point 3: 'to manage any bias, promote appropriate and generalizable performance across the intended patient population, assess usability and identify circumstances where the model may underperform'.[189] Furthermore, the Association for Computing Machinery produced recommendations based on data scientists and medical ethicists collaborating to mitigate AI algorithm bias.[190] There must be an element of accountability and evaluation of what constructs social prejudices ingrained in medical diagnosis and what constitutes true difference in medical diagnosis, and this must be proactively addressed as a patient safety issue.[191] Finally, minority ethnic and underrepresented groups must be placed at the heart of this issue, and active efforts must be made to increase the representation of these groups in available AI data. The STANDING Together initiative also hopes to help tackle this problem by increasing patient engagement to improve data diversity.[192] There are also initiatives to adapt current bias assessment tools for AI models, such as the PROBAST tool, currently used in systematic reviews.[186,193] Through these efforts, the sociocultural biases currently prevalent in AI may be mitigated, making AI a more suitable clinical decision tool for patients in LMICs.

3.4 | Impacts on access: Patient factors, sociocultural factors and regulatory requirements

3.4.1 | Portable MR developments

Portable MRI can reach rural communities and allow for earlier diagnosis of patients who cannot access conventional MRI facilities. RAD-AID's programme with the Postgraduate Institute of Medical Education and Research in Chandigarh, India, was able to overcome several factors that prevent patients from seeking healthcare earlier.[16,194] These included a lack of infrastructure, which allows them to travel, the cost of travelling to the hospital/care facility and an inability to leave home for a prolonged time to seek healthcare.

The implementation of portable imaging facilities of phased breast-screening programmes with mammograms has been successful in many locations.[195] First, patients presenting with breast cancer symptoms were scanned before an expansion to screening programmes targeting at-risk groups. This helped to improve awareness of early breast cancer symptoms and the importance of breast screening in more isolated communities. With the development of portable, low-cost MRI, these programmes have the potential to diagnose patients early and help reduce cancer-related mortality.

Commercial portable MRI scanners, such as the Hyperfine 0.064 T, are used for point-of-care neuroimaging in HICs.[88] This allows for rapid, emergency imaging with reduced risk from ferromagnetic materials or having to transport patients to dedicated imaging units. This may suit patients in LMICs undergoing neurological emergencies who live far away from appropriate imaging services.[88,124,196] With further development, current neuroimaging solutions can be optimised for LMICs to match the population's needs without compromising image quality or exceeding price limitations.[197]

3.4.2 | Teleradiology

Over the last 50 years, advances in communication technology have led to an expansion in telehealth, remote consultation and storage of data on centralised databases or clouds.[198] This development has only become more rapid with the advent of the COVID-19 pandemic, with a rise in virtual clinics and online consultations.[199] This rapid expansion could make MRI more accessible to LMICs using telemedicine.

The primary purpose of teleradiology in LMICs is to ease the burden of an already depleted workforce. It also allows senior radiologists from other countries to provide professional opinions without travelling. Image sharing allows for more collaborative partnerships between radiologists. The most prominent use of teleradiology is seen by the nongovernmental organisation Medicines Sans Frontiers (MSF), whose teleradiology service has been operating since 2010.[200] A study found that this service helped aid diagnosis, with an average turnaround time of 6.1 h. 'Asynchronous transmission'—where scans are uploaded and interpreted later and not in real time—was employed in this study to compensate for unreliable real-time connections in LMICs.[201] While this helped aid diagnosis, there are a few criticisms of this method: asynchronous transmission occasionally requires scans performed in real time to corroborate the diagnosis, and with prolonged waiting times, they may not be entirely suitable for emergency situations.[202]

Any teleradiology platform needs to be affordable and adapted to suit the conditions of the native country, including loss of Internet and poor bandwidth. To achieve this goal, Adambounou et al. developed an MRI-suited platform that accounted for high and low bandwidth speeds.[203] The expansion of teleradiology will make it more reliable and capable of real-time assessment, helping to ameliorate the dearth of radiology staffing in LMICs.

3.4.3 | Regulatory bodies and standards

Each country has its own regulatory body that sets policies for device regulation, for example, the Caribbean falls under the Pan American Health Organization.[204] To introduce further regulatory device management, the World Health Organization established the Global Harmonization Task Force,[205] now known as the International Medical Device Regulators Forum (IMDRF), which conducts work to regularise global regulation by establishing key principles on how LMICs could go about instilling regulation.

Certification of medical imaging devices is complex and expansive, requiring appropriate and timely quality assurance, conformity with regulations and safety centred around protecting patients and users. These constitute substantial practical and financial obstacles for LMIC manufacturers, services and markets. This may explain why few African countries have taken the IMDRF recommendations on board, with 40% of regions without device regulation.[206] Similarly, less stringent medical device criteria place patients at significant risk in South America, as individual devices can be licensed without comprehensive testing.[207] LMICs require further support to establish more local regulatory bodies, as these may help set and enforce clear guidelines that local manufacturers can follow. Local regulatory bodies can also carry out long-term surveillance of scanners donated from HICs to ensure their safety.[16,182] Regulation and standards also have the potential to open markets for local technologies, such as MRI, as it instils trust in the technology.

3.4.4 | Patient comfort

The main patient complaints about MRI are claustrophobia and noise,[208] which may discourage patients from attending appointments, leading to wasted time and resources. Studies have elaborated on how LF systems have reduced acoustic noise[209] and reported techniques that can reduce noise by approximately 80%.[210] Considering neonatal/paediatric patients and those who may be claustrophobic, scanners can be developed for LMICs with open bore configurations. Draper et al. found that the open bore 0.5-T system could be used to study joint load-bearing, despite the reduced SNR and frame rate compared with the 1.5-T closed system.[211]

3.4.5 | Improving infrastructure

Improving infrastructure has a vital role in reducing health inequality. Frija et al. laid out a framework for organising imaging services, including training, structuring of services and layout guidelines.[37] Publishing guidelines in the native language and recognising specific nuances in the local culture can help cross current barriers in international regulation.[16] This makes guidelines more inclusive, as local practitioners can weigh in on the suitability of policies and how they can be adapted to suit the practical challenges in these locations.

Infrastructure can also make the most of the communications technology that is widespread and local to the region to improve healthcare; for example, using social media to increase screening and contact awareness. A systematic review found that social media increased HIV awareness in sub-Saharan Africa by disseminating health information, health promotion and shared experiences, providing social support and promoting medication adherence.[212] Mobile phone technology is also widely used in LMICs. For example, WelTel in Rwanda allows monitoring of patient symptoms through text messages, which streamlines patients' access to healthcare.[213] This could be extended to radiology to enable people to learn more about their scan procedure and receive reminders of their appointments, two of the key factors contributing to missed MRI appointments.[214]

3.4.6 | Education

Educating patients

In many LMICs, patients may not recognise worrisome symptoms, trust doctors or be aware of common diseases.[59,61] Educating patients to recognise symptoms of common diseases increases disease awareness and creates vigilance among the patient population to look out for these abnormal signs in the body. RAD-AID's work with breast cancer survivors in China to have 'breast cancer ambassadors' has been shown to encourage screening uptake for imaging programmes and improved relationships between doctors and local communities.[195] In LMICs, reaching out to trusted community members, such as spiritual leaders, to encourage collaboration or using ambassadors that community members can identify with may increase community engagement with healthcare. The King's Fund[215] studied numerous ways in which communities have a role in improving health and well-being, including how the community where people are born influences how healthy they are and how this may be a more substantial influence than the availability of healthcare services.[216] If communities see the overcoming of health challenges and access as a collective responsibility, the social stigma associated with illness or poor health can be broken down over time.

Upskilling healthcare professionals

A multidisciplinary approach is needed to upskill radiologists by engaging local institutions and with help from organisations in HICs. Rosman et al. demonstrated how a radiology residency in Rwanda might be developed with experts from US medical institutions.[217] They proposed that supervision, consistency, integration, sustainability, duration and concentration are the six main criteria for a sustainable radiology global health interaction programme. RAD-AID and the American Society of Radiologic Technologists foundation have worked to upskill professionals in Haiti and India. RAD-AID has also worked with the American College of Radiology to initiate international radiology training programmes for LMICs.[43] In addition to tailored programmes, many professional societies offer free online education and training programmes.[218–222]

4 | CONCLUSION

MRI has the potential to become a widely available imaging modality in LMICs. With the rapid expansion of technology, it is anticipated that it will not be long before more feasible MRI solutions become widely available at a lower cost. As the balance shifts from reliance on donations to local manufacturing, there is a greater emphasis on community engagement to ensure better, more sustainable access and adapt machinery to local challenges. While the road may be long, the not-too-distant future promises a more equitable diagnostic imaging and healthcare service in LMICs.

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