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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.

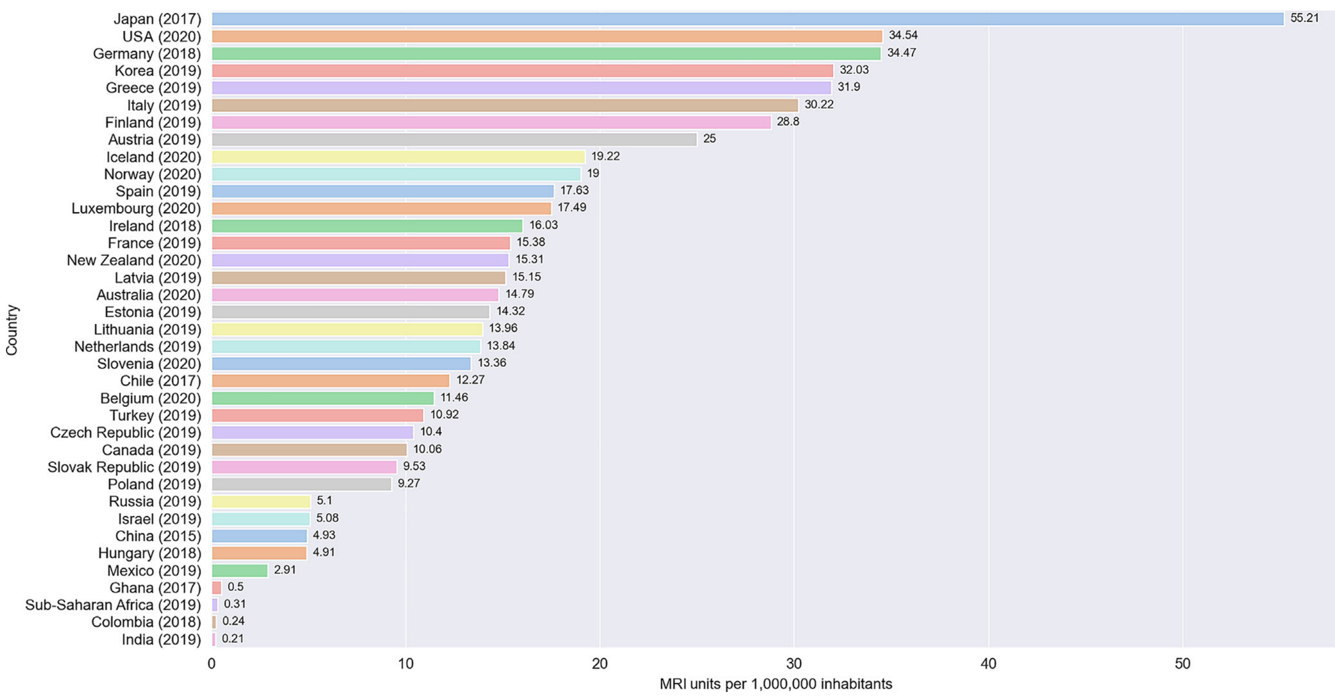

FIGURE 1 Bar chart displaying the MRI units per million population, according to the Organization for Economic Co-operation and Development. The data are organized by density, with Japan having the highest density at 55.21 units per million population. The barchart is from Qin et al.[68]

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

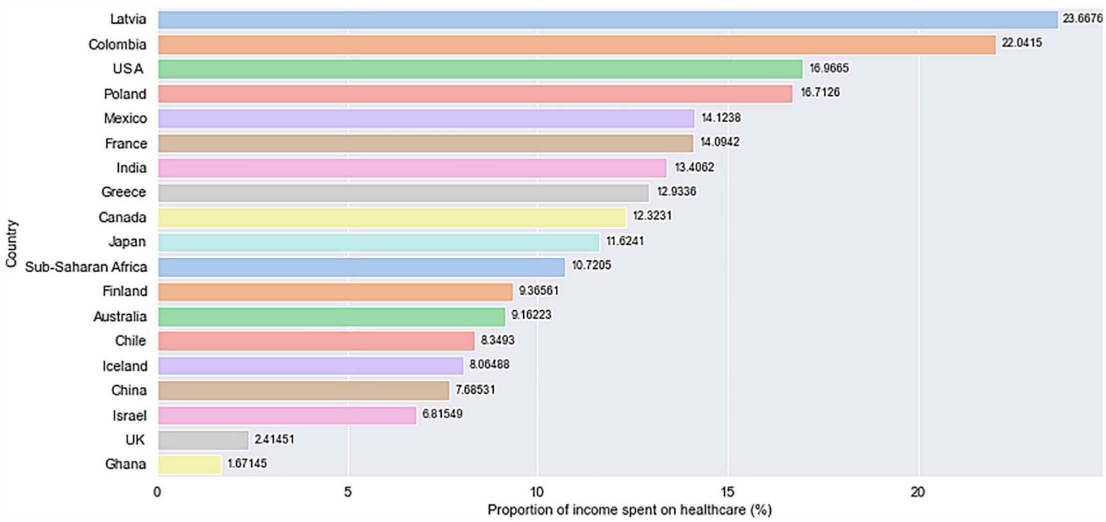

FIGURE 2 Bar chart showing the percentage, ranked by largest to smallest, of the average amount per capita spent on healthcare in each country as a percentage of overall income per capita. For many high-income countries, the proportion of money spent on healthcare is a mandatory payment, and for many 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 neuro-imaging 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

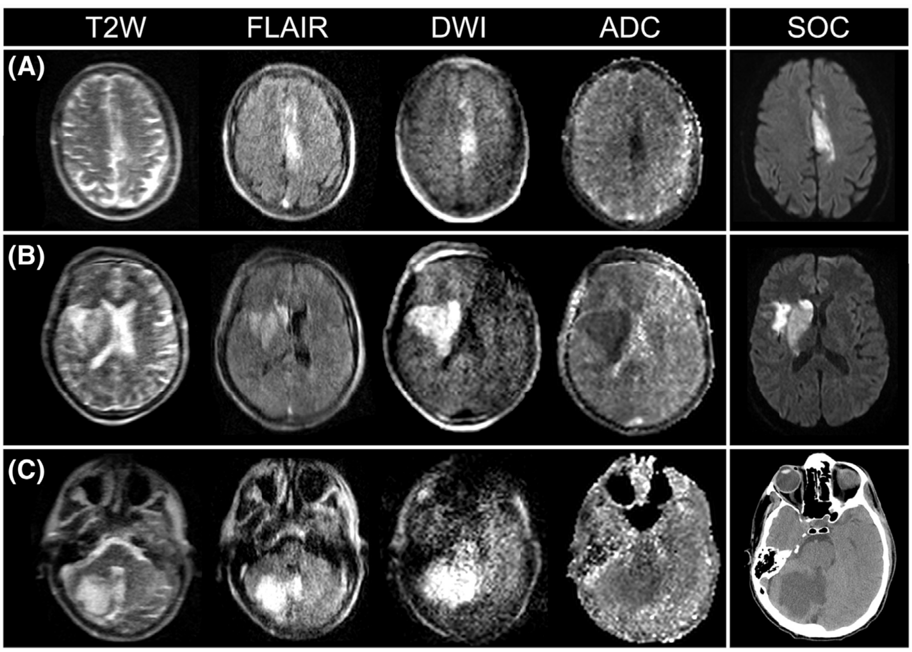

FIGURE 3 Panel of multiple images comparing low-field MRI at 0.064 T (parametric MRI [pMRI]) using Hyperfine Swoop imaging compared with standard care (SOC) capturing ischaemic infarcts in multiple brain regions. (A) The pMRI and SOC (1.5-T) images (32 and 29 h since last known normal, respectively) 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.

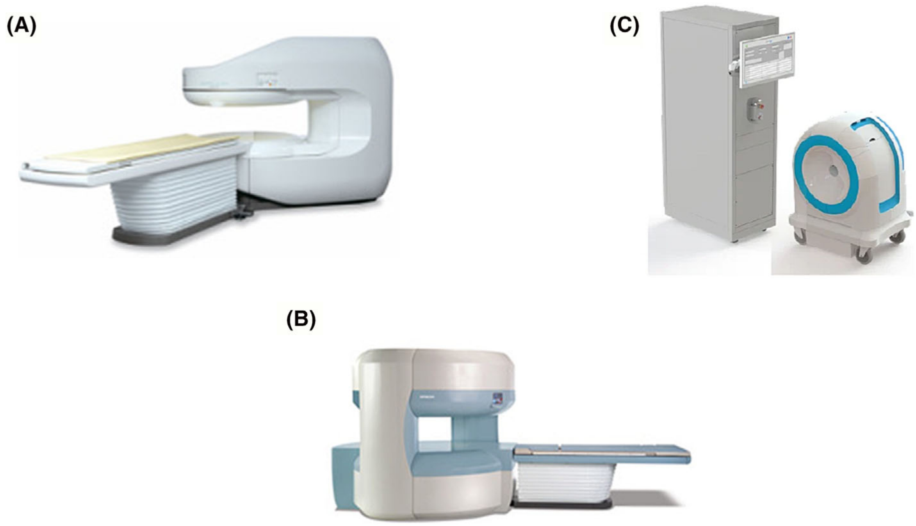

FIGURE 4 (A) An image of the Hitachi Aperto 0.4-T scanner, which utilises a permanent magnet. (B) An image of the Hitachi Oasis 1.2-T high field open (HFO) scanner, which uses an electromagnet. (C) An image of the Promaxo 0.064-T single-sided scanner, which utilises Halbach arrays. Images (A) and (B) 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 $\sqrt{Q}$. 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 $\sim$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 $\sim$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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REFERENCES

1. Zhang Y, Yu J. The role of MRI in the diagnosis and treatment of gastric cancer. *Diagn Interv Radiol.* 2020;26(3):176-182. doi:10.5152/dir.2019.19375
2. Stusińska M, Szabo-Moskal J, Bobek-Billewicz B. Diagnostic value of dynamic and morphologic breast MRI analysis in the diagnosis of breast cancer. *Pol J Radiol.* 2014;79:99-107. doi:10.12659/pjr.889918
3. Bi Q, Bi G, Wang J, et al. Diagnostic accuracy of MRI for detecting cervical invasion in patients with endometrial carcinoma: a meta-analysis. *J Cancer.* 2021;12(3):754-764. doi:10.7150/jca.52797
4. Alabousi M, McInnes MD, Salameh JP, et al. MRI vs. CT for the detection of liver metastases in patients with pancreatic carcinoma: a comparative diagnostic test accuracy systematic review and meta-analysis. *J Magn Reson Imaging.* 2021;53(1):38-48. doi:10.1002/jmri.27056
5. Schmidt GP, Reiser MF, Baur-Melnyk A. Whole-body MRI for the staging and follow-up of patients with metastasis. *Eur J Radiol.* 2009;70(3):393-400. doi:10.1016/j.ejrad.2009.03.045
6. Samet JD. Pediatric sports injuries. *Clin Sports Med.* 2021;40(4):781-799. doi:10.1016/j.csm.2021.05.012
7. Jacobson JA. Musculoskeletal ultrasound and MRI: which do I choose? *Semin Musculoskelet Radiol.* 2005;9(2):135-149. doi:10.1055/s-2005-872339
8. von Knobelsdorff-Brenkenhoff F, Pilz G, Schulz-Menger J. Representation of cardiovascular magnetic resonance in the AHA/ACC guidelines. *J Cardiovasc Magn Reson.* 2017;19(1):70. doi:10.1186/s12968-017-0385-z

9. von Knobelsdorff-Brenkenhoff F, Schulz-Menger J. Role of cardiovascular magnetic resonance in the guidelines of the European Society of Cardiology. *J Cardiovasc Magn Reson.* 2016;18(1):6. doi:10.1186/s12968-016-0225-6
10. World Health Organization. *Global atlas of medical devices*. WHO Medical device technical series. World Health Organization; 2017.
11. Geethanath S, Vaughan JT Jr. Accessible magnetic resonance imaging: A review. *J Magn Reson Imaging.* 2019;49(7):e65-e77. doi:10.1002/jmri.26638
12. World Health Organization. Current health expenditure (% of GDP). Accessed January 27, 2022. https://data.worldbank.org/indicator/SH.XPD.CHEX.GD.ZS
13. Campus IAEAHH. IMAGINE - MRI units (per 1 mil). Accessed February 7, 2022. https://humanhealth.iaea.org/HHW/DBStatistics/IMAGINEMaps3.html
14. OECD. Magnetic resonance imaging (MRI) units (indicator). 2022. Accessed February 11, 2022. https://data.oecd.org/healtheqt/magnetic-resonance-imaging-mri-units.htm
15. Ogbole GI, Adeyomoye AO, Badu-Peprah A, Mensah Y, Nzeh DA. Survey of magnetic resonance imaging availability in West Africa. *Pan Afr Med J.* 2018;30:240. doi:10.11604/pamj.2018.30.240.14000
16. Mollura DJ, Culp MP, Lungren MP. *Radiology in Global Health Strategies, Implementation, and Applications*. 2nd ed. Springer International Publishing; 2019.
17. Ayasrah M. Current status, utilization, and geographic distribution of MRI devices in Jordan. *Appl Nanosci.* 2021;13(2):1125-1134. doi:10.1007/s13204-021-01904-6
18. Burdorf BT. Comparing magnetic resonance imaging and computed tomography machine accessibility among urban and rural county hospitals. *J Public Health Res.* 2021;11(1):2527. doi:10.4081/jphr.2021.2527
19. United Nations. The 17 goals. Accessed February 17, 2022. https://sdgs.un.org/goals
20. World Health Organization. *First WHO global forum on medical devices: context, outcomes, and future actions*. World Health Organization; 2011.
21. Omran AR. The epidemiologic transition: a theory of the epidemiology of population change. 1971. *Milbank Q.* 2005;83(4):731-757. doi:10.1111/j.1468-0009.2005.00398.x
22. Boutayeb A. The double burden of communicable and non-communicable diseases in developing countries. *Trans R Soc Trop Med Hyg.* 2006;100(3):191-199. doi:10.1016/j.trstmh.2005.07.021
23. Mendenhall E, Kohrt BA, Norris SA, Ndetei D, Prabhakaran D. Non-communicable disease syndemics: poverty, depression, and diabetes among low-income populations. *Lancet.* 2017;389(10072):951-963. doi:10.1016/s0140-6736(17)30402-6
24. Temu F, Leonhardt M, Carter J, Thiam S. Integration of non-communicable diseases in health care: tackling the double burden of disease in African settings. *Pan Afr Med J.* 2014;18:202. doi:10.11604/pamj.2014.18.202.4086
25. World Health Organization. Noncommunicable diseases. Accessed March 15, 2022. https://www.who.int/news-room/fact-sheets/detail/noncommunicable-diseases
26. Kawel-Boehm N, Hetzel SJ, Ambale-Venkatesh B, et al. Reference ranges ("normal values") for cardiovascular magnetic resonance (CMR) in adults and children: 2020 update. *J Cardiovasc Magn Reson.* 2020;22(1):87. doi:10.1186/s12968-020-00683-3
27. Kramer CM, Barkhausen J, Bucciarelli-Ducci C, Flamm SD, Kim RJ, Nagel E. Standardized cardiovascular magnetic resonance imaging (CMR) protocols: 2020 update. *J Cardiovasc Magn Reson.* 2020;22(1):17. doi:10.1186/s12968-020-00607-1
28. Hricak H, Abdel-Wahab M, Atun R, et al. Medical imaging and nuclear medicine: a Lancet Oncology Commission. *Lancet Oncol.* 2021;22(4):e136-e172. doi:10.1016/S1470-2045(20)30751-8
29. World Health Organization. Breast cancer. Accessed February 12, 2022. https://www.who.int/news-room/fact-sheets/detail/breast-cancer
30. Kuhl CK, Schrading S, Strobel K, Schild HH, Hilgers RD, Bieling HB. Abbreviated breast magnetic resonance imaging (MRI): first postcontrast subtracted images and maximum-intensity projection-a novel approach to breast cancer screening with MRI. *J Clin Oncol*. 2014;32(22):2304-2310. doi:10.1200/jco.2013.52.5386
31. van Beek EJR, Hoffman EA. Functional imaging: CT and MRI. *Clin Chest Med.* 2008;29(1):195-216. doi:10.1016/j.ccm.2007.12.003
32. Excedr. How much does an MRI machine cost? Updated 14 May 2020. Accessed January 27, 2022. https://www.excedr.com/blog/how-much-does-an-mri-machine-cost/
33. Fan VY, Savedoff WD. The health financing transition: A conceptual framework and empirical evidence. *Soc Sci Med.* 2014;105:112-121. doi:10.1016/j.socscimed.2014.01.014
34. de Rooij M, Crienen S, Witjes JA, Barentsz JO, Rovers MM, Grutters JP. Cost-effectiveness of magnetic resonance (MR) imaging and MR-guided targeted biopsy versus systematic transrectal ultrasound-guided biopsy in diagnosing prostate cancer: a modelling study from a health care perspective. *Eur Urol.* 2014;66(3):430-436. doi:10.1016/j.eururo.2013.12.012
35. Gyftopoulos S, Guja KE, Subhas N, Virk MS, Gold HT. Cost-effectiveness of magnetic resonance imaging versus ultrasound for the detection of symptomatic full-thickness supraspinatus tendon tears. *J Shoulder Elbow Surg.* 2017;26(12):2067-2077. doi:10.1016/j.jse.2017.07.012
36. European Society of Radiology. The consequences of the economic crisis in radiology. *Insights Imaging.* 2015;6(6):573-577. doi:10.1007/s13244-015-0434-9
37. Frija G, Blažić I, Frush DP, et al. How to improve access to medical imaging in low- and middle-income countries? *EClinicalMedicine.* 2021;38:101034. doi:10.1016/j.eclinm.2021.101034
38. Sippel S, Muruganandan K, Levine A, Shah S. Review article: Use of ultrasound in the developing world. *Int J Emerg Med.* 2011;4:72. doi:10.1186/1865-1380-4-72
39. Baldursdóttir S, Gunnlaugsson G, Einarsdóttir J. Donor dilemmas in a fragile state: NGO-ization of community healthcare in Guinea-Bissau. *Dev Stud Res.* 2018;5(sup1):S27-S39. doi:10.1080/21665095.2018.1500143
40. Khan MS, Meghani A, Liverani M, Roychowdhury I, Parkhurst J. How do external donors influence national health policy processes? Experiences of domestic policy actors in Cambodia and Pakistan. *Health Policy Plan.* 2017;33(2):215-223. doi:10.1093/heapol/czx145
41. Pfeiffer J. International NGOs and primary health care in Mozambique: the need for a new model of collaboration. *Soc Sci Med.* 2003;56(4):725-738. doi:10.1016/S0277-9536(02)00068-0
42. Ly C, Eozenou P, Nandakumar A, Pablos-Mendez A, Evans T, Adeyi O. The economic transition of health in Africa: a call for progressive pragmatism to shape the future of health financing. *Health Syst Reform.* 2017;3(4):290-300. doi:10.1080/23288604.2017.1325549

43. Mollura DJ, Mazal J, Everton KL. White paper report of the 2012 RAD-AID conference on international radiology for developing countries: planning the implementation of global radiology. *J Am Coll Radiol.* 2013;10(8):618-624. doi:10.1016/j.jacr.2013.01.019
44. World Health Organization. Global spending on health: a world in transition. 2019 Accessed February 3, 2022. https://www.who.int/publications/i/item/WHO-HIS-HGF-HFWorkingPaper-19.4
45. World Bank: people spend half a trillion dollars out of pocket on health in developing countries annually 2019. Accessed February 18, 2022. https://www.worldbank.org/en/news/press-release/2019/06/27/world-bank-people-spend-half-a-trillion-dollars-out-of-pocket-on-health-in-developing-countries-annually#:~:text=TOKYO%2C%20Japan%2C%20June%2027%2C,ahead%20of%20the%20G20%20Summit
46. Aranas LL, Khanam R, Rahman MM, Nghiem S. Combining microfinance and health in reducing poverty-driven healthcare costs: evidence from the Philippines. Mini review. *Front Public Health.* 2020;8:583455. doi:10.3389/fpubh.2020.583455
47. Rubtsova V. *Rethinking microfinance*. *Berkeley*. Economic Review. 2018. Accessed February 19, 2022. https://econreview.berkeley.edu/rethinking-microfinance/
48. Banerjee SB, Jackson L. Microfinance and the business of poverty reduction: Critical perspectives from rural Bangladesh. *Hum Relat*. 2017;70(1):63-91. doi:10.1177/0018726716640865
49. van Hees SGM, O'Fallon T, Hofker M, et al. Leaving no one behind? Social inclusion of health insurance in low- and middle-income countries: a systematic review. *Int J Equity Health.* 2019;18(1):134. doi:10.1186/s12939-019-1040-0
50. Friebel R, Josephson E, Forman R, Calza S. Challenges of social health insurance in low- and lower-middle income countries: balancing limited budgets and pressure to provide universal health coverage. Accessed February 22, 2020. https://www.cgdev.org/blog/challenges-social-health-insurance-low-and-lower-middle-income-countries-balancing-limited
51. Dao A, Nichter M. The social life of health insurance in low- to middle-income countries: an anthropological research agenda. *Med Anthropol Q.* 2016;30(1):122-143. doi:10.1111/maq.12191
52. DeStigter K, Pool K-L, Leslie A, et al. Optimizing integrated imaging service delivery by tier in low-resource health systems. *Insights Imaging.* 2021;12(1):129. doi:10.1186/s13244-021-01073-8
53. Espinoza J, Sikder AT, Dickhoner J, Lee T. Assessing health data security risks in global health partnerships: development of a conceptual framework. *JMIR Form Res.* 2021;5(12):e25833. doi:10.2196/25833
54. Labrique AB, Wadhwani C, Williams KA, et al. Best practices in scaling digital health in low and middle income countries. *Glob Health.* 2018;14(1):103. doi:10.1186/s12992-018-0424-z
55. DeStigter K, Horton S, Atalabi OM, et al. Equipment in the global radiology environment: why we fail, how we could succeed. *J Glob Radiol.* 2019;5(1):3.
56. Rehani B, Brown I, Dandekar S, et al. Radiology education in Africa: analysis of results from 13 African countries. *J Am Coll Radiol.* 2017;14(2):247-252. doi:10.1016/j.jacr.2016.08.012
57. Rehani B, Zhang YC, Gao KT, et al. Radiology education in Latin America. *J Am Coll Radiol.* 2017;14(3):397-403. doi:10.1016/j.jacr.2016.10.005
58. Stangl AL, Earnshaw VA, Logie CH, et al. The health stigma and discrimination framework: a global, crosscutting framework to inform research, intervention development, and policy on health-related stigmas. *BMC Med.* 2019;17(1):31. doi:10.1186/s12916-019-1271-3
59. Lau LLH, Hung N, Dodd W, Lim K, Ferma JD, Cole DC. Social trust and health seeking behaviours: a longitudinal study of a community-based active tuberculosis case finding program in the Philippines. *SSM - Popul Health.* 2020;12:100664. doi:10.1016/j.ssmph.2020.100664
60. Bhattacharya Chakravarty A, Rangan S, Dholakia Y, et al. Such a long journey: what health seeking pathways of patients with drug resistant tuberculosis in Mumbai tell us. *PLoS ONE.* 2019;14(1):e0209924. doi:10.1371/journal.pone.0209924
61. Christian C, Burger C, Claassens M, Bond V, Burger R. Patient predictors of health-seeking behaviour for persons coughing for more than two weeks in high-burden tuberculosis communities: the case of the Western Cape, South Africa. *BMC Health Serv Res.* 2019;19(1):160. doi:10.1186/s12913-019-3992-6
62. Riley JC. The timing and pace of health transitions around the World. *Popul Dev Rev.* 2005;31(4):741-764. doi:10.1111/j.1728-4457.2005.00096.x
63. NCD Alliance. The global epidemic. Accessed July 29, 2022. https://ncdalliance.org/the-global-epidemic
64. O'Flaherty M, Buchan I, Capewell S. Contributions of treatment and lifestyle to declining CVD mortality: why have CVD mortality rates declined so much since the 1960s? *Heart.* 2013;99(3):159-162. doi:10.1136/heartjnl-2012-302300
65. Hoerr V, Faber C. Magnetic resonance imaging characterization of microbial infections. *J Pharm Biomed Anal.* 2014;93:136-146.
66. Ruiz-Cabello J, Barnett BP, Bottomley PA, Bulte JW. Fluorine (19F) MRS and MRI in biomedicine. *NMR Biomed.* 2011;24(2):114-129. doi:10.1002/nbm.1570
67. Radermacher KA, Beghein N, Boutry S, et al. In vivo detection of inflammation using pegylated iron oxide particles targeted at E-selectin: a multimodal approach using MR imaging and EPR spectroscopy. *Invest Radiol.* 2009;44(7):398-404. doi:10.1097/rli.0b013e3181a49639
68. Qin C, Murali S, Lee E, et al. Sustainable low-field cardiovascular magnetic resonance in changing healthcare systems. *Eur Heart J Cardiovasc Imaging.* 2022;23(6):e246-e260. doi:10.1093/ehjci/jeab286
69. Obungoloch J, Harper JR, Consevage S, et al. Design of a sustainable prepolarizing magnetic resonance imaging system for infant hydrocephalus. *MAGMA.* 2018;31(5):665-676. doi:10.1007/s10334-018-0683-y
70. Liu Y, Leong ATL, Zhao Y, et al. A low-cost and shielding-free ultra-low-field brain MRI scanner. *Nat Commun.* 2021;12(1):7238. doi:10.1038/s41467-021-27317-1
71. Hyperfine. Hyperfine swoop. Accessed May 9, 2023. https://hyperfine.io/
72. Zotev VS, Matlashov AN, Savukov IM, et al. SQUID-based microtesla MRI for in vivo relaxometry of the human brain. *IEEE Trans Appl Superconduct.* 2009;19(3):823-826. doi:10.1109/TASC.2009.2018764
73. Sarracanie M, LaPierre CD, Salameh N, Waddington DEJ, Witzel T, Rosen MS. Low-cost high-performance MRI. *Sci Rep.* 2015;5(1):15177. doi:10.1038/srep15177
74. Simonetti OP, Ahmad R. Low-field cardiac magnetic resonance imaging. *Circ Cardiovasc Imaging.* 2017;10(6):e005446. doi:10.1161/CIRCIMAGING.117.005446
75. Mutic S, Dempsey JF. The ViewRay system: magnetic resonance–guided and controlled radiotherapy. *Semin Radiat Oncol.* 2014;24(3):196-199. doi:10.1016/j.semradonc.2014.02.008

76. Van Speybroeck CDE, O'Reilly T, Teeuwisse W, Arnold PM, Webb AG. Characterization of displacement forces and image artifacts in the presence of passive medical implants in low-field (<100 mT) permanent magnet-based MRI systems, and comparisons with clinical MRI systems. *Phys Med.* 2021;84:116-124. doi:10.1016/j.ejmp.2021.04.003
77. Rashid S, Han F, Gao Y, et al. Cardiac balanced steady-state free precession MRI at 0.35 T: a comparison study with 1.5 T. *Quant Imaging Med Surg.* 2018;8(7):627-636. doi:10.21037/qims.2018.08.09
78. Bandettini WP, Shanbhag SM, Mancini C, et al. A comparison of cine CMR imaging at 0.55 T and 1.5 T. *J Cardiovasc Magn Reson.* 2020;22(1):37. doi:10.1186/s12968-020-00618-y
79. IEC. Medical electrical equipment. Particular requirements for the safety of magnetic resonance equipment for medical diagnosis. 2010.
80. Agency UMaHpR. Safety guidelines for magnetic resonance imaging equipment in clinical use. Radiofrequency magnetic fields (B1). 2021.
81. Ghazinoor S, Crues JV III, Crowley C. Low-field musculoskeletal MRI. *J Magn Reson Imaging.* 2007;25(2):234-244. doi:10.1002/jmri.20854
82. Leigheb M, Guzzardi G, Barini M, et al. Role of low field MRI in detecting knee lesions. *Acta Biomed.* 2018;90(1-S):116-122. doi:10.23750/abm.v90i1-S.7977
83. Voxelgrids. Voxelgrids: lightweight, ultra-fast, next-generation magnetic resonance imaging (MRI) scanners. Accessed February 12, 2022. http://www.voxelgrids.com/
84. Breit HC, Vosshenrich J, Bach M, Merkle EM. New clinical applications for low-field magnetic resonance imaging: T=technical and physical aspects. *Radiologe.* 2022;62(5):394-399. doi:10.1007/s00117-022-00967-y Neue klinische Anwendungsbereiche der Niederfeld-Magnetresonanztomographie: Technische und physikalische Aspekte.
85. Chandarana H, Bagga B, Huang C, et al. Diagnostic abdominal MR imaging on a prototype low-field 0.55 T scanner operating at two different gradient strengths. *Abdom Radiol.* 2021;46(12):5772-5780. doi:10.1007/s00261-021-03234-1
86. Esaote. MRI systems: S-scan. Accessed February 17, 2022. https://www.esaote.com/dedicated-mri/mri-systems/p/s-scan/
87. Lu W, Yang J, Chen S, Zhu Y, Zhu C. Abnormal patella height based on Insall-Salvati ratio and its correlation with patellar cartilage lesions: an extremity-dedicated low-field magnetic resonance imaging analysis of 1703 Chinese cases. *Scand J Surg.* 2016;105(3):197-203. doi:10.1177/1457496915607409
88. Mazurek MH, Cahn BA, Yuen MM, et al. Portable, bedside, low-field magnetic resonance imaging for evaluation of intracerebral hemorrhage. *Nat Commun.* 2021;12(1):5119. doi:10.1038/s41467-021-25441-6
89. Zhuang Y, Potchen MJ, Kampondeni SD, Tivarus M, Birbeck GL, Zhong J. Validation of diffusion measurements obtained on a 0.35T MR in Malawi: important insights for radiologists in low income settings with low field MRI. *Magn Reson Imaging.* 2018;45:120-128. doi:10.1016/j.mri.2017.10.001
90. Terada H, Gomi T, Harada H, et al. Development of diffusion-weighted image using a 0.3T open MRI. *J Neuroradiol.* 2006;33(1):57-61. doi:10.1016/s0150-9861(06)77229-7
91. Yuen MM, Prabhat AM, Mazurek MH, et al. Portable, low-field magnetic resonance imaging enables highly accessible and dynamic bedside evaluation of ischemic stroke. *Sci Adv.* 2022;8(16):eabm3952. doi:10.1126/sciadv.abm3952
92. Bhat SS, Fernandes TT, Poojar P, et al. Low-field MRI of stroke: challenges and opportunities. *J Magn Reson Imaging.* 2021;54(2):372-390. doi:10.1002/jmri.27324
93. Ogbole GI, Adeyinka OA, Okolo CA, Ogun AO, Atalabi OM. Low field MR imaging of sellar and parasellar lesions: experience in a developing country hospital. *Eur J Radiol.* 2012;81(2):e139-e146. doi:10.1016/j.ejrad.2011.01.056
94. Wu JS, Shou XF, Yao CJ, et al. Transsphenoidal pituitary macroadenomas resection guided by PoleStar N20 low-field intraoperative magnetic resonance imaging: comparison with early postoperative high-field magnetic resonance imaging. *Neurosurgery.* 2009;65(1):63-70; discussion 70-71. doi:10.1227/01.Neu.0000348549.26832.51
95. Campbell-Washburn AE, Ramasawmy R, Restivo MC, et al. Opportunities in interventional and diagnostic imaging by using high-performance low-field-strength MRI. *Radiology.* 2019;293(2):384-393. doi:10.1148/radiol.2019190452
96. Satya P, Adams J Jr, Venkataraman SS, et al. Office-based, single-sided, low-field MRI-guided prostate biopsy. *Cureus.* 2022;14(5):e25021. doi:10.7759/cureus.25021
97. Hennig J. Magnetresonanztomographie bei niedrigeren Feldstärken. *Radiologe.* 2022;62((5)):385-393. doi:10.1007/s00117-022-00977-w
98. Wald LL, McDaniel PC, Witzel T, Stockmann JP, Cooley CZ. Low-cost and portable MRI. *J Magn Reson Imaging.* 2020;52(3):686-696. doi:10.1002/jmri.26942
99. Cosmus TC, Parizh M. Advances in whole-body MRI magnets. *IEEE Trans Appl Superconduct.* 2011;21(3):2104-2109. doi:10.1109/TASC.2010.2084981
100. Siemens. The liquid gold of MRI. Accessed February 12, 2022. https://www.siemens-healthineers.com/perspectives/mso-helium-and-mri-technology
101. Wenzel K, Alhamwey H, O'Reilly T, Riemann LT, Silemek B, Winter L. B0-Shimming methodology for affordable and compact low-field magnetic resonance imaging magnets. *Front Phys.* 2021;9:704566. doi:10.3389/fphy.2021.704566
102. Wang G, Xie H, Hou S, Chen W, Zhao Q, Li S. Development of the 1.2 T∼1.5 T permanent magnetic resonance imaging device and its application for mouse imaging. *Biomed Res Int.* 2015;2015:858694. doi:10.1155/2015/858694
103. Sarracanie M, Salameh N. Low-field MRI: how low can we go? A fresh view on an old debate. *Front Phys.* 2020;8:172. doi:10.3389/fphy.2020.00172
104. Cooley CZ, Haskell MW, Cauley SF, et al. Design of sparse Halbach magnet arrays for portable MRI using a genetic algorithm. *IEEE Trans Magn.* 2018;54(1):5100112. doi:10.1109/TMAG.2017.2751001
105. Stockmann JP, Cooley CZ, Guerin B, Rosen MS, Wald LL. Transmit array spatial encoding (TRASE) using broadband WURST pulses for RF spatial encoding in inhomogeneous B0 fields. *J Magc Res.* 2016;268:36-48. doi:10.1016/j.jmr.2016.04.005
106. Huang S, Ren ZH, Obruchkov S, Gong J, Dykstra R, Yu W. Portable low-cost MRI system based on permanent magnets/magnet arrays. *Investig Magn Reson Imaging.* 2019;23(3):179-201.
107. Turner R. Gradient coil design: a review of methods. *Magn Reson Imaging.* 1993;11(7):903-920. doi:10.1016/0730-725X(93)90209-V
108. Handler WB, Harris CT, Scholl TJ, et al. New head gradient coil design and construction techniques. *J Magn Reson Imaging.* 2014;39(5):1088-1095. doi:10.1002/jmri.24254
109. Hidalgo-Tobón SS. Theory of gradient coil design methods for magnetic resonance imaging. *Concepts Mag Res Part A.* 2010;36:223-242.

110. O'Reilly T, Teeuwisse WM, Webb AG. Three-dimensional MRI in a homogenous 27 cm diameter bore Halbach array magnet. *J Magn Reson.* 2019;307:106578. doi:10.1016/j.jmr.2019.106578
111. Lother S, Schiff SJ, Neuberger T, Jakob PM, Fidler F. Design of a mobile, homogeneous, and efficient electromagnet with a large field of view for neonatal low-field MRI. *MAGMA.* 2016;29(4):691-698. doi:10.1007/s10334-016-0525-8
112. Galante A, Sinibaldi R, Conti A, et al. Fast room temperature very low field-magnetic resonance imaging system compatible with magnetoencephalography environment. *PLoS ONE.* 2015;10(12):e0142701. doi:10.1371/journal.pone.0142701
113. Galante A, Catallo N, Sebastiani P, et al. Very low field MRI: a fast system compatible with magnetoencephalography. 2015 IEEE International Symposium on Medical Measurements and Applications (MeMeA) Proceedings. 2015;560-564. doi:10.1109/MeMeA.2015.7145266
114. McDaniel P, Cooley CZ, Stockmann JP, Wald LL. 3D imaging with a portable MRI scanner using an optimized rotating magnet and 1D gradient coil. Proceedings of the International Society for Magnetic Resonance in Medicine, Paris. 2018:0029.
115. Gruber B, Froeling M, Leiner T, Klomp DWJ. RF coils: a practical guide for nonphysicists. *J Magn Reson Imaging.* 2018;48(3):590-604. doi:10.1002/jmri.26187
116. Giovannetti G, Hartwig V, Landini L, Santarelli MF. Low-field MR coils: comparison between strip and wire conductors. *Appl Mag Res.* 2010;39(4):391-399. doi:10.1007/s00723-010-0173-5
117. Resmer F, Seton HC, Hutchison JM. Cryogenic receive coil and low noise preamplifier for MRI at 0.01T. *J Magn Reson.* 2010;203(1):57-65. doi:10.1016/j.jmr.2009.11.021
118. Luyben WL. Estimating refrigeration costs at cryogenic temperatures. *Comput Chem Eng.* 2017;103:144-150. doi:10.1016/j.compchemeng.2017.03.013
119. Lee KH, Cheng MC, Chan KC, et al. Performance of large-size superconducting coil in 0.21T MRI system. *IEEE Trans Biomed Eng.* 2004;51(11):2024-2030. doi:10.1109/TBME.2004.831539
120. Cheong H-S, Wild J, Alford NM, Valkov I, Randell C, Paley M. A high temperature superconducting imaging coil for low-field MRI. *Concepts Magn Reson Part B Magn Reson Eng.* 2010;37B:56-64. doi:10.1002/cmr.b.20158
121. Laistler E, Poirier-Quinot M, Lambert SA, et al. In vivo MR imaging of the human skin at subnanoliter resolution using a superconducting surface coil at 1.5 Tesla. *J Magn Reson Imaging.* 2015;41(2):496-504. doi:10.1002/jmri.24549
122. Wang W, Sánchez-Heredia JD, Olin RB, et al. A cryogenic 14-channel (13) C receiver array for 3T human head imaging. Magn Reson Med. 2023;89(3):1265-1277. doi:10.1002/mrm.29508
123. Gatt R, inventor. High temperature superconductors. Patent application 16/189,751. 2018.
124. Cooley CZ, McDaniel PC, Stockmann JP, et al. A portable scanner for magnetic resonance imaging of the brain. *Nat Biomed Eng.* 2021;5(3):229-239. doi:10.1038/s41551-020-00641-5
125. Wang S, Zou XL, Wu LX, et al. Epidemiology of intracerebral hemorrhage: a systematic review and meta-analysis. *Front Neurol.* 2022;13:915813. doi:10.3389/fneur.2022.915813
126. Cooley CZ, Stockmann JP, Armstrong BD, et al. Two-dimensional imaging in a lightweight portable MRI scanner without gradient coils. *Magn Reson Med.* 2015;73(2):872-883. doi:10.1002/mrm.25147
127. Varghese J, Craft J, Crabtree CD, et al. Assessment of cardiac function, blood flow and myocardial tissue relaxation parameters at 0.35 T. *NMR Biomed.* 2020;33(7):e4317. doi:10.1002/nbm.4317
128. Seemann F, Javed A, Chae R, et al. Imaging gravity-induced lung water redistribution with automated inline processing at 0.55 T cardiovascular magnetic resonance. *J Cardiovasc Magn Reson.* 2022;24(1):35. doi:10.1186/s12968-022-00862-4
129. Vincent JM, Gim M, Rispoli JV. Elastically stretchable and flexible RF receive coils for magnetic resonance imaging. 2021 International Conference on Electromagnetics in Advanced Applications (ICEAA). 2021:319-319. doi:10.1109/ICEAA52647.2021.9539531
130. Gruber B, Rehner R, Laistler E, Zink S. Anatomically adaptive coils for MRI—a 6-channel array for knee imaging at 1.5 Tesla. *Front Phys.* 2020;8:80. doi:10.3389/fphy.2020.00080
131. Eigentler TW, Kuehne A, Boehmert L, et al. 32-Channel self-grounded bow-tie transceiver array for cardiac MR at 7.0T. *Magn Reson Med.* 2021;86(5):2862-2879. doi:10.1002/mrm.28885
132. Zhang B, Sodickson DK, Cloos MA. A high-impedance detector-array glove for magnetic resonance imaging of the hand. *Nat Biomed Eng.* 2018;2(8):570-577. doi:10.1038/s41551-018-0233-y
133. Evetts N, Conradi MS. Low-cost gradient amplifiers for small MRI systems. *J Magn Reson.* 2022;335:107127. doi:10.1016/j.jmr.2021.107127
134. de Vos B, Parsa J, Abdulrazaq Z, et al. Design, characterisation and performance of an improved portable and sustainable low-field MRI system. *Front Phys.* 2021;413. doi:10.3389/fphy.2021.701157
135. Blücher C, Han H, Hoffmann W, et al. COSI transmit: open source soft-and hardware transmission system for traditional and rotating MR. Proc 25th Annu Meet ISMRM Honol. 2017;184:2017.
136. Harper JR, Zárate C, Krauch F, et al. An unmatched radio frequency chain for low-field magnetic resonance imaging. *Front Phys.* 2022;9:824.
137. Stang PP, Conolly SM, Santos JM, Pauly JM, Scott GC. Medusa: a scalable MR console using USB. *IEEE Trans Med Imaging.* 2012;31(2):370-379. doi:10.1109/TMI.2011.2169681
138. Tang W, Wang W, Liu W, et al. A home-built digital optical MRI console using high-speed serial links. *Magn Reson Med.* 2015;74(2):578-588. doi:10.1002/mrm.25403
139. Hasselwander CJ, Cao Z, Grissom WA. gr-MRI: a software package for magnetic resonance imaging using software defined radios. *J Magn Reson.* 2016;270:47-55. doi:10.1016/j.jmr.2016.06.023
140. Takeda K. A highly integrated FPGA-based nuclear magnetic resonance spectrometer. *Rev Sci Instrum.* 2007;78(3):033103. doi:10.1063/1.2712940
141. Anand S. Low-cost, open-source FPGA-based MRI console capable of real-time control. 2018. PhD thesis. https://dspace.mit.edu/handle/1721.1/121619
142. Cooley CZ, Stockmann JP, Witzel T, et al. Design and implementation of a low-cost, tabletop MRI scanner for education and research prototyping. *J Magn Reson.* 2020;310:106625. doi:10.1016/j.jmr.2019.106625
143. Takeda K. OPENCORE NMR: open-source core modules for implementing an integrated FPGA-based NMR spectrometer. *J Magn Reson.* 2008;192(2):218-229.

144. Jie S, Qin X, Ying L, Gengying L. Home-built magnetic resonance imaging system (0.3 T) with a complete digital spectrometer. *Rev Sci Instrum.* 2005;76(10):105101. doi:10.1063/1.2069707
145. Witzel T. OCRA MRI. Accessed July 9, 2022. https://openmri.github.io/ocra/
146. Anand S, Stockmann JP, Wald LL, Witzel T. A low-cost (< $500 USD) FPGA-based console capable of real-time control. Proc Jt Annu Meet ISMRM-ESMRM. 2018:0948.
147. RAD-AID. Radiology readiness. Accessed January 29, 2022. https://rad-aid.org/resource-center/radiology-readiness
148. RAD-AID. RAD-AID 2021 annual report. 2021:36. Accessed October, 2021. https://rad-aid.org/wp-content/uploads/2021_RAD-AID_Annual-Report_Oct%202021%20-HiRes-Compressed.pdf
149. Elahi A, Dako F, Zember J, et al. Overcoming challenges for successful PACS installation in low-resource regions: our experience in Nigeria. *J Digit Imaging*. 2020;33(4):996-1001. doi:10.1007/s10278-020-00352-y
150. Menacho-Medina K, Ntusi NAB, Moon JC, Walker JM, Jacob R. Rapid cardiac MRI protocols: feasibility and potential applications. *Curr Radiol Rep.* 2020;8(2):2. doi:10.1007/s40134-020-0344-6
151. Menacho Medina K, Seraphim A, Katekaru D, et al. Noninvasive rapid cardiac magnetic resonance for the assessment of cardiomyopathies in low-middle income countries. *Expert Rev Cardiovasc Ther.* 2021;19(5):387-398. doi:10.1080/14779072.2021.1915130
152. Körzdörfer G, Kirsch R, Liu K, et al. Reproducibility and repeatability of MR fingerprinting relaxometry in the human brain. *Radiology*. 2019;292(2):429-437. doi:10.1148/radiol.2019182360
153. Buonincontri G, Biagi L, Retico A, et al. Multi-site repeatability and reproducibility of MR fingerprinting of the healthy brain at 1.5 and 3.0 T. *Neuroimage.* 2019;195:362-372. doi:10.1016/j.neuroimage.2019.03.047
154. Tippareddy C, Zhao W, Sunshine JL, Griswold M, Ma D, Badve C. Magnetic resonance fingerprinting: an overview. *Eur J Nucl Med Mol Imaging.* 2021;48(13):4189-4200. doi:10.1007/s00259-021-05384-2
155. Bipin Mehta B, Coppo S, Frances McGivney D, et al. Magnetic resonance fingerprinting: a technical review. *Magn Reson Med.* 2019;81(1):25-46. doi:10.1002/mrm.27403
156. Ma D, Gulani V, Seiberlich N, et al. Magnetic resonance fingerprinting. *Nature.* 2013;495(7440):187-192. doi:10.1038/nature11971
157. Campbell-Washburn AE, Jiang Y, Körzdörfer G, Nittka M, Griswold MA. Feasibility of MR fingerprinting using a high-performance 0.55 T MRI system. *Magn Reson Imaging.* 2021;81:88-93. doi:10.1016/j.mri.2021.06.002
158. Tanenbaum LN, Tsiouris AJ, Johnson AN, et al. Synthetic MRI for clinical neuroimaging: results of the magnetic resonance image compilation (MAGiC) prospective, multicenter, multireader trial. *Am J Neuroradiol.* 2017;38(6):1103-1110. doi:10.3174/ajnr.A5227
159. Krauss W, Gunnarsson M, Nilsson M, Thunberg P. Conventional and synthetic MRI in multiple sclerosis: a comparative study. *Eur Radiol.* 2018;28(4):1692-1700. doi:10.1007/s00330-017-5100-9
160. Benjamens S, Dhunnoo P, Meskó B. The state of artificial intelligence-based FDA-approved medical devices and algorithms: an online database. *npj Digit Med.* 2020;3(1):118. doi:10.1038/s41746-020-00324-0
161. Food U, Administration D. Artificial intelligence and machine learning (AI/ML)-enabled medical devices. 2022. https://www.fda.gov/medical-devices/software-medical-device-samd/artificial-intelligence-and-machine-learning-aiml-enabled-medical-devices
162. Yokosawa S, Taniguchi Y, Bito Y, et al. Automated scan plane planning for spine MRI using 2D scout images. Proceedings of 19th ISMRM Annual meeting and exhibition, Montreal Quebec, May 2011. https://archive.ismrm.org/2011/4535.html
163. Schlemper J, Oktay O, Chen L, et al. Attention-gated networks for improving ultrasound scan plane detection. ArXiv. 2018;abs/1804.05338.
164. Battalapalli D, Rao BVVSNP, Yogeeswari P, Kesavadas C, Rajagopalan V. An optimal brain tumor segmentation algorithm for clinical MRI dataset with low resolution and non-contiguous slices. *BMC Med Imaging*. 2022;22(1):89. doi:10.1186/s12880-022-00812-7
165. Ravi KS, Geethanath S. Autonomous magnetic resonance imaging. *Magn Reson Imaging.* 2020;73:177-185. doi:10.1016/j.mri.2020.08.010
166. Loktyushin A, Herz K, Dang N, et al. MRzero - automated discovery of MRI sequences using supervised learning. *Magn Reson Med.* 2021;86(2):709-724. doi:10.1002/mrm.28727
167. Hoinkiss DCK, Konstandin S, Günther M. Constraint-based sequence optimization in a scanner-independent MRI framework. Presented at: ISMRM; 2022; London, UK. Accessed June 17, 2023. https://archive.ismrm.org/2022/2770.html
168. Zhu B, Liu J, Koonjoo N, Rosen BR, Rosen MS. AUTOmated pulse SEQuence generation (AUTOSEQ) using Bayesian reinforcement learning in an MRI physics simulation environment. Proceedings of ISMRM Annual Meeting and Exhibition, Paris, June 2018. https://archive.ismrm.org/2018/0438.html
169. Wu D, Kim K, Li Q. Digital breast tomosynthesis reconstruction with deep neural network for improved contrast and in-depth resolution. 2020 IEEE 17th International Symposium on Biomedical Imaging (ISBI). 2020:656-659.
170. Singh R, Wu W, Wang G, Kalra MK. Artificial intelligence in image reconstruction: The change is here. *Phys Med.* 2020;79:113-125. doi:10.1016/j.ejmp.2020.11.012
171. Vogel MW, Guridi RP, Su J, Vegh V, Reutens DC. 3D-Spatial encoding with permanent magnets for ultra-low field magnetic resonance imaging. *Sci Rep.* 2019;9(1):1522. doi:10.1038/s41598-018-37953-1
172. Hyun CM, Kim HP, Lee SM, Lee S, Seo JK. Deep learning for undersampled MRI reconstruction. *Phys Med Biol*. 2018;63(13):135007. doi:10.1088/1361-6560/aac71a
173. Johnson PM, Recht MP, Knoll F. Improving the speed of MRI with artificial intelligence. *Semin Musculoskelet Radiol.* 2020;24(1):12-20. doi:10.1055/s-0039-3400265
174. Bustin A, Fuin N, Botnar RM, Prieto C. From compressed-sensing to artificial intelligence-based cardiac MRI reconstruction. *Front Cardiovasc Med.* 2020;7:17. doi:10.3389/fcvm.2020.00017
175. Koonjoo N, Zhu B, Bagnall GC, Bhutto D, Rosen MS. Boosting the signal-to-noise of low-field MRI with deep learning image reconstruction. *Sci Rep.* 2021;11(1):8248. doi:10.1038/s41598-021-87482-7
176. Manso Jimeno M, Ravi KS, Jin Z, Oyekunle D, Ogbole G, Geethanath S. ArtifactID: identifying artifacts in low-field MRI of the brain using deep learning. *Magn Reson Imaging.* 2022;89:42-48. doi:10.1016/j.mri.2022.02.002
177. Currie G, Rohren E. Social asymmetry, artificial intelligence and the medical imaging landscape. *Semin Nucl Med.* 2021;52(4):498-503. doi:10.1053/j.semnuclmed.2021.11.011

178. Botwe BO, Akudjedu TN, Antwi WK, et al. The integration of artificial intelligence in medical imaging practice: perspectives of African radiographers. *Radiography*. 2021;27(3):861-866. doi:10.1016/j.radi.2021.01.008
179. Botwe BO, Antwi WK, Arkoh S, Akudjedu TN. Radiographers' perspectives on the emerging integration of artificial intelligence into diagnostic imaging: the Ghana study. *J Med Rad Sci*. 2021;68(3):260-268. doi:10.1002/jmrs.460
180. Mollura DJ, Culp MP, Pollack E, et al. Artificial intelligence in low- and middle-income countries: innovating global health radiology. *Radiology*. 2020; 297(3):513-520. doi:10.1148/radiol.2020201434
181. Alexander A, Jiang A, Ferreira C, Zurkiya D. An intelligent future for medical imaging: a market outlook on artificial intelligence for medical imaging. *J Am Coll Radiol*. 2020;17(1, Part B):165-170. doi:10.1016/j.jacr.2019.07.019
182. Forum WE. Diagnostics for better health: considerations for global implementation. 2021. Accessed June 17, 2023. https://www3.weforum.org/docs/WEF_Diagnostics_for_Better_Health_Considerations_for_Globa_%20Implementation_2021.pdf
183. Porayska-Pomsta K, Rajendran G. Accountability in human and artificial intelligence decision-making as the basis for diversity and educational inclusion. In: Knox J, Wang Y, Gallagher M, eds. *Artificial Intelligence and Inclusive Education: Speculative Futures and Emerging Practices*. Springer Singapore; 2019:39-59.
184. Straw I. The automation of bias in medical artificial intelligence (AI): decoding the past to create a better future. *Artif Intell Med*. 2020;110:101965. doi:10.1016/j.artmed.2020.101965
185. Cirillo D, Catuara-Solarz S, Morey C, et al. Sex and gender differences and biases in artificial intelligence for biomedicine and healthcare. *npj Digit Med*. 2020;3(1):81. doi:10.1038/s41746-020-0288-5
186. Parikh RB, Teeple S, Navathe AS. Addressing bias in artificial intelligence in health care. *JAMA*. 2019;322(24):2377-2378. doi:10.1001/jama.2019.18058
187. Obermeyer Z, Powers B, Vogeli C, Mullainathan S. Dissecting racial bias in an algorithm used to manage the health of populations. *Science*. 2019; 366(6464):447-453. doi:10.1126/science.aax2342
188. Rajkomar A, Hardt M, Howell MD, Corrado G, Chin MH. Ensuring fairness in machine learning to advance health equity. *Ann Intern Med*. 2018; 169(12):866-872. doi:10.7326/M18-1990
189. Good machine learning practice for medical device development: guiding principles. 2021. Accessed June 17, 2023. https://www.gov.uk/government/publications/good-machine-learning-practice-for-medical-device-development-guiding-principles/good-machine-learning-practice-for-medical-device-development-guiding-principles
190. Machinery UAfC. Statement on algorithmic transparency and accountability. ACM US Public Policy Council 1701 Pennsylvania Ave NW, Suite 300 Washington, DC 200062017.
191. DeCamp M, Lindvall C. Latent bias and the implementation of artificial intelligence in medicine. *J Am Med Inform Assoc*. 2020;27(12):2020-2023. doi:10.1093/jamia/ocaa094
192. Ganapathi S, Palmer J, Alderman JE, et al. Tackling bias in AI health datasets through the STANDING Together initiative. *Nat Med*. 2022;28(11): 2232-2233. doi:10.1038/s41591-022-01987-w
193. Wolff RF, Moons KGM, Riley RD, et al. PROBAST: a tool to assess the risk of bias and applicability of prediction model studies. *Ann Intern Med*. 2019;170(1):51-58. doi:10.7326/m18-1376
194. Initiative CG. Asha Jyoti: women's healthcare mobile outreach program - RAD-AID International [video]. 2013. Accessed February 13, 2022. https://www.youtube.com/watch?v=zx02U8LzdHY
195. Ginsburg O, Yip C-H, Brooks A, et al. Breast cancer early detection: a phased approach to implementation. *Cancer*. 2020;126(S10):2379-2393. doi:10.1002/cncr.32887
196. Hovis G, Langdorf M, Dang E, Chow D. MRI at the bedside: a case report comparing fixed and portable magnetic resonance imaging for suspected stroke. *Cureus*. 2021;13(8):e16904. doi:10.7759/cureus.16904
197. Deoni SCL, Medeiros P, Deoni AT, et al. Development of a mobile low-field MRI scanner. *Sci Rep*. 2022;12(1):5690. doi:10.1038/s41598-022-09760-2
198. Rouleau G, Gagnon M-P, Côté J. Impacts of information and communication technologies on nursing care: an overview of systematic reviews (protocol). *Syst Rev*. 2015;4:75. doi:10.1186/s13643-015-0062-y
199. Bokolo AJ. Use of telemedicine and virtual care for remote treatment in response to COVID-19 pandemic. *J Med Syst*. 2020;44(7):132. doi:10.1007/s10916-020-01596-5
200. Halton J, Kosack C, Spijker S, et al. Teleradiology usage and user satisfaction with the telemedicine system operated by médecins sans frontières. *Front Public Health*. 2014;2:202. doi:10.3389/fpubh.2014.00202
201. Marsh-Feiley G, Eadie L, Wilson P. Telesonography in emergency medicine: a systematic review. *PLoS ONE*. 2018;13(5):e0194840. doi:10.1371/journal.pone.0194840
202. Kim C, Kang BS, Choi HJ, Lim TH, Oh J, Chee Y. Clinical application of real-time tele-ultrasonography in diagnosing pediatric acute appendicitis in the ED. *Am J Emerg Med*. 2015;33(10):1354-1359. doi:10.1016/j.ajem.2015.07.048
203. Adambounou K, Adjenou V, Salam AP, et al. A low-cost tele-imaging platform for developing countries. *Front Public Health*. 2014;2:135. doi:10.3389/fpubh.2014.00135
204. Lamph S. Regulation of medical devices outside the European Union. *J R Soc Med*. 2012;105(Suppl 1):S12-S21. doi:10.1258/jrsm.2012.120037
205. World Health Organization. Medical device regulations: global overview and guiding principles. 2003. Accessed June 17, 2023. https://apps.who.int/iris/handle/10665/42744
206. Hubner S, Maloney C, Phillips SD, et al. The evolving landscape of medical device regulation in east, central, and southern Africa. *Glob Health: Sci Pract*. 2021;9(1):136-148. doi:10.9745/ghsp-d-20-00578
207. Rey-Ares L, Hernández-Vásquez A, Garay OU, et al. Medical devices: from licensing to coverage. Highlights from Argentina, Brazil, Colombia and Mexico. *Expert Rev Med Devices*. 2016;13(11):1053-1065. doi:10.1080/17434440.2016.1245611
208. Brunnquell CL, Hoff MN, Balu N, Nguyen XV, Oztek MA, Haynor DR. Making magnets more attractive: physics and engineering contributions to patient comfort in MRI. *Top Magn Reson Imaging*. 2020;29(4):167-174. doi:10.1097/rmr.0000000000000246
209. Moelker A, Wielopolski PA, Pattynama PM. Relationship between magnetic field strength and magnetic-resonance-related acoustic noise levels. *MAGMA*. 2003;16(1):52-55. doi:10.1007/s10334-003-0005-9

210. Glans A, Wilén J, Lindgren L. Maintaining image quality while reducing acoustic noise and switched gradient field exposure during lumbar MRI. *J Magn Reson Imaging*. 2021;54(1):315-325. doi:10.1002/jmri.27527
211. Draper CE, Santos JM, Kourtis LC, et al. Feasibility of using real-time MRI to measure joint kinematics in 1.5T and open-bore 0.5T systems. *J Magn Reson Imaging*. 2008;28(1):158-166. doi:10.1002/jmri.21413
212. Taggart T, Grewe ME, Conserve DF, Gliwa C, Roman IM. Social media and HIV: a systematic review of uses of social media in HIV communication. *J Med Internet Res*. 2015;17(11):e248. doi:10.2196/jmir.4387
213. WelTel. WelTel health. Accessed February 21, 2022. https://www.weltelhealth.com/Home
214. O AlRowaili M, Ahmed AE, Areabi HA. Factors associated with no-shows and rescheduling MRI appointments. *BMC Health Serv Res*. 2016;16(1):679. doi:10.1186/s12913-016-1927-z
215. Buck DW, Lillie, Beech, Jake. Communities and health. King's Fund. Accessed February 19, 2022. https://www.kingsfund.org.uk/publications/communities-and-health
216. Shen FX, Wolf SM, Bhavnani S, et al. Emerging ethical issues raised by highly portable MRI research in remote and resource-limited international settings. *Neuroimage*. 2021;238:118210. doi:10.1016/j.neuroimage.2021.118210
217. Rosman DA, Bamporiki J, Stein-Wexler R, Harris RD. Developing diagnostic radiology training in low resource countries. *Curr Radiol Rep*. 2019;7(9): 27. doi:10.1007/s40134-019-0336-6
218. Radiological Society of North America. Radiological Society of North America (RSNA). Accessed February 19, 2022. https://www.rsna.org/
219. European Society of Radiology. European Society of Radiology (ESR). Accessed February 19, 2022. https://www.myesr.org/
220. European Association of Nuclear Medicine. European Association of Nuclear Medicine (EANM). Accessed February 19, 2022. https://www.eanm.org/
221. International Organisation for Medical Physics. International Organisation for Medical Physics (IOMP). Accessed February 19, 2022. https://www.iomp.org/
222. International Society of Radiographers and Radiological Technologists. International Society of Radiographers and Radiological Technologists (ISRRT). Accessed February 19, 2022. https://www.isrrt.org/
223. OECD. Health spending (indicator). Accessed March 18, 2022. https://data.oecd.org/healthres/health-spending.htm
224. WorldData.info. Average income around the world. Accessed March 18, 2022. https://www.worlddata.info/average-income.php

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