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Content Advisor: Kevin N. Sheth, MD

Role of Low-Field MRI in Acute Stroke

Annabel Sorby-Adams¹ PhD; Nandor K. Pinter² MD; Keith W. Muir³ MBChB, MD; Kathryn E. Keenan⁴ PhD; Juan Eugenio Iglesias, PhD; Matthew S. Rosen⁵ PhD; Kevin N. Sheth⁶ MD; Joshua N. Goldstein⁷ MD, PhD; W. Taylor Kimberly⁸ MD, PhD

ABSTRACT: Portable, low-field (LF) magnetic resonance imaging (MRI) is emerging as a clinically relevant adjunct in acute stroke care, enabling MRI in environments where conventional neuroimaging access is delayed, unavailable, or impractical. Advances in permanent magnet design, compact gradient and radiofrequency hardware, and the use of contemporary reconstruction methods have improved LF image quality and operational feasibility, supporting deployment at the point-of-care in emergency departments, intensive care units, and resource-limited settings. This review summarizes the evolving role of LF-MRI for acute stroke. LF sequence principles most relevant to stroke evaluation are summarized, focusing on how constraints in signal-to-noise ratio, achievable diffusion weighting, acquisition time, and diffusion direction sampling at LF influence lesion conspicuity and the reliability of quantification. The current clinical evidence base is then reviewed, including the role of LF-MRI in supporting stroke-type classification and tissue confirmation, in wake-up and unknown-onset stroke for tissue-based triage, and in posttherapeutic settings to enable serial assessment after thrombolysis or thrombectomy. Practical implementation considerations emphasize use case-driven deployment that preserves time-critical computed tomography and angiography pathways and clearly defines when LF-MRI should be used as an adjunct rather than a substitute for established initial imaging. Future directions include pragmatic workflow studies to determine where LF-MRI changes management, continued advances in hardware and pulse sequence development, and careful application of artificial intelligence for reconstruction and enhancement with task-specific validation in acute stroke.

GRAPHIC ABSTRACT: A graphic abstract is available for this article.

Key Words: artificial intelligence ■ magnetic resonance imaging ■ neuroimaging ■ stroke ■ thrombectomy

Neuroimaging is foundational to contemporary acute stroke care.¹ As treatment options have expanded and become increasingly time-dependent,² stroke management has evolved into an image-guided paradigm in which the timing, type, and sequencing of neuroimaging directly determine triage, treatment eligibility, and clinical outcomes. In some circumstances, such as endovascular thrombectomy (EVT) evaluation, the imperative for simple and rapid neuroimaging has emphasized the use of computed tomography (CT)-based technology.³ In other scenarios where increased sensitivity for ischemic detection is clinically informative, magnetic resonance imaging (MRI) offers advantages over CT,⁴ but limitations in its accessibility preclude widespread use.

Over the past decade, advances in permanent magnet design, compact gradient and radiofrequency electronics, and the use of contemporary reconstruction and denoising methods including artificial intelligence (AI)-based approaches have enabled renewed interest in MRI systems operating at lower magnetic field strengths.^{5–13} These developments have supported the emergence of portable, low-field (LF) MRI systems designed to operate outside a conventional MRI suite, enabling imaging at the point-of-care in environments where high-field (HF; 1.5–3 T) MRI access is delayed, unavailable, or unsafe for transport. Sites of care include the emergency department, intensive care unit, and resource-limited settings.^{9,14–23} For this review, we adopt the field strength terminology summarized by a 2022 International Society for Magnetic

Correspondence to: W. Taylor Kimberly, MD, PhD, Department of Neurology and the Center for Genomic Medicine, Mass General Brigham and Harvard Medical School, 55 Fruit St, Lunder 644, Boston, MA 02114. Email wtkimberly@mgh.harvard.edu
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Resonance in Medicine LF-MRI workshop: mid field (0.1–1 T), LF (0.01–0.1 T), and ultralow field (<0.01 T).⁶

LF-MRI is now transitioning from proof-of-concept to early clinical implementation across diverse care settings. This review summarizes LF sequence principles most relevant to acute stroke, the current clinical evidence base, practical considerations for workflow integration, and future directions needed to establish decision impact and support broader adoption.

SEQUENCE PRINCIPLES FOR LF-MRI SPECIFIC TO ACUTE STROKE

MRI acquisition protocols for acute stroke frequently focus on diffusion-weighted imaging (DWI) and fluid-attenuated inversion recovery (FLAIR), with additional roles for blood-sensitive and vascular sequences. DWI and FLAIR are the core MRI sequences for assessing acute ischemic stroke (AIS), providing complementary sensitivity to evolving infarction. DWI is uniquely sensitive to early cytotoxic edema, where restricted diffusion due to a compartmental shift of water from the extracellular to intracellular space consequent to failure of energy-dependent cellular Na⁺/K⁺-ATPase pumps produces hyperintensity on DWI within minutes of stroke onset.²⁴ In contrast, T₂-weighted FLAIR eliminates cerebrospinal fluid signal using an appropriately selected inversion time, improving conspicuity of parenchymal and sulcal abnormalities as net tissue water increases, with hyperintensity evolving over hours as ionic and vasogenic edema develop.

Some sequence types face fundamental challenges at LF. Blood-sensitive sequences such as susceptibility-weighted imaging (SWI) and T₂*-weighted gradient-echo (GRE) imaging depend on field-dependent susceptibility phase accrual and dephasing, whereas time-of-flight magnetic resonance angiography (MRA) depends on inflow contrast, background saturation, sufficient signal-to-noise ratio (SNR), and spatial resolution. At LF, these mechanisms are limited by reduced equilibrium magnetization, attenuated susceptibility effects, altered relaxation times, and hardware-specific constraints. The following sections discuss the principles underlying each sequence class and the constraints specific to LF implementation.

Diffusion-Weighted Imaging

Conventionally, DWI is acquired with a specified diffusion weighting (*b* value), which is determined by the strength and timing of diffusion gradients. When images are acquired at multiple *b* values, typically *b*=0 and at least one higher *b* value (eg, *b*=1000 s/mm²), an apparent diffusion coefficient (ADC) map can be estimated using a monoexponential signal model:

$$S(b) = S_0 \cdot \exp(-b \cdot \text{ADC})$$

where *S*₀ is the signal without diffusion weighting, and ADC is the fitted diffusion coefficient (with physical units). ADC provides a quantitative metric that can be compared with reference values and can help distinguish true diffusion restriction from T₂ shine-through; however, in routine clinical stroke imaging, qualitative DWI is often sufficient for diagnosis when interpreted alongside ADC.

Implementing DWI at LF introduces 3 interrelated constraints that shape lesion conspicuity and quantitative reliability. First, achieving diagnostic image quality often requires signal averaging due to reduced SNR, which increases acquisition time and thus the potential for motion artifact. Second, diffusion imaging relies on gradient performance to generate sufficient diffusion weighting. On HF-MRI systems, DWI commonly uses *b* values up to ≈1000 s/mm² for routine stroke detection, and higher *b* values in selected contexts. LF systems are frequently designed for lower cost and portability and may incorporate gradient hardware with lower maximum amplitude or slew rate, and space constraints can further limit gradient design in portable architectures. Consequently, achievable *b* values may be lower (<1000 s/mm²), which can reduce sensitivity to diffusion restriction and affect the stability and interpretability of ADC estimation. Third, HF-DWI is typically acquired with diffusion gradients applied along multiple directions and combined into a trace-weighted image to minimize confounding effects of diffusion anisotropy, improve signal uniformity, and reduce tract-related directional hyperintensity.

At LF, SNR and scan-time constraints can limit DWI to a single diffusion direction or a small set of *b* values. LF-MRI DWI implementations at 0.064 T historically acquired diffusion weighting in a single direction along the scanner's *z* axis (anterior to posterior), yielding directionally dependent contrast and susceptibility to white matter anisotropy artifact. Recent hardware and sequence advances have enabled multidirectional *b*=900 s/mm² DWI acquisition in orthogonal inferior to superior, left to right, and anterior to posterior planes at 0.064 T, accompanied by a single *b*=0.²⁵ Resulting trace-weighted images were shown to improve signal uniformity relative to single-direction protocols.

Although multidirectional DWI improves image homogeneity,²⁵ limited *b* value sampling constrains ADC estimation. With only 2 *b* values, the monoexponential decay model is weakly constrained, and measurement noise limits accurate estimation of high ADC values. For example, if diffusion-weighted scans are acquired at *b*=10 and *b*=900 s/mm² with 10% measurement noise, the second measurement falls below the noise floor when ADC ≈ −10⁶ ln(0.10)/900, corresponding to ≈2600 μm²/s. Adding an intermediate *b* value, for example, 500 s/mm², shifts this threshold upward to ≈4600 μm²/s, improving dynamic range for high ADC estimation, albeit at the cost of increased scan duration. There is thus a trade-off at LF between increased scan time

and reduced dynamic range of the ADC estimation. With limited b values, ADC estimation is also more susceptible to noise-floor and partial-volume effects, particularly in higher-diffusivity voxels. This can reduce the reliability of quantitative ADC thresholds used for infarct core delineation and lesion-age characterization, particularly for small lesions and lesions adjacent to cerebrospinal fluid interfaces. In threshold-based workflows, this may bias infarct sizing and reduce stability of automated maps that assume well-separated ADC distributions across tissue classes, increasing false positives near cerebrospinal fluid spaces or reducing sensitivity as ADC approaches pseudo-normalization in the subacute poststroke phase.

Fluid-Attenuated Inversion Recovery

In comparison to DWI, FLAIR at LF is more robust because it depends primarily on longitudinal relaxation and inversion recovery timing rather than high-performance gradients. At lower field strengths, T_1 values are typically shorter and susceptibility-related dephasing is reduced, which enables robust inversion recovery contrast, mitigating signal loss relative to higher field imaging.⁶ However, LF-FLAIR remains constrained by the same fundamental limitation that impacts all LF imaging, namely reduced SNR. This often requires thicker slices, longer acquisition times, or increased averaging to achieve sufficiently interpretable image quality, and FLAIR is inherently time-consuming as it uses long repetition and echo times to achieve heavy T_2 weighting. Additional practical constraints include greater sensitivity to main static magnetic field (B_0) and radiofrequency magnetic field (B_1) inhomogeneity in permanent magnets, which can reduce inversion efficiency and lead to imperfect cerebrospinal fluid nulling, and the potential for environmental electromagnetic interference in unshielded settings, which must be addressed through hardware and reconstruction strategies.¹⁵

SWI and GRE Imaging

Conventional SWI and GRE sequences derive much of their clinical value from magnetic susceptibility-induced phase accrual and intravoxel dephasing produced by deoxyhemoglobin, methemoglobin, hemosiderin, and other paramagnetic blood products. These effects are strongly field dependent, with phase accrual and susceptibility-related signal loss reduced at LF. As a result, the blooming that makes cerebral microbleeds, petechial hemorrhagic transformation (HT), cortical superficial siderosis, venous thrombus, and small hemorrhagic foci conspicuous on HF SWI/GRE is markedly attenuated at LF.

This limitation does not imply that all hemorrhage is invisible at LF. Larger primary hematomas can be detected using T_2 -, FLAIR-, T_1 -, and spin-echo-based

contrasts, likely because lesion size, edema, clot evolution, and bulk relaxation changes remain visible even when susceptibility blooming is reduced. However, this is mechanistically distinct from HF SWI/GRE-based blood-product detection, and thus LF-MRI is currently better suited for detecting larger hemorrhages than for excluding small blood products or petechial HT. Alternative approaches, including optimized spin-echo-based contrasts, tailored inversion-recovery approaches such as hematoma-enhanced inversion recovery (HEIR) demonstrated at 0.23 T,²⁶ and reconstruction methods designed to preserve hemorrhage signatures under low-SNR, motion-prone acquisition conditions remain important areas for development.

Magnetic Resonance Angiography

Time-of-flight-MRA relies on inflow enhancement, in which unsaturated blood entering an imaging slab appears bright relative to partially saturated stationary tissue. At LF, this contrast mechanism is challenged by several interacting factors rather than by field strength alone. Although lower Boltzmann polarization reduces SNR, shorter T_1 values also reduce saturation of stationary background tissue for a given repetition time and flip angle; and the spatial resolution, gradient performance, radiofrequency profile, and acquisition-time constraints of LF-MRI further limit visualization of small or distal vessels. These factors make HF time-of-flight-MRA difficult to translate directly to current LF platforms. Consequently, LF-MRI should not currently be considered a substitute for CT angiography or MRA when large-vessel occlusion (LVO) is suspected. Early work has explored alternative vascular contrast mechanisms, including time-reversed fast imaging with steady-state precession, which may provide dark-blood visualization of large intracranial arteries at 0.064 T,²⁷ but these approaches remain preliminary and require clinical validation for LVO detection, stenosis assessment, and treatment triage.

Collectively, these sequence constraints highlight that LF-MRI protocols must be designed around hardware-specific limitations and tailored to the specific clinical task, whether the priority is acute stroke lesion detection, quantitative characterization, or both.

CURRENT EVIDENCE BASE FOR LF-MRI IN ACUTE STROKE

Rapid neuroimaging is central to the triage of patients with suspected stroke. CT is most widely available for initial imaging, yet has limited sensitivity for early ischemia, particularly in minor stroke and posterior fossa presentations.^{28,29} MRI provides superior sensitivity for acute infarction and facilitates tissue-based decision-making using multiparametric sequences.^{1,30,31} HF-MRI, however,

is often limited by cost, staffing, safety screening, and transport logistics. Conversely, LF-MRI systems operate with minimal fringe magnetic fields and reduced power requirements, permitting use at the point-of-care near clinical monitoring equipment and enabling imaging of patients who are hemodynamically unstable, mechanically ventilated, under isolation precautions, or for whom transportation to an imaging suite may be unsafe or delayed. Advances in LF hardware, reconstruction, and sequence development have iteratively improved diagnostic performance and image quality (Figure 1). The following sections present the evidence base for LF-MRI across the continuum of acute stroke care.

Acute Stroke Detection and Emergency Department Triage

Guideline-based pathways outline stepwise neuroimaging recommendations for patients presenting with suspected stroke to guide emergency department triage.¹ These encompass initial imaging evaluation to exclude intracranial hemorrhage (ICH) and estimate infarct burden; emergent brain imaging (≤ 25 minutes) in patients with suspected AIS; rapid vascular imaging when LVO is suspected; and selective use of multiparametric imaging to guide reperfusion decisions in hyperacute and unknown-onset presentations.¹

Differentiation of Ischemia From Hemorrhage

Early clinical studies established the feasibility of LF-MRI for stroke-type classification, demonstrating reliable detection of ICH and AIS at 0.064 T in patients on mechanical ventilation, and in proximity to ferromagnetic bedside equipment such as infusion pumps and physiological monitors, establishing initial clinical utility at the bedside.¹⁴ A prospective study of 144 patients with ICH or AIS and 40 healthy controls subsequently evaluated LF-MRI for dedicated hemorrhage-ischemia differentiation. Participants were imaged at 0.064 T in the hyperacute (< 24 hours, $n=13$), subacute (24 hours–7 days, $n=68$), and chronic phase (> 1 week, $n=13$), with T_2 and FLAIR images interpreted by board-certified neuroradiologists.¹⁶ Across all examinations, scans were correctly classified as positive or negative for ICH in 130 of 144 cases, corresponding to 90.3% overall accuracy. Of those cases with confirmed hemorrhage on conventional imaging, ICH was correctly detected in 45 of 56 patients (80.4% sensitivity), whereas AIS and healthy control cases were correctly classified as blood negative in 85 of 88 patients (96.6% specificity).¹⁶ An additional study performed at 0.064 T imaged 189 patients with ICH, AIS, or no intracranial abnormality, with images acquired primarily in the hyperacute (< 24 hours, $n=67$) and subacute (24 hours–7 days, $n=62$) phase across T_1 , T_2 , FLAIR, and DWI acquisitions.¹⁹ Exams were correctly classified as positive or negative for ICH in 185

of 189 cases, corresponding to 97.9% overall accuracy. ICH was correctly detected in 35 of 38 patients (92.1% sensitivity), whereas 139 of 140 patients with confirmed AIS or no intracranial abnormality were correctly classified as blood negative (99.3% specificity). A single-center prospective feasibility study of a 0.1 T LF-MRI system in 28 acute stroke patients scanned within 25 hours of last-known well, including 24 with AIS and 4 with ICH, reported no safety concerns and target SNR in 82.1% of images acquired, although diagnostic performance for ischemia-hemorrhage differentiation has yet to be demonstrated.³² A study using a 0.23 T mid-field system reported differentiation of AIS versus ICH within 24 hours of onset using DWI paired with a novel HEIR sequence. Diagnostic criteria were based on DWI hyperintensity with HEIR isointensity for AIS versus hyperintensity on both sequences for ICH.²⁶ Across 30 AIS and 30 patients with ICH, blinded readers achieved 100% overall accuracy relative to differential diagnosis on HF-MRI or CT, highlighting the utility of tailored contrast mechanisms for stroke-type classification at lower field strength.²⁶

ICH Characterization

LF-MRI has demonstrated initial sensitivity for compartmental ICH characterization across supratentorial, infratentorial, intraventricular, and subarachnoid hemorrhage subtypes. In a study of 56 patients with confirmed ICH imaged at 0.064 T with T_2 and FLAIR sequences, blinded neuroradiologists correctly identified supratentorial ICH in 44 of 50 patients (88.0% sensitivity) and intraventricular hemorrhage in 13 of 14 patients (92.8% sensitivity), whereas infratentorial ICH was not reliably detected.¹⁶ Quantitative analysis of LF-MRI–derived hematoma volumes was strongly correlated with those derived from HF-MRI counterparts acquired within 36 hours, providing proof-of-concept that hematoma quantification is feasible at LF.¹⁶ A subsequent study demonstrated higher accuracy of compartmental hemorrhage characterization across 38 ICH, 8 subarachnoid hemorrhage, and 3 primary intraventricular hemorrhage cases scanned at 0.064 T with a combination of T_1 , T_2 , FLAIR, and DWI sequences.¹⁹ Primary ICH located in the supratentorial compartment was detected in 29 of 30 patients (96.7% sensitivity), with higher accuracy of infratentorial intraparenchymal hemorrhage detection relative to prior studies, with 6 of 8 cases correctly identified (75.0% sensitivity). Subarachnoid hemorrhage was correctly detected in 8 of 8 cases (100% sensitivity), whereas intraventricular hemorrhage was detected in 23 of 24 cases (95.8% sensitivity). Authors further reported higher diagnostic performance with deep learning (DL)–based reconstruction (96.6% sensitivity; 99.3% specificity) compared with non-DL reconstructions (77.8% sensitivity; 97.1% specificity).¹⁹ At 0.23 T, DWI and HEIR sequences acquired in 30 patients with ICH scanned

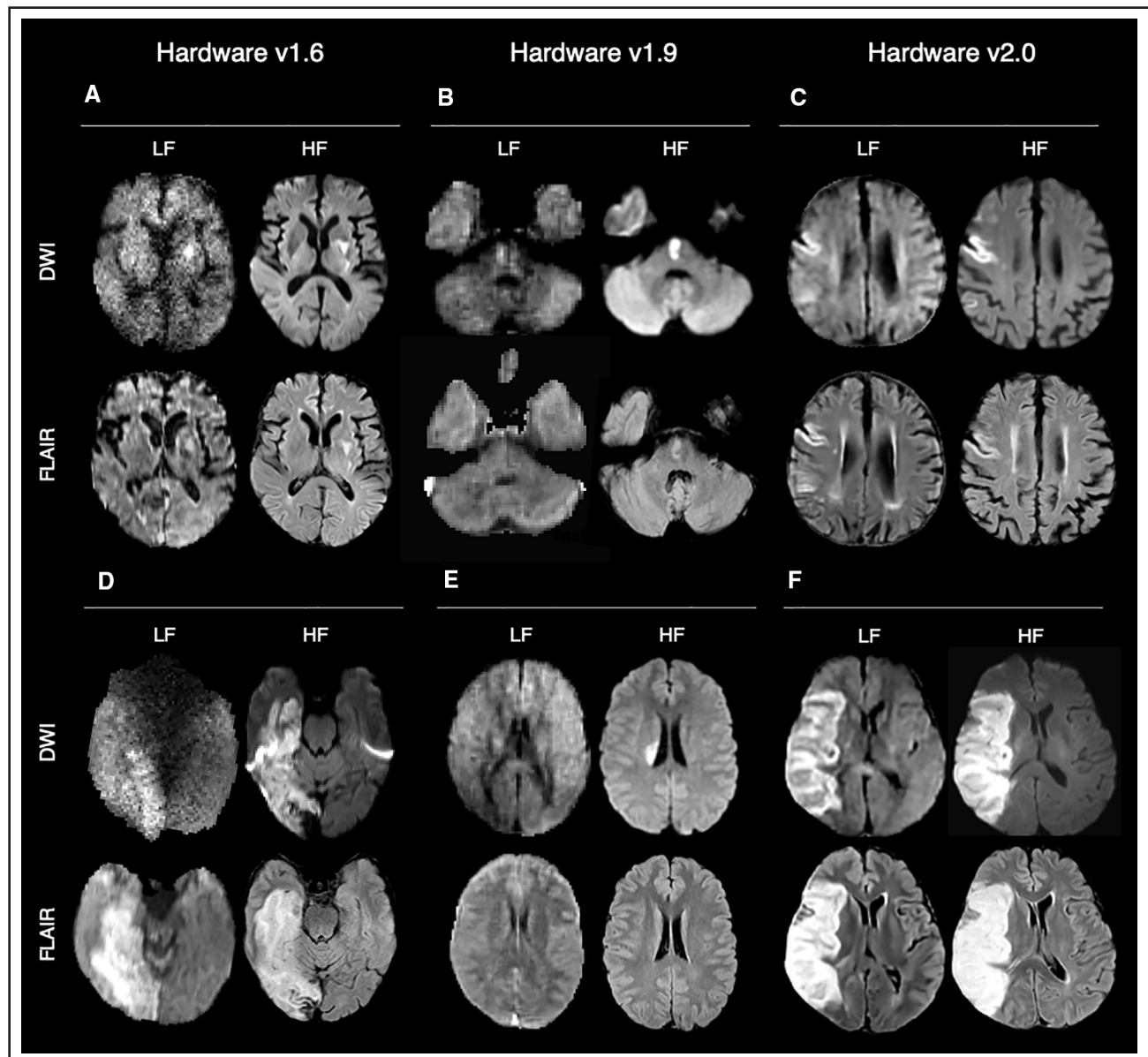


Figure 1. Low-field (LF; 0.064 T) magnetic resonance imaging (MRI) acute ischemic stroke examples on diffusion-weighted imaging (DWI) and fluid-attenuated inversion recovery (FLAIR) sequences relative to conventional, high-field (HF; 1.5–3 T) MRI counterparts.

Case examples acquired on Hyperfine Inc v1.6 hardware (circa 2020), including a subcortical infarct in the left caudate (**A**), and a right inferior temporal infarct, which is more difficult to detect on LF-DWI due to image inhomogeneity and lower signal-to-noise ratio relative to LF-FLAIR (**D**). Case examples acquired on Hyperfine Inc v1.9 hardware (circa 2022), where modified gradient amplifiers improve DWI image resolution, increasing sensitivity for lesion detection, including an infratentorial infarct in the right pons visualized on LF-DWI (**B**). However, due to single-direction LF-DWI acquisition, directional anisotropy can obfuscate lesions adjacent to white matter tracts, as seen in the case example of DWI-FLAIR mismatch shown in panel **E**, where the right caudate infarct clearly visualized on the HF-DWI trace image is more difficult to detect on the LF-DWI single-direction counterpart. Case examples acquired on Hyperfine Inc v2.0 hardware (circa 2024), where advanced gradient amplifiers, forced cooling, wider form factor, and deep learning image reconstruction approaches improve both DWI and FLAIR image quality, enabling better differentiation of multifocal lesions such as those shown in the right cortex in panel **C**, and of evolving infarction, as shown in the right middle cerebral artery territory infarct shown in panel **F**, although single-direction LF-DWI acquisition still results in regional anisotropy of white matter tracts and potential obfuscation of small lesions adjacent to axonal bundles. The skull has been removed from all images to improve visualization of the parenchyma.

within 24 hours of onset demonstrated 100% accuracy for hemorrhage detection, including lesions located in the supratentorial (n=15), infratentorial (n=6), intraventricular (n=8) and subdural (n=1) compartments.²⁶ Beyond

compartmental hemorrhage detection, LF-MRI at 0.23 T has also been evaluated in aneurysmal subarachnoid hemorrhage to identify early cerebral infarction patterns linked to delayed cerebral ischemia and outcome,

supporting a potential role for lower-field MRI in early risk stratification within hemorrhagic stroke pathways.³³

AIS Characterization

A single-patient, case-based clinical study was among the first to demonstrate the utility of LF-MRI in suspected AIS, where noncontrast CT was unrevealing but LF-DWI/ADC identified scattered embolic infarcts.³⁴ Thereafter, a prospective cohort of 50 patients with confirmed AIS was imaged at 0.064 T across acute (<24 hours, $n=16$), subacute (24 hours–7 days, $n=33$), and chronic (>7 days, $n=4$) poststroke phases.¹⁷ LF-FLAIR and DWI ($b=0$ and $b=900$ s/mm² in a single diffusion direction) demonstrated infarcts in 45 of 50 (90%) of cases across cortical, subcortical, and posterior fossa locations relative to HF-MRI, with visualization of lesions as small as 4 mm.¹⁷ Infarcts missed on DWI were small (4–10 mm in diameter) and primarily located subcortically adjacent to white matter tracts. Of those infarcts detected, quantitative LF volume measurements were consistent across sequences and correlated with stroke severity (National Institutes of Health Stroke Scale score) and discharge functional outcome (modified Rankin Scale score), suggesting utility not only for AIS diagnosis but also early severity phenotyping.¹⁷ Preliminary retrospective data from another AIS cohort imaged at 0.064 T similarly demonstrated acute infarcts in 9 of 12 patients, with lesions missed significantly smaller than those detected (7.7 versus 21.7 mm), supporting feasibility in inpatient hospital settings while underscoring reduced sensitivity for small infarcts.³⁵

At 0.23 T, a retrospective study analyzed 61 patients with AIS across acute (<24 hours, $n=25$), subacute (24 hours–7 days, $n=22$), and chronic (>7 days, $n=14$) phases.³⁶ The imaging protocol included a single-direction DWI ($b=0$ and $b=1000$ s/mm²) with 3 T HF-MRI acquired within <30 minutes. Neuroradiologists evaluated raw DWI/ADC images relative to those enhanced with a DL super-resolution algorithm and compared against HF-MRI. On raw images, sensitivity and specificity for lesion detection were 77.1% and 71%, improving to 89% and 91.3% with DL enhancement. Intraclass correlations for LF lesion volumes improved from 0.453 on raw images to 0.987 with DL. Mean ADC values (10⁻⁶ mm²/s) within the lesion at HF were 666.8 ± 169.7 , DL LF were 647.9 ± 170.0 , whereas raw LF were 761.4 ± 180.1 . This corresponded to an intraclass correlation of 0.656 for raw LF and 0.890 for DL LF relative to HF-ADC counterparts.

These studies demonstrate that restricted diffusion can be identified qualitatively at 0.064 T as regions of reduced ADC signal, and that at 0.23 T, absolute ADC quantification shows improved agreement with HF-MRI when DL enhancement is applied. However, systematic evaluation of ADC values at field strengths <0.1 T, including calibration across scanners and protocols

and assessment of concordance with HF-ADC thresholds used for ischemic core estimation, remains limited. Furthermore, due to limitations in time-of-flight-MRA at LF, detection of LVO in the setting of AIS has yet to be demonstrated.

Minor Stroke, Transient Ischemic Attack, and Stroke Mimics

The first dedicated study evaluating transient ischemic attack (TIA) and minor stroke at lower field strength was performed at 0.23 T in 102 patients scanned within 14 days of last-known well using T₁, T₂, FLAIR, and DWI/ADC sequences. Relative to HF-MRI counterparts, the specificity and sensitivity of infarct detection were 96.1% and 97.9%, respectively, with limitations in the detection of small lesions, particularly subcortical and brainstem infarcts <5 mm.³⁷ A subsequent 0.23 T study scanned 2590 patients with minor ischemic stroke and TIA presenting within <72 hours of symptom onset and National Institutes of Health Stroke Scale score ≤ 5 .³⁸ Multivariable analysis of predictors of DWI positivity in this study revealed positive associations between higher National Institutes of Health Stroke Scale score at symptom onset, longer time from last-known well to image acquisition, and symptoms including hemiplegia and aphasia. Conversely, symptoms such as vertigo and disturbance of consciousness were negatively associated with DWI positivity, while presentation of nausea or headache did not reveal any associations. The rates of DWI positivity were 51.9% in patients with only focal neurological symptoms and 11.7% in those with only nonfocal symptoms. At 0.064 T, a single-center pilot study of suspected AIS imaged 17 patients presenting within 72 hours of symptom onset with FLAIR and DWI sequences. Differentiation of clinically diagnosed TIA or MRI-negative stroke demonstrated a specificity of 100% (3/3 patients) and 67% (2/3 patients). Ischemic lesions were detected in 8 of 12 cases confirmed on HF-MRI corresponding to 67% sensitivity, with all missed infarcts <6 mm in diameter.³⁹

A recurring limitation across the literature is reduced sensitivity for very small ischemic lesions at LF, with a practical detection boundary in the 5 to 6 mm range, reflecting the combined effects of lower SNR, spatial-resolution constraints, and common use of single-direction diffusion encoding, where anisotropy-related tract hyperintensity can obscure subtle diffusion restriction within or adjacent to white matter tracts (Figure 2). Multicenter prospective work in a cohort of 95 patients scanned at 0.064 T implemented multidirection diffusion acquisition across C-shaped and H-shaped scanner configurations to establish utility for minor stroke and AIS differentiation relative to single-direction counterparts.²⁵ Multidirection DWI acquisition demonstrated improved interrater agreement and higher positive predictive value for differentiating AIS

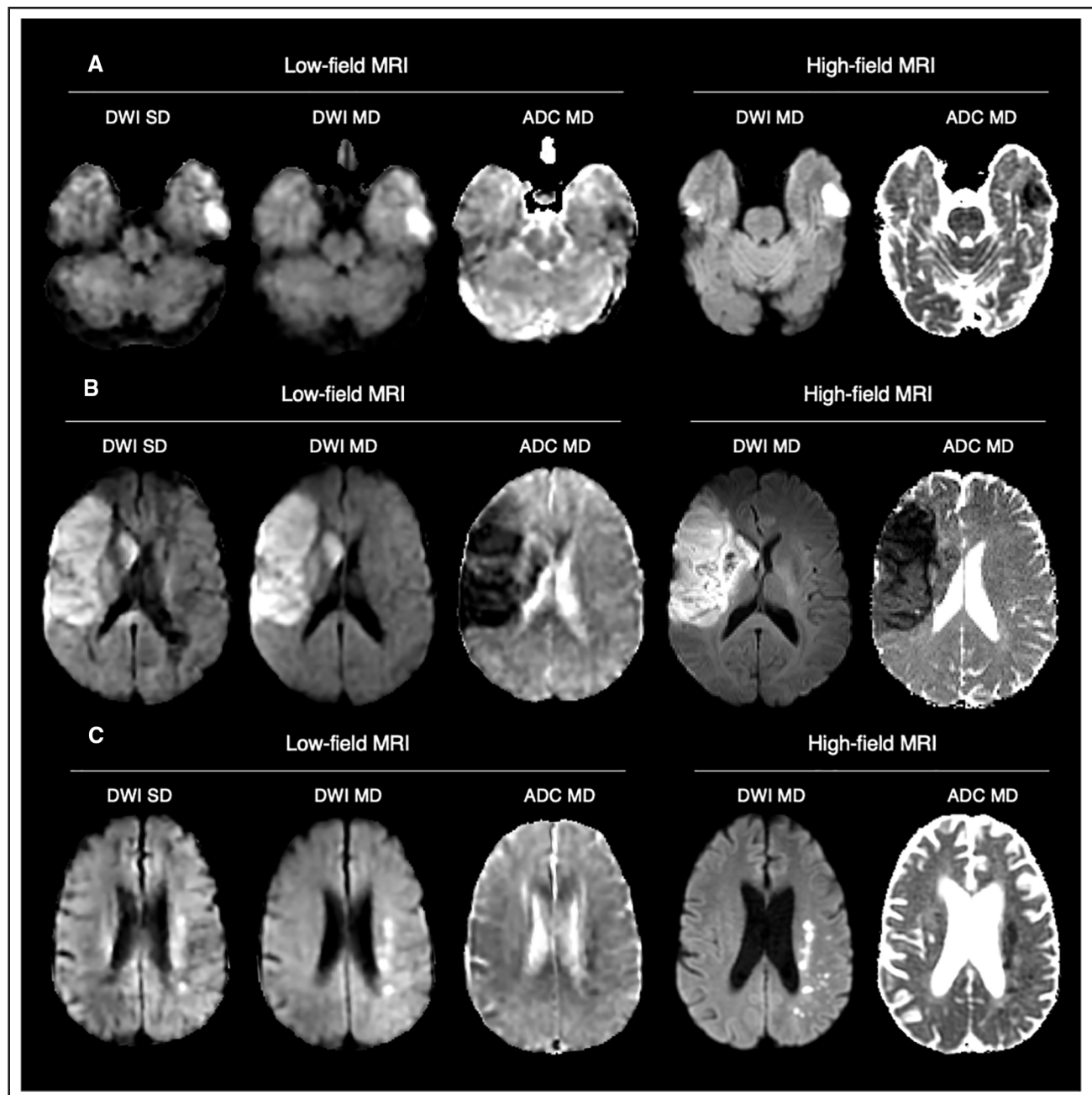


Figure 2. Low-field (LF; 0.064 T) magnetic resonance imaging (MRI) acute ischemic stroke examples acquired with a single-direction (SD) diffusion-weighted imaging (DWI) relative to multidirectional (MD) DWI and apparent diffusion coefficient (ADC) images acquired at LF relative to conventional, high-field (HF; 1.5–3 T) MRI counterparts.

Example cases acquired on Hyperfine Inc v2.0 hardware (circa 2024) in the left anterior temporal lobe (A), right middle cerebral artery territory including the caudate head (B), and multifocal lesions in the left corona radiata (C). Relative to DWI SD acquisitions, MD DWI and ADC reduce the confounding appearance of white matter tracts and improve image homogeneity, with MD images more comparable to HF-MRI, which by nature is acquired with multiple diffusion directions. The skull has been removed from all images to improve visualization of the parenchyma.

from stroke mimics (95% for multidirection versus 78.2% for single-direction). H-shaped LF hardware with active cooling, higher-performance diffusion gradients, and reduced B_0 inhomogeneity demonstrated improved signal uniformity and a 30% reduction in scan time. Notably, multidirection DWI enabled the detection of lesions as small as 2.8 mm on the H-shaped hardware.²⁵

Although the principal LF performance gap most relevant to minor stroke is small lesion detection, with significant variation in DWI hyperintensity and temporal evolution observed even at HF, contemporary tissue-based definitions classify symptom resolution with DWI-positive infarction as ischemic stroke rather than TIA.^{40,41} SNR and spatial-resolution constraints at LF thus limit confident

differentiation of tissue-negative TIA from minor stroke with punctate DWI-positive lesions.⁴² Furthermore, the published LF-MRI literature does not yet expressly characterize performance for specific common stroke mimics such as migraine with aura or seizure-related changes, which may not produce structural DWI or FLAIR abnormalities. Nevertheless, LF-MRI, in particular multidirection DWI, may enhance differentiation of DWI-positive lesions from stroke mimics and refine triage decisions in settings where CT is nondiagnostic and access to HF-MRI is limited.⁴³

Wake-Up and Unknown-Onset Thrombolysis

LF-MRI may improve diagnostic precision for AIS by enabling multiparametric tissue characterization. The temporal dissociation between early DWI positivity and delayed FLAIR signal change underpins the DWI-FLAIR mismatch concept, which has been validated as a surrogate marker of stroke onset and operationalized for tissue-based decision-making in unwitnessed and wake-up stroke presentations.^{30,31,44,45} In the PRE-FLAIR HF-MRI trial (Predictive Value of FLAIR and DWI for the Identification of Acute Ischemic Stroke Patients ≤ 3 and ≤ 4.5 h of Symptom Onset: A Multicenter Observational Study), an inflection point of ≈ 4.5 hours was identified in patients with known onset and translated into imaging selection protocols for unknown-onset stroke.³⁰ In the subsequent WAKE-UP trial (Efficacy and Safety of MRI-Based Thrombolysis in Wake-Up Stroke), selection based on HF-MRI DWI-FLAIR mismatch identified patients with unknown onset who derived clinically meaningful benefit from intravenous thrombolysis with recombinant tissue-type plasminogen activator.³¹ Among WAKE-UP participants who also underwent MRI perfusion, DWI-FLAIR mismatch was more frequently observed than perfusion-DWI mismatch (48% versus 13%), supporting the premise that DWI-FLAIR may identify a substantial subgroup potentially eligible for treatment.⁴⁶ Despite these findings, acute multiparametric MRI remains limited in many centers, highlighting an opportunity for LF systems.

Prospective data at 0.064 T evaluated DWI and FLAIR for time-uncertain triage in a cohort of 71 patients with AIS.²⁰ The study revealed good interrater agreement and specificity (82%) but lower sensitivity (60%) for detecting LF-DWI-FLAIR mismatch relative to HF-MRI within 4.5 hours of last-known well.²⁰ Notably, visually detectable FLAIR lesions had a signal intensity ratio of 1.37, whereas FLAIR-negative lesions had a FLAIR signal intensity ratio of 1.11, with an optimal time window of 6.6 hours for a FLAIR signal intensity ratio < 1.15 , comparable to that reported clinically on HF-MRI.⁴⁷ These data suggest that LF-DWI-FLAIR can inform mismatch-based triage but also identify small lesion detection and early/subtle mismatch sensitivity as performance constraints.

Given current guidelines emphasize intravenous thrombolysis for eligible patients with disabling deficits

regardless of National Institutes of Health Stroke Scale score, limitations in very small lesion detection at LF are less likely to affect thrombolysis decisions in patients with clearly disabling presentations.¹ However, these limitations remain clinically relevant in minor or nondisabling presentations, where CT is frequently nondiagnostic, and management often hinges on tissue confirmation and accurate DWI-FLAIR mismatch classification. More data characterizing sensitivity and specificity in hyperacute care environments are thus needed to determine whether LF-MRI can serve as an alternative to HF-MRI for wake-up and unknown-onset triage and potentially guide thrombolysis decisions.

Poststroke Therapeutic Monitoring

LF-MRI may enable longitudinal monitoring of therapeutic effects and evolving neurological status after intravenous thrombolysis or EVT, including assessment of infarct progression, HT, and mass effect.

Infarct Evolution

In the setting of EVT, peri-procedural deployment of LF-MRI has demonstrated feasibility and highlighted clinically meaningful heterogeneity in infarct evolution. In a cohort of 24 patients undergoing EVT, LF-MRI performed at 0.064 T in the interventional radiology suite immediately after the procedure added < 1 hour to workflow and was not associated with scanning-related complications, supporting safety and operational feasibility.⁴⁸ Postprocedural imaging identified infarct core progression in a subset of patients despite successful revascularization, with additional cases demonstrating delayed growth on HF-MRI within ≈ 72 hours, highlighting that reperfusion does not uniformly arrest tissue injury. This early growth signal may be clinically relevant, as infarct expansion despite recanalization has been associated with reduced odds of good outcome and may represent a therapeutic target for personalized post-EVT care in the setting of reperfusion injury.⁴⁹ Precise quantification of infarct evolution across time points may, however, be limited by geometric distortion and registration error in sequentially acquired LF data, which can affect volumetric comparisons between repeat scans.⁵⁰

After intravenous thrombolysis, infarct evolution may include the appearance of early new ischemic lesions on serial DWI, reflecting thrombus fragmentation and distal embolization as the occluding clot lyses. These new lesions are characteristically small and may fall below the current detection threshold of LF systems, comparable to that reported in the setting of TIA. Reliable monitoring of infarct evolution in this context is therefore contingent on continued improvements in spatial resolution and DWI sensitivity, with the development of multidirection DWI acquisitions representing a meaningful step toward detecting small lesions that typify postthrombolysis infarct evolution.

Hemorrhagic Transformation

HT is a clinically consequential complication of AIS, influencing secondary prevention strategies and anticoagulation initiation. Despite LF-MRI's utility for primary ICH detection, identifying HT is more challenging, as petechial or confluent hemorrhagic foci within an established infarct are inherently difficult to resolve at low-SNR. The sole study to expressly evaluate LF-MRI for HT detection examined 97 patients with confirmed ischemic infarcts imaged at 0.064 T, of whom 20 (20.6%) demonstrated HT on conventional neuroimaging, predominantly petechial in pattern. Sensitivity for HT detection was low across independent readers (0.1–0.17), with consensus sensitivity of 0.10, despite specificity and positive predictive values of 1.00, indicating that when LF-MRI identified HT it was correct, but the majority of cases were missed.⁵¹

These findings are mechanistically consistent with the fundamental dependence of HT detection on susceptibility contrast, which is challenging at LF. Conversely, larger hemorrhagic events, such as parenchymal hematoma-type transformation and primary ICH, are detectable at LF given their greater volume and T_2 signal contribution, though this distinction has not been systematically evaluated to date.

Mass Effect

Evolving cerebral edema and midline shift are complications of large-territory AIS, including malignant middle cerebral artery infarction, where early detection of mass effect informs decisions regarding osmotic therapy, neurosurgical intervention, and decompressive hemicraniectomy. Repeated transport of critically ill patients for conventional neuroimaging to monitor these changes carries substantial procedural risk, creating a use case for LF-MRI. In an observational study of 102 intensive care unit patients imaged at 0.064 T, including 48 with AIS and 54 with ICH, T_2 LF-MRI demonstrated concordance with conventional imaging for both dichotomous and continuous midline shift measurements, with a sensitivity of 93% and specificity of 96%. LF-derived midline shift measurements were independently predictive of poor functional outcome at discharge, with adjusted odds ratios of 7.98 and 1.59 for dichotomous and continuous midline shift assessments, respectively, supporting the prognostic relevance of bedside mass effect monitoring.¹⁸

CLINICAL UTILITY IN ACUTE STROKE CARE

Although the evidence base in support of LF-MRI for acute stroke is rapidly evolving, utility in clinical workflows is likely to be most beneficial when HF-MRI access is the principal constraint, CT is nondiagnostic, and when additional tissue information is expected to alter triage,

disposition, or monitoring decisions. Such scenarios include tissue-level confirmation of ischemia and refinement of triage in suspected minor stroke, discrimination of stroke mimics, bedside imaging in intensive care unit or transport-limited patients, time-uncertain presentations where DWI-FLAIR can support tissue-based treatment selection, and posttherapy monitoring to assess infarct evolution without repeated transport (Table S1).

It should be emphasized that LF-MRI should currently be regarded as complementary to, rather than a replacement for, CT or HF-MRI in acute treatment decision-making, and that it cannot substitute for vascular imaging (CT angiography/MRA) when LVO is suspected, since rapid angiography of the cervical and intracranial vessels remains central to EVT triage and is not currently available at LF. Nonetheless, LF-MRI may offer higher sensitivity than noncontrast CT for detecting ischemic lesions. LF-MRI is thus likely to be most impactful in environments without on-site MRI capability, in patients unable to tolerate HF-MRI, and where transport risk is high. LF-MRI may also be beneficial in selected patients with passive implants where imaging may be permitted under device labeling despite limited feasibility on HF 1.5 to 3 T systems, although safety gaps for patients with active implantable medical devices such as cardiac pacemakers remain.^{52,53}

Operational Feasibility and Clinical Implementation

Operational feasibility depends on protocol design, workflow integration, and minimizing imaging-related delays to intervention. This requires balancing competing requirements, including scan times compatible with acute workflows (often ≤ 10 minutes for DWI-inclusive protocols), sufficient spatial resolution to detect clinically meaningful infarcts, and robustness to anisotropy-related confounds. Achieving this at LF requires accelerated diffusion encoding, management of echo time and distortion, and continued optimization of diffusion direction sampling to improve lesion conspicuity. Reduced SNR at LF may also necessitate thicker slices, averaging, or reconstruction strategies, while diffusion acquisition choices (direction sampling, achievable b values) influence both conspicuity and quantitative reliability. Environment-specific factors (eg, ventilator-associated motion, electromagnetic interference from adjacent monitoring equipment) can materially affect interpretability and should be addressed through standardized patient preparation, positioning, and quality control. Implementation also requires clear ordering and escalation pathways (who orders, when performed relative to CT/CT angiography, and how results trigger transfer, admission, or repeat imaging), staff training for device operation and safety screening, and delineation of scenarios in which LF-MRI is adjunctive versus substitutive (eg, transport-limited patients).

FUTURE DIRECTIONS

Future work should focus on expanding clinical use cases, pragmatic workflow studies, hardware and pulse sequence development, and validated AI approaches, as detailed in the subsequent sections.

Establishing Alternative Clinical Use Cases

As access and sequence performance improve, the future clinical role of LF-MRI may extend beyond initial diagnosis and triage of acute stroke to include tissue characterization and longitudinal assessment in time-uncertain presentations. American Heart Association/American Stroke Association guidance¹ supports extended-window thrombolysis in selected patients with unknown onset beyond 4.5 hours when imaging demonstrates either DWI-FLAIR mismatch or perfusion-based mismatch.^{54,55} In settings where access to HF-MRI is the primary rate-limiting step, LF-MRI systems may enable more scalable implementation of tissue-based selection and delayed window thrombolysis by bringing DWI-FLAIR closer to the point-of-care, and by facilitating repeated imaging where clinical evolution, rather than a single time point, is most informative.

Demonstrating Clinical Workflow Integration

Pragmatic workflow studies that define where LF-MRI changes management and where it is best positioned as an adjunct within established imaging pathways are essential for demonstrating decision impact and supporting broader adoption. In a single-center analysis of LF-MRI implementation in an academic intensive care unit, total workflow time was reduced from ≈ 24 hours to 60 to 90 minutes compared with HF-MRI, attributed to expedited screening, patient preparation, and elimination of intrahospital transfer.⁵⁶ Multicenter, prospective workflow studies to quantify whether LF-MRI reduces time-to-decision, avoids unnecessary transfers, decreases downstream resource utilization, changes management relative to conventional CT and MRI pathways, and improves appropriate routing to EVT-capable centers will be essential to establishing its value across diverse healthcare settings. Consideration of cost-effectiveness and health system impact are also important, as the capital cost of LF-MRI systems is substantially lower than HF-MRI, but the incremental benefit over existing pathways must be demonstrated prospectively.

Hardware and Pulse Sequence Development

Next-generation H-shaped 0.064 T LF-MRI systems incorporating higher-performance gradients and improved thermal and B_0 stabilization provide a pathway to shorter diffusion encoding, higher b values, and reduced distortion, thereby improving detection of small

infarcts and strengthening performance in minor stroke and TIA pathways. Nevertheless, even with these protocol and hardware advances, limited availability of established perfusion and angiographic protocols and hemorrhage-sensitive approaches that are routinely leveraged at HF-MRI currently preclude LF-MRI from functioning as a stand-alone comprehensive stroke imaging technology in most settings.

Furthermore, the existing evidence base does not yet extend to the full spectrum of hemorrhage pathologies, including cerebral microbleeds, venous thrombosis, and the temporal evolution of blood products, all of which depend on susceptibility contrast fundamentally attenuated at LF. Approaches such as the HEIR sequence at 0.23 T represent progress toward mechanistic alternatives, though analogous approaches below 0.1 T have not yet been realized. Achieving comparable performance at <0.1 T will likely require alternative strategies, including optimized spin-echo-based contrasts, tailored inversion-recovery approaches, and validated reconstruction methods designed to preserve subtle hemorrhage signatures. Novel hemodynamic approaches to assess cerebrovascular architecture, such as LF-compatible arterial spin labeling, and distortion-aware reconstruction and registration approaches to support reliable longitudinal comparisons in motion-prone environments are additional developmental priorities.

AI and Machine Learning Approaches

A complementary technical advance is computational image reconstruction and enhancement using AI. Machine learning reconstruction methods that map sparse sensor measurements directly to images (pioneered by *AUTOMAP*⁵⁷) have enabled efficient reconstruction from fewer measurements, supporting faster imaging and improved SNR. Although *AUTOMAP* is powerful, it is typically tied to a fixed measurement model, such as a specific k-space sampling pattern. Recent Bayesian approaches combine deep generative priors⁵⁸ with acquisition-specific likelihood models, offering flexibility across sampling schemes albeit at increased computational cost.⁵⁹ Unlike *AUTOMAP*, which performs a single forward pass, these methods require iterative sampling, but have shown strong results in settings where acquisition constraints, noise, and undersampling make robust prior information especially valuable.⁶⁰

Post-reconstruction, DL methods have been used to enhance LF images by improving apparent spatial resolution, increasing effective SNR, supporting downstream quantification, and translating LF images toward HF appearance. One class of approaches frames this problem as LF-to-HF image translation or style transfer. Unpaired LF and HF data can be used through cycle-consistent adversarial networks (*CycleGAN*⁶¹), which have been explored in stroke imaging.⁶² Most current

approaches use paired HF-LF data for stronger supervision,⁶³ training networks with losses combining pixel-wise similarity terms, such as absolute or squared differences, and adversarial objectives that encourage LF outputs to match the visual statistics of HF images.⁶⁴ In this context, *LoHiResGAN*⁶³ demonstrated improved image-quality metrics and yielded morphometric estimates more consistent with 3 T than native 0.064 T images in a paired data set, with a qualitative demonstration in a participant with focal encephalomalacia due to prior ICH.

A key limitation of DL-based image enhancement is susceptibility to domain shift,⁶⁵ in which performance degrades when the statistical distribution of the input data differs from that seen during training. This is particularly relevant for LF-MRI, where scanner hardware, field strength, pulse sequences, image contrast, resolution, noise properties, and reconstruction pipelines vary substantially. To address this, recent approaches have used synthetic training data and domain randomization.⁶⁶ In this framework, training examples are generated synthetically, with image appearance, resolution, contrast, artifacts, and noise sampled randomly at each training iteration, encouraging the network to learn representations that are robust across a wide range of acquisition conditions, although often at the cost of a lower performance ceiling. For example, *SynthSR*^{67,68} provides a general framework for super-resolution from heterogeneous clinical scans and has been applied to LF images acquired at 0.064 T to generate higher-resolution structural images that better support morphometry and segmentation pipelines, including stroke cases.⁶⁹ Generative diffusion models have also been applied after reconstruction to synthesize HF-like images from 0.064 T LF scans.⁶⁹ *SynPoC* reported improved anatomic clarity and closer alignment with HF-MRI across a multisite paired data set that included ICH and AIS.⁶⁹ *SynthMRI*, a SCUNet-based DL super-resolution approach, has also been applied directly to 0.23 T AIS images, demonstrating improved agreement of lesion-level quantitative metrics derived from raw DWI/ADC images, including lesion volume and mean lesion ADC.³⁶

These advances must be interpreted in the context of an important safety limitation: DL-based reconstruction and enhancement methods can produce misleading image features, particularly when applied to data that differ from the distribution used for training. In image reconstruction, deep networks have been shown to exhibit instabilities under small perturbations and structural changes, while learned priors in ill-posed inverse problems can hallucinate plausible but measurement-unsupported structures.⁷⁰ For acute stroke, these limitations are especially consequential, as lesion margins, small infarcts, posterior fossa lesions, hemorrhage conspicuity, and subtle diffusion abnormalities can directly inform triage, eligibility for reperfusion therapies, and decision-making when the time of onset is uncertain. These are

also known failure modes even for HF-DWI, with false-negative studies occurring disproportionately in posterior circulation and small early infarcts.⁷¹ Improvements in visual quality, apparent resolution, SNR, morphometry, or similarity to HF images therefore do not necessarily imply improved diagnostic accuracy.

Consequently, AI-based LF-MRI reconstruction and enhancement approaches for acute stroke should be evaluated not only as image-quality tools, but as clinical decision-support technologies with potential failure modes. Large-scale, task-specific validation of diagnostic performance remains essential before these approaches can be relied upon for acute stroke decision-making. Such studies should directly compare raw LF images, enhanced reconstructions, and HF-MRI acquisitions across clinically relevant end points. Validation should also include multisite data spanning multiple MRI vendors, field strengths, acquisition protocols, and diverse patient populations to mitigate evaluation bias and improve generalizability.

CONCLUSIONS

LF-MRI is emerging as a promising adjunct for acute stroke detection, triage, and monitoring, with potential to improve diagnostic precision where CT is limited and HF-MRI access unavailable, refine triage in suspected minor stroke and stroke mimics, and support tissue-based decision-making. In systems of care, LF-MRI may be most impactful when deployed to answer targeted questions that change management while preserving speed.

Integration into acute stroke pathways requires defining where LF-MRI changes management rather than serving only as an alternative modality, specifying use case-specific performance thresholds, and establishing streamlined protocols. Continued advances in LF diffusion acquisition, hardware performance, and workflows will be critical to improving sensitivity for small lesions and expanding the feasibility of multiparametric paradigms. With these developments, LF-MRI has the potential to expand access to advanced stroke imaging across diverse and resource-limited settings, complementing rather than replacing established CT and vascular imaging pathways.

ARTICLE INFORMATION

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Affiliations

Department of Neurology and the Center for Genomic Medicine (A.S.-A., W.T.K.), A.A. Martinos Center for Biomedical Imaging, Department of Radiology (J.E.L., M.S.R.), and Department of Emergency Medicine (J.N.G.), Mass General Brigham and Harvard Medical School, Boston. Department of Radiology (N.K.P.) and Department of Neurosurgery (N.K.P.), Jacobs School of Medicine & Biomedical Sciences, University of Buffalo, NY. School of Psychology and Neuroscience, University of Glasgow, United Kingdom (K.W.M.). National Institute of Standards and

Technology, Boulder, CO (K.E.K.). Department of Neurology, Yale Center for Brain & Mind Health, Yale School of Medicine, New Haven, CT (K.N.S.).

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Supplemental Material

Table S1

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