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RESEARCH ARTICLE

MAGNETIC RESONANCE ELASTOGRAPHY: ADVANCEMENTS IN NON-INVASIVE TISSUE CHARACTERIZATION

Dr. Ashish Kumar Shukla[1*], Anshu Kumari[2], Shivanshu Chauhan[2], Bharat Bhushan Dagur[2], Rukmanee[2], Anoushka Gupta[3], Ranjeet Singh[3], Manvi Dhingra[3] and Chaudhary raj Saurabh[3]

[1]Professor and HOD, Department of Radiodiagnosis, SMC,Santosh Deemed to be University, Ghaziabad, Uttar Pradesh, India; [2]PhD Scholar, Department of Radiodiagnosis, SMC, Santosh Deemed to be University, Ghaziabad, Uttar Pradesh, India; [3]Junior Resident, Department of Radiodiagnosis, SMC, Santosh Deemed to be University, Ghaziabad, Uttar Pradesh, India

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****Corresponding author:***
Dr. Ashish Kumar Shukla

ABSTRACT

Magnetic Resonance Elastography (MRE) is a rapidly evolving, non-invasive imaging technique that quantifies tissue stiffness by integrating mechanical wave propagation with MRI. This review explores the fundamental principles, technological advancements, and expanding clinical applications of MRE. Recent innovations such as AI-driven inversion algorithms, compact actuators, and high-resolution imaging sequences have enhanced MRE's diagnostic precision and accessibility. Clinically, MRE is now used across a wide spectrum of diseases, including liver fibrosis, cancer, neurodegeneration, musculoskeletal disorders, and cardiac conditions. Despite its potential, MRE faces challenges including motion artifacts, hardware limitations, and inter-vendor variability. Future directions point to real-time imaging, multi-omics integration, paediatric adaptations, and global standardization efforts. MRE stands at the forefront of precision medicine, offering promise for early diagnosis, disease monitoring, and personalized therapy planning across organ systems.

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INTRODUCTION

Tissue stiffness changes occur in many major diseases, including liver fibrosis, cancer and neurodegenerative disorders. These alterations often appear early, yet clinical assessment still relies on palpation and biochemical markers, which are subjective and cannot evaluate deep tissues[1, 2]. This creates the need for non-invasive methods that directly quantify mechanical properties, especially given their diagnostic and prognostic value[3, 4]. Magnetic resonance elastography (MRE) was developed to address this gap. By combining MRI with externally induced shear waves, it produces quantitative stiffness maps that can reveal pathology before structural abnormalities appear[1, 2]. Since its introduction in the 1990s, MRE has been validated across multiple organs and often outperforms conventional imaging for detecting biomechanical alterations[3, 4, 5]. Despite this progress, routine adoption remains limited due to technical complexity, heterogeneous protocols, lack of standardization and uneven clinician familiarity[6,7,8.] Current literature remains fragmented. Most studies focus on single-organ applications or isolated technical innovations, and few integrate recent advances in hardware, acquisition strategies and inversion methods with their clinical implications[7,8,9,10]. This gap makes it difficult to evaluate how prepared modern MRE is for widespread clinical use[10].

This review aims to address that gap by summarizing recent technological developments in MRE and assessing their impact on diagnostic accuracy, reproducibility and clinical translation. The guiding question is: How have recent advances in MRE improved its diagnostic performance and its ability to support clinical decision-making across organ systems? By aligning technological progress with unmet clinical needs, this review highlights how continued refinement of MRE could enhance early diagnosis, disease staging and treatment monitoring across diverse conditions.

PRINCIPLES OF MRE: Magnetic resonance elastography (MRE) measures tissue stiffness by combining externally induced shear waves with MRI-based motion imaging[1]. The technique involves wave generation, motion encoding and mathematical inversion to create quantitative elastograms.

Wave Generation and Propagation: External pneumatic, electromagnetic or piezoelectric drivers generate shear waves that travel through tissue[2]. Lower frequencies improve deep penetration, while higher frequencies increase resolution[3]. Shear waves are preferred because they are more sensitive to stiffness than compressional waves[4]. However, attenuation, boundary reflections

and tissue anisotropy can distort wave propagation and affect measurement accuracy.

MRI Acquisition and Motion Encoding: Motion-encoding gradients (MEGs) synchronized with the shear waves record tissue displacement[3]. Phase-contrast imaging captures these motions at multiple time points, while respiratory or cardiac gating reduces abdominal motion artifacts[5].

Inversion Algorithms: Stiffness estimation relies on solving the Helmholtz equation[6]. Direct inversion is fast but noise-sensitive[7], whereas iterative and viscoelastic models provide more stable estimates in heterogeneous tissues[8].

Outputs: MRE produces elastograms (kPa) overlaid on anatomical images, alongside confidence maps used to judge measurement reliability. MRE provides deeper penetration, higher reproducibility, and whole-organ stiffness mapping compared with ultrasound-based elastography techniques, making it particularly advantageous for liver, brain, and musculoskeletal evaluation Summarized in Table 1.

ADVANCEMENTS IN MRE TECHNOLOGY

Magnetic resonance elastography has evolved from an experimental concept into a clinically robust, multi-organ imaging tool. This progress has been shaped by major technical advances in hardware, MRI sequences and computational modelling. A clear understanding of this evolution highlights how MRE overcame early limitations and became suitable for routine clinical use.

Development Timeline and Evolution

Early Phase (1995–2000): Conceptualization and Feasibility: MRE originated in the mid-1990s, with initial work focused on demonstrating that externally generated mechanical waves could be visualized using MRI. Early systems used single-frequency drivers and basic 2D gradient-echo sequences, primarily applied to liver imaging[1].

Expansion and Algorithm Development (2000–2010): During the 2000s, MRE moved beyond the liver to the brain, breast and musculoskeletal system. Pneumatic actuator systems were introduced, and early inversion methods based on the Helmholtz equation provided the foundation for quantitative stiffness mapping[2,8].

Clinical Acceleration and Faster Imaging (2010–2015): The introduction of 3D MRE, echo-planar imaging (EPI) and improved phase-contrast techniques reduced scan times and improved reliability. These developments marked the first major steps toward routine clinical implementation[4].

Technological Diversification (2015–2020): High-density coil arrays, electromagnetic drivers and AI-assisted reconstruction techniques increased accuracy, especially in neurodegenerative and oncologic applications. Commercial availability expanded significantly during this period[5,12].

Modern Era (2020–Present): Multimodal, Real-Time and Predictive MRE: Recent innovations include multimodal MRE (e.g., MRE combined with DWI), dynamic and real-time imaging, 4D flow MRE and machine-learning models for automated interpretation and outcome prediction. These developments reflect a shift from purely structural assessment toward functional and prognostic imaging[7].

Hardware Innovations: Multifrequency drivers improve wave penetration in stiff or heterogeneous tissues, such as cirrhotic liver. Compact electromagnetic drivers simplify setup and support broader clinical use. High-density coil arrays enhance signal-to-noise ratio, improving performance in paediatric and obese patients[13].

Advanced Imaging Sequences: EPI-based MRE significantly reduces scan time, improving breath-hold success in liver imaging[14]. Spiral and radial trajectories provide motion robustness for fetal and cardiac applications[15]. New 3D multi-slice sequences offer sub-2-mm isotropic resolution, useful for detailed brain assessment[16].

Artificial Intelligence Integration: U-Net architectures improve inversion accuracy in low-SNR conditions[16]. GAN-based motion correction enhances abdominal MRE quality[17]. Machine-learning predictors link stiffness measurements to clinical outcomes such as hepatic decompensation[18].

Multimodal and Functional MRE: Combining MRE with DWI, MR spectroscopy or quantitative MRI improves tumour grading and tissue characterization[19]. Dynamic MRE enables tracking of physiological processes such as muscle contraction[20], while 4D flow MRE helps evaluate anisotropy in skeletal muscle[21].

Clinical Translation Challenges: Standardization efforts continue to address inter-vendor variability and reproducibility issues[22]. Pediatric MRE requires size-appropriate drivers and motion-robust sequences, and remains underrepresented in clinical validation[23].

CLINICAL APPLICATIONS

MRE is widely applied for non-invasive tissue characterization across hepatic, neurological, oncologic, musculoskeletal, cardiac and renal disorders. Its quantitative nature provides consistent, reproducible biomarkers useful for diagnosis, disease staging and treatment monitoring.

Hepatic Disorders: MRE reliably stages liver fibrosis, demonstrating AUROC values >0.90 for advanced fibrosis across NAFLD, viral hepatitis and alcoholic liver disease[24]. It outperforms transient elastography, particularly in obese patients where TE failure rates reach ~20%[24]. MRE also helps differentiate NASH from simple steatosis; values >3.6 kPa predict NASH with ~85% sensitivity[24]. Spleen stiffness >8.5 kPa correlates with clinically significant portal hypertension (HVPG ≥10 mmHg) [25]. Reductions ≥15% after antiviral therapy predict sustained virologic response[26].Comparative performance of MRE against other fibrosis assessment tools is summarized in Table 2.

Clinical guidelines (liver)

- Major liver society guidelines recommend MRE as a preferred non-invasive option when TE is unreliable (obesity, ascites, narrow intercostal space) or when more accurate fibrosis staging is required, particularly in NAFLD.
- Spleen stiffness by MRE is increasingly mentioned as a tool to stratify the risk of clinically significant portal hypertension.

Patient selection criteria (liver)

MRE is particularly appropriate for

- Patients with NAFLD/NASH and suspected advanced fibrosis.
- Individuals in whom TE has failed or is unreliable (BMI > 30 kg/m², ascites).
- Chronic viral hepatitis patients undergoing baseline staging and treatment-response monitoring.
- Patients being evaluated for portal hypertension or pre-transplant assessment.

Workflow integration (liver)

- **Step 1:** Initial risk stratification with clinical scores (FIB-4, NFS).
- **Step 2:** TE as first-line elastography where feasible.
- **Step 3:** MRE when TE is not feasible, discordant with clinical/lab findings, or when more precise staging is needed.
- **Step 4:** Serial MRE for monitoring fibrosis regression after therapy or progression in high-risk NAFLD.

Table 1. Comparative Analysis with Other Elastography Technique

Feature	MRE	Ultrasound Elastography (USE)	Acoustic Radiation Force Impulse (ARFI)
Modality	MRI	Ultrasound	Ultrasound
Wave Source	External shear waves	External or internal shear waves	ARFI-generated shear waves
Penetration	Good, especially at low frequencies	Limited by acoustic window	Moderate
Quantification	Fully quantitative elastograms	Often semi-quantitative	Quantitative point shear-wave speed
Spatial Coverage	Whole-organ mapping	Localized regions	Point or small-area sampling
Operator Dependence	Low	High	Moderate
Reproducibility	High	Variable	Moderate
Strengths	Deep penetration, high reproducibility, whole-organ mapping	Low cost, portable, real time	Useful in challenging acoustic windows
Limitations	Cost, complexity, motion sensitivity	Depth limits, operator variability	Small field of view, artifacts

Table 2. Comparison of MRE with other methods for liver fibrosis assessment (illustrative framework)

Modality	Invasiveness	Main Output	Typical Sensitivity for ≥F3*	Typical Specificity for ≥F3*	Key Limitations
MRE	Non-invasive	Liver stiffness (kPa)	High (~85–95%)	High (~85–92%)	Cost, MRI access, longer exam time
Transient elastography (TE)	Non-invasive	Liver stiffness (kPa)	Moderate–high	Moderate	Failures in obesity/ascites
Serum scores (FIB-4, APRI)	Non-invasive	Composite biochemical risk	Low–moderate	Low–moderate	Poor staging accuracy
Liver biopsy	Invasive	Histologic fibrosis stage	Reference standard	Reference standard	Sampling error, complications, cost

Table 3. MRE in neurological diseases: comparison with conventional imaging

Condition	Conventional Modality	MRE Contribution	Diagnostic / Prognostic Confidence*
Alzheimer's disease	Structural MRI, PET	Detects global/local stiffness reduction	Research-level, high potential
Parkinson's disease	MRI, DAT-SPECT	Assesses basal ganglia stiffness changes	Exploratory
Multiple sclerosis	MRI (FLAIR, T1, DWI)	Distinguishes active vs chronic lesions	Adjunct to standard MRI
Brain tumours	MRI with contrast, perfusion	Helps grade gliomas by stiffness	Complements conventional MRI
Neonatal HIE	MRI	Early prognostic biomarker	Emerging

Table 4. Oncologic MRE: comparison with standard imaging / biopsy

Tumour Site	Standard Reference	MRE Role	Typical Diagnostic Gain*
Liver	CT/MRI, biopsy	Differentiates benign vs HCC/metastasis	Improved specificity, whole-liver assessment
Pancreas	CT, EUS, biopsy	Stiffness linked to unrespectability	Better surgical planning
Breast	MRI (BI-RADS), US, biopsy	Increases specificity, reduces benign biopsies	Higher PPV for malignancy
Prostate	MRI, biopsy	Correlates with Gleason score, guides targeting	Better localization of significant disease

Table 5. MRE in musculoskeletal disorders

Condition	Conventional Modality	MRE Advantage
Tendinopathy	US, MRI	Detects early stiffness changes
Rotator cuff tear	MRI	Predicts surgical repair outcome
Early osteoarthritis	X-ray, MRI	Identifies biomechanical changes pre-radiograph
Muscular dystrophy	MRI, CK	Quantifies fibrosis, monitors progression
Myositis	MRI, CK, EMG	Stiffness correlates with disease activity

Table 6. Cardiac MRE in comparison with standard imaging

Indication	Standard Modality	MRE Contribution
Diastolic dysfunction	Echo, CMR	Direct quantification of myocardial stiffness, prognostic value
Cardiac amyloidosis	Echo, CMR with LGE	Non-invasive stiffness threshold, higher sensitivity
Cardiomyopathy phenotyping	CMR	Additional biomechanical characterization

Table 7. Renal and endocrine MRE applications

Organ / Condition	Standard Reference	MRE Role
CKD / renal fibrosis	Biopsy, eGFR	Correlates with fibrosis, non-invasive staging
Thyroid nodules	US, FNA biopsy	Stiffness threshold improves malignancy risk stratification

Neurological Applications: Brain MRE shows decreased stiffness in Alzheimer's disease reflecting amyloid/tau pathology[12]. In Parkinson's disease, basal ganglia stiffness changes correlate with symptom progression[12].

Active MS lesions demonstrate ~25% greater stiffness compared to chronic lesions[27]. Glioblastomas show markedly higher stiffness than grade II gliomas[28]. Reduced neonatal brain stiffness after hypoxic-ischemic injury correlates with long-term outcomes[29].A schematic comparison of MRE with standard neuroimaging is given in **Table 3**.

Clinical Guidelines (neuro)

- Formal incorporation into major neurology or neuroradiology guidelines is still limited; MRE currently appears mainly in expert consensus papers and advanced research protocols rather than routine recommendations.

Patient selection criteria (neuro)

- Patients with suspected early neurodegenerative disease where conventional MRI is non-specific.

- MS patients where distinguishing active vs chronic lesions could affect treatment decisions.
- Patients with intracranial tumors undergoing pre-surgical planning or non-invasive grading.
- Neonates with hypoxic-ischemic injury enrolled in tertiary-care protocols.

Workflow integration (neuro)

- Performed as an add-on sequence to standard brain MRI in tertiary centres.
- Used after initial MRI to refine differential diagnosis, support grading or provide prognostic information.

Oncological Applications: MRE distinguishes malignant from benign liver lesions, with HCC typically measuring 8–12 kPa vs. 4–6 kPa for hemangiomas[14]. Pancreatic tumours >5 kPa often indicate unresectability[30]. Breast tumour stiffness >3.5 kPa improves specificity and reduces unnecessary biopsies[31]. Prostate cancer stiffness correlates with Gleason score (r = 0.75) [32]. Key oncologic applications are summarized in Table 4.

Guidelines (oncology)

- MRE is not yet a formal requirement in most oncologic guidelines but is increasingly mentioned as an adjunct technique in liver and breast imaging position papers, particularly in complex cases or research settings.

Patient selection criteria (oncology)

- Indeterminate liver lesions on MRI or US.
- Breast lesions categorized as BI-RADS 3–4 where non-invasive risk stratification is desirable.
- Prostate cancer patients undergoing MRI-guided biopsy planning.
- Borderline-resectable pancreatic cancers where stiffness may inform operability.

Workflow integration (oncology)

- Integrated as part of problem-solving MRI protocols for liver, breast and prostate.
- Used in pre-surgical planning or when conventional imaging and biopsy are discordant.

Musculoskeletal System

Achilles tendon stiffness <60 kPa suggests early degeneration[33]. MRE predicts rotator cuff repair outcomes[34]. In osteoarthritis, a ~20% stiffness reduction may precede structural damage[35]. MRE quantifies fibrosis in muscular dystrophy and correlates with inflammatory activity in myositis[34, 35]. A comparative overview is shown in Table 5.

Guidelines (MSK)

- No formal MSK society guidelines currently mandate MRE, but it is being incorporated into advanced research protocols for tendon and cartilage disease.

Patient selection criteria (MSK)

- Athletes at high risk of tendon pathology.
- Patients scheduled for rotator cuff surgery where prognosis is uncertain.
- Individuals with early joint pain but normal radiographs.
- Patients with known or suspected neuromuscular disease requiring longitudinal follow-up.

Workflow integration (MSK)

- Added to routine MRI when mechanical characterization is expected to influence surgical planning, rehabilitation strategies or early disease detection.

Cardiac Applications

Cardiac MRE quantifies myocardial stiffness and predicts outcomes in diastolic dysfunction; ≥2.4 kPa is linked to increased adverse events[36]. Stiffness >3.0 kPa helps detect cardiac amyloidosis with high sensitivity[36].**Table 6** summarizes the role of MRE relative to established cardiac tools.

Guidelines (cardiac)

- MRE is not yet part of routine heart failure or cardiomyopathy guidelines, but it is mentioned in advanced CMR research protocols and early position papers on myocardial stiffness imaging.

Patient selection criteria (cardiac)

- Patients with HFpEF where diastolic dysfunction is suspected but not clearly quantified.
- Patients with suspected or confirmed cardiac amyloidosis.
- Complex cardiomyopathy cases where standard imaging is inconclusive.

Workflow integration (cardiac)

- Performed as an extension of standard CMR, typically in tertiary centres, where stiffness information can refine risk stratification and guide therapy.

Renal and Other Organ Systems: Magnetic resonance elastography (MRE) is extending its diagnostic capabilities beyond the liver and brain to include renal and endocrine systems. In chronic kidney disease (CKD), renal stiffness measured by MRE has been shown to correlate strongly with the degree of fibrosis. A correlation coefficient of r=0.79 supports its utility as a non-invasive biomarker for staging CKD and potentially monitoring disease progression[37].

In the evaluation of thyroid nodules, MRE contributes to malignancy risk assessment by quantifying tissue stiffness. Nodules with stiffness values greater than 4.0 kPa have been associated with a higher likelihood of malignancy, with an AUROC of 0.88. This application aids in reducing the rate of indeterminate results from fine-needle aspiration (FNA) biopsies, thereby improving diagnostic confidence[38]. Table 7 outlines these emerging organ applications.

Guidelines (renal / endocrine)

- Formal guideline incorporation is still limited; current use is largely restricted to research protocols and early clinical feasibility studies.

Patient selection criteria (renal/endocrine)

- CKD patients in whom biopsy are high risk or undesirable.
- Thyroid nodules with indeterminate cytology or discordant imaging and FNA.

Workflow integration (renal/endocrine)

- Used as an adjunct to routine MRI or ultrasound-based pathways when conventional workup leaves significant uncertainty.

Emerging Applications

- **Fetal MRE**: Pilot studies assess placental stiffness in preeclampsia[39].
- **Pulmonary MRE**: Experimental protocols map lung stiffness in idiopathic pulmonary fibrosis[40].

CHALLENGES AND LIMITATIONS

While MRE has transformed non-invasive tissue characterization, several challenges continue to limit its universal adoption, diagnostic consistency and scalability. The following sections outline the major technical, biological, clinical and practical limitations, expanded with

reproducibility data, patient-related considerations, operator training needs and failure-rate analysis.

Technical Challenges: Shear wave behaviour poses inherent physical constraints. Wave attenuation is significant in highly stiff tissues such as bone or calcified tumours, reducing the reliability of MRE in conditions like osteoporosis or intracranial calcifications[2]. Motion artifacts from respiration, cardiac pulsation or patient movement frequently degrade image quality, especially during abdominal imaging, leading to repeat scans in approximately 10–15% of liver MRE examinations despite gating measures[6]. Achieving high spatial resolution (<2 mm^3 for brain or spinal MRE) often requires longer acquisition times, which increases sensitivity to motion[4]. Inversion algorithms remain a critical bottleneck. Noise, incomplete wave fields and signal dropout can produce errors in stiffness estimation, particularly in heterogeneous tissues such as steatotic or cirrhotic liver[8]. Hardware-related issues also persist: passive drivers may fail to generate adequate wave amplitude in obese patients (BMI > 35), resulting in low SNR or complete acquisition failure[5]. MRE performed on higher-field systems (7T) faces additional synchronization challenges and increased susceptibility to artifacts[4].

Reproducibility limitations

A major technical challenge is variability across platforms and operators:

- **Inter-vendor variability**: Stiffness values can differ by up to **10–15%** between manufacturers (GE, Siemens, Philips), largely due to differences in drivers, coil configurations and inversion algorithms[9].
- **Test–retest variability**: Liver MRE shows **3–5% variability**, while brain and muscle MRE may exhibit up to **8–10%** depending on ROI and frequency used[5].
- **Inter-operator variability**: Although lower than ultrasound-based elastography, segmentation technique and ROI placement can still contribute **5–7%** variation.

These reproducibility limitations complicate the establishment of universal stiffness thresholds and hinder adoption into standardized pathways.

Biological and Patient-Related Limitations: MRE accuracy is influenced by biological variability. Patchy fibrosis, fat infiltration and inflammatory heterogeneity as seen in NAFLD/NASH can distort regional stiffness measurements[3]. Dynamic tissues such as muscle, heart and vasculature demonstrate time-varying mechanical properties, limiting the utility of static MRE[4]. Anatomical variability between pediatric and adult organs (size, compliance, geometry) affects wave propagation and requires age-specific protocols[23].

Patient-related factors

Several patient-specific issues also affect MRE performance:

- **BMI**: High BMI reduces wave penetration and increases failure rates, with up to **20% failure** reported in obese patients using transient elastography, and approximately **5–10% suboptimal acquisitions** in MRE despite stronger drivers.
- **Respiratory motion**: Patients with limited breath-hold capacity (COPD, pediatric, elderly) show higher motion artifact burden.
- **Contraindications**: Patients with MRI-incompatible implants, severe claustrophobia or inability to lie supine may not tolerate MRE.
- **Patient comfort**: Vibrational drivers can cause discomfort in sensitive patients, particularly children or those with rib tenderness.

Clinical and Standardization Hurdles

Significant variability exists across MRI platforms. Inter-vendor differences in reconstruction pipelines and hardware can produce up to 15% discrepancy in stiffness values[9]. There is still no universal agreement on stiffness cutoffs for disease staging. For example, the threshold of 3.6 kPa for NASH remains center-dependent and has not been validated across all populations or vendors. Pediatric MRE remains significantly underrepresented, with only ~5% of published studies focusing on children[23], limiting normative data and hindering integration into pediatric radiology guidelines.

Training and operator competency

Widespread clinical adoption is hindered by limited training opportunities:

- MRE requires proficiency in sequence selection, driver placement, inversion-model interpretation and quality-checking[4].
- Few formal training pathways exist; most radiologists rely on **site-based training** or **vendor workshops**.
- Learning curves show that **10–20 supervised readings** are typically required before achieving consistent interpretation accuracy.
- No global certification program currently exists, contributing to variability in clinical reporting.

These gaps slow integration into routine workflows and reduce diagnostic confidence among non-expert readers.

Economic and Accessibility Barriers: Cost remains a major barrier. MRE adds to baseline MRI expenses, making it less accessible in low-resource settings. Limited availability of MRE-compatible hardware (drivers, coils) further restricts access. Interpretation requires subspecialty training, causing workflow delays in centers without experienced radiologists. Regulatory challenges persist. While liver MRE is widely accepted, newer applications such as cardiac, pancreatic and neuromuscular MRE still lack broad FDA or CE approval[41], limiting clinical deployment.

Failure Rate and Clinical Implications: Technical failure, although lower than ultrasound elastography, is still clinically relevant. Common causes include poor wave penetration (obesity), misalignment of drivers, motion contamination and inversion algorithm instabilities. Typical reported failure rates:

- **Liver MRE:** 5–10% (mainly motion-related)
- **Brain MRE:** <5% but increases in patients with tremor or inability to remain still
- **MSK MRE:** 10–12% due to difficulty in positioning and muscle anisotropy

Failures can delay diagnosis, increase costs and reduce confidence in elastogram-based decision-making. Establishing standardized protocols and quality-control metrics is essential to reduce these rates.

Validation and Knowledge Gaps: There remain important gaps in scientific validation. Correlation between MRE stiffness and histopathology is imperfect ($r \approx 0.7–0.8$) [4], partly due to sampling error in biopsy. Most clinical protocols focus on shear stiffness alone (μ), while viscosity (G'') and complex modulus may provide additional diagnostic value[9]. Longitudinal data remain scarce; few studies have tracked MRE changes over 10+ years, limiting understanding of disease evolution.

FUTURE DIRECTIONS

The rapid advancement of magnetic resonance elastography (MRE) is positioning it as a core component of precision medicine. Ongoing research and innovation continue to expand its capabilities, offering new avenues for clinical impact across organ systems and global populations.

Technological Innovations: AI integration is transforming MRE processing. Deep learning models like physics-informed neural networks (PINNs) allow real-time inversion, potentially generating electrograms within seconds—useful for intraoperative tumor margin

assessment. Generative AI models may soon create synthetic electrograms from conventional MRI data, eliminating the need for mechanical wave generation in low-resource settings. Federated learning models, as explored in the ETHICAST trial (2024), aim to harmonize stiffness thresholds across diverse populations by leveraging multi-center datasets[42]. Next-generation hardware is also evolving. Wearable actuators, such as flexible piezoelectric patches, may allow continuous monitoring of musculoskeletal stiffness. Compatibility with ultra-high-field 7T MRI systems will improve signal-to-noise ratio (SNR), especially for detecting subtle brain changes in early neurodegeneration. Additionally, multiparametric actuators that combine shear waves with ultrasound or optical excitation are emerging to probe complex, anisotropic tissues such as myocardial fibers[43].

Clinical and Translational Advances: Dynamic and functional applications of MRE are expanding. In cardiology, time-resolved cardiac MRE may allow mapping of stiffness throughout the cardiac cycle (systole/diastole), potentially predicting heart failure risk using stiffness-phase loops[44]. Exercise-based MRE applications are under investigation to optimize training and rehabilitation by measuring muscle and tendon stiffness during activity[20]. Fetal and placental MRE is gaining momentum as a non-invasive tool for assessing placental health in high-risk pregnancies such as preeclampsia[39]. In oncology, MRE could help monitor immunotherapy responses, as changes in tumor stiffness may reflect immune activation. It may also aid in lymph node staging by differentiating metastatic from reactive nodes, with stiffness cutoffs (e.g., >5 kPa) indicating malignancy[14].
In neurology and psychiatry, MRE is being studied for early detection of neurodevelopmental disorders like autism through cortical stiffness mapping. Research initiatives such as ENIGMA-MRE are exploring links between brain viscoelasticity and psychiatric conditions like depression and schizophrenia[12].

Multimodal and Multi-Omics Integration: MRE is poised to integrate with other imaging and molecular data streams. Combining MRE with PET imaging, for instance, allows for the correlation of tissue stiffness with metabolic activity (e.g., 18F-FDG uptake in tumors). Genetic studies are exploring stiffness quantitative trait loci (sQTLs) to identify genomic factors—such as PNPLA3 in NAFLD—that influence tissue mechanics. Proteomic analysis may further enhance MRE by associating stiffness with extracellular matrix proteins like collagen VI[2, 9].

Global Health and Accessibility: Efforts to democratize MRE access are gaining traction. Compact, low-cost MRE systems using portable 0.5T MRI paired with piezoelectric actuators are being developed for use in rural or underserved regions[2]. Tele-MRE platforms with cloud-based inversion algorithms allow centralized experts to interpret scans remotely. Pediatric-specific initiatives, including the NIH-funded PEDAL trial (2025), are advancing MRE protocols for children with conditions like biliary atresia and muscular dystrophy[45].

Standardization and Validation: For widespread adoption, standardization is critical. The RSNA-QIBA MRE Biomarker Committee is currently working to establish consensus imaging protocols for liver, brain, and breast MRE, with expected release in 2025. Digital phantoms and open-source simulation tools like "ElastoSim" are being created to benchmark algorithm performance across sites. Longitudinal biobanks, such as the UK Biobank, have begun including MRE data, enabling long-term studies into the relationship between stiffness and chronic disease progression[15].

Frontier Applications: MRE is expanding into unexpected domains. In microbiology, researchers are exploring bacterial biofilm stiffness measurement to optimize antibiotic treatment strategies. In space medicine, MRE may monitor musculoskeletal stiffness degradation during extended missions. Even in agriculture, MRE is being tested to assess plant tissue integrity under stress conditions such as drought[2, 15].

Key Challenges to Address: Despite these advances, key issues remain. Ethical considerations around AI use in diagnosis require transparent, interpretable models. Environmental concerns include the energy demand of high-field MRI systems. Finally, promoting equity in MRE development is essential particularly for neglected diseases like Chagas cardiomyopathy, where diagnostic innovation is sorely needed.

CONCLUSION

Magnetic Resonance Elastography has undeniably revolutionized diagnostic imaging by bridging biomechanics and clinical medicine. Its ability to quantify tissue stiffness non-invasively has redefined standards in hepatic fibrosis staging, neuroimaging, and oncology, offering prognostic insights previously unattainable without biopsy. However, the technology's full potential remains tempered by persistent challenges.

Technical innovations, such as AI-driven artifact correction and compact actuators, are poised to mitigate current limitations. For instance, deep learning models now reduce inversion errors by 30% in noisy datasets, while portable MRE systems are expanding access to rural clinics. Standardization efforts led by the Quantitative Imaging Biomarkers Alliance (QIBA) aim to harmonize protocols across vendors, ensuring consistent diagnostic thresholds. Clinically, MRE's expansion into dynamic and functional imaging (e.g., cardiac stiffness during systole) and multimodal integration (e.g., MRE + PET for tumor metabolism) will unlock new applications. Yet, addressing socioeconomic disparities in MRE access and fostering collaborative research particularly in paediatric and low-resource settings are critical to democratizing its benefits. In conclusion, while MRE is not without limitations, its trajectory points toward a future where mechanical phenotyping becomes as routine as anatomical imaging. By confronting existing barriers through innovation and global cooperation, MRE will solidify its role as a cornerstone of precision medicine, transforming how we diagnose, monitor, and treat diseases across organ systems.

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