Non-Invasive Biomechanical Assessment for Military Brain Health: A Case for MR Elastography on High-Performance Gradient Systems

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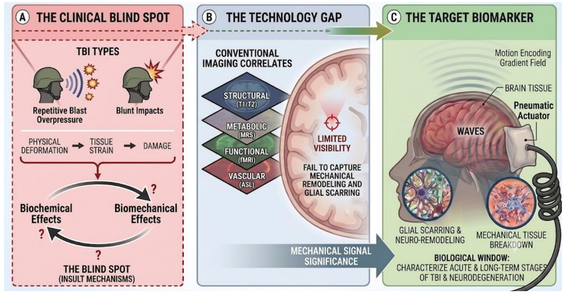
BACKGROUND

The Clinical Blind Spot: Military TBI, from blast exposures to blunt impacts, alters brain tissue through physical deformation, glial activation, and mechanical remodeling[1][2]

The Technology Gap: Conventional neuroimaging fails to evaluate the fundamental mechanical shifts driving pathology[3].

The Target Biomarker: Mechanical and cellular remodeling (such as glial scarring and tissue breakdown) offer a vital biological window to characterize both acute TBI and long-term neurodegeneration[8][10].



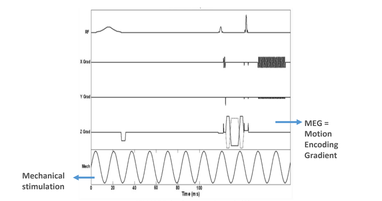
CAPABILITY DESCRIPTION

Magnetic Resonance Elastography (MRE) non-invasively measures viscoelastic mechanical tissue properties. These reflect physiological features like cellular density, membrane, and extracellular matrix (ECM) integrity [10].

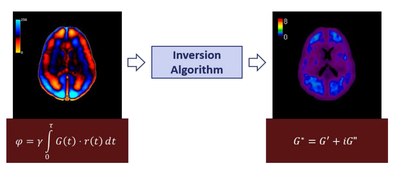
Step 1: A pneumatic driver sends vibrating pulses through a pillow actuator, triggering physical wave generation through the brain.

Step 2: The MRI scanner uses a phase contrast technique which implements Motion Encoding Gradients (MEG) to map physical tissue displacements on a microscopic scale

Step 3: Mathematical processing transforms raw wave images via an inversion algorithm into outputs characterizing material properties, including stiffness



EPI MRE Pulse Sequence Example [7]



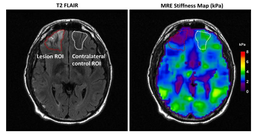
Basic MRE Pulse Sequence [top], wave image [left], and elastogram [right]

TECHNOLOGY & APPLICATION

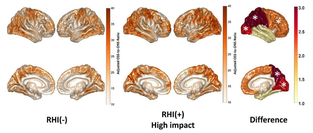
Clinical Precedent

Cortical Tissue Changes:

MRE has detected direct localized changes in human cortical stiffness following impact-based traumatic brain injuries (TBI)[4].



T2 Flair [left] and shear stiffness map [right] of a subject with moderate-severe TBI. Reproduced from Figure 2 of Esterov et. al, 2024[4].



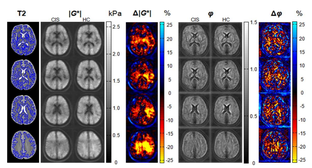
Octahedral shear to normal strain ratio comparison between subjects with high impact repetitive head injury (RHI +) vs control (RHI-). Reproduced from Figure 5 of Shan et. al, 2024 [5].

Decoupling Signatures:

MRE has been used to identify skull-brain mechanical decoupling in subjects exposed to repetitive head impacts [5].

Neuroinflammatory Markers:

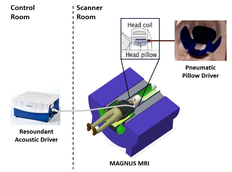
High-resolution MRE protocols have proven capable of capturing early mechanical signatures of neuroinflammation within clinical patient populations [7].



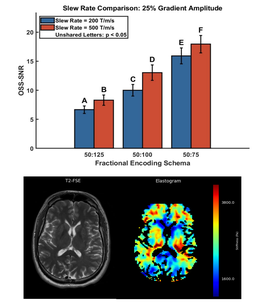
Viscoelastic property maps (shear modulus [left] and phase angle [right]) and their respective changes when comparing a subject with clinically isolated syndrome to a healthy control. Reproduced from Figure 1 of Fehlner et. al, 2016 [7].

The High-Gradient Shift

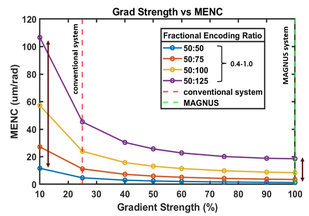
- **The High-Performance Leap**: The MAGNUS 3T MR system (a GEHC head-only gradient with amplitude: 200 mT/m and slew rate: 500 T/m/s) unlocks technological benefits for MRE
- **Technical Advantages:** MAGNUS reduces echo times (TE) and provides an 8.5-fold improvement in motion encoding efficiency (MENC) which can enhance signal-to-noise ratio (OSS-SNR)



MRE in the MAGNUS setup



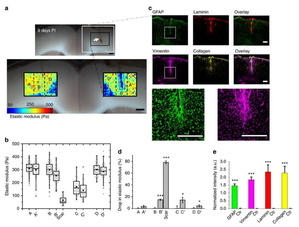
Improved SNR with faster slew rates across schemas [top]. T2 FSE and Elastogram collected on the MAGNUS [bottom]



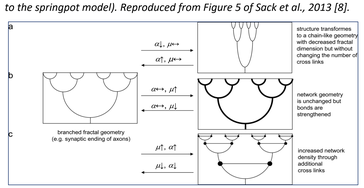
How MENC changes under different encoding schemas with the gradient strengths enabled by high performance gradients [right]. Lower MENC = higher efficiency.

Viscoelastic Changes with TBI

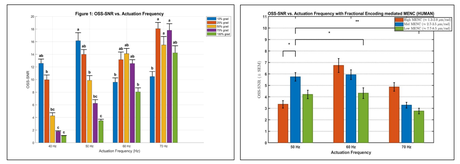
- **Injury Mechanisms:** Injury-induced strains at anatomical boundaries are theorized to cause structural tissue remodeling via cellular, membrane, and ECM degradation or glial scar formation. Such tissue density and fluid boundary changes induce viscoelasticity changes [8].
- **Evidence in Literature:** Animal models support that glial scarring and structural remodeling from stab or crush injuries[9] as well as TBI injuries[6] correlates directly with localized reductions in tissue stiffness.
- **Pre-Symptomatic Window:** Mechanical alteration can occur prior to structural or metabolic degradation seen on conventional neuroimaging[6], offering an objective window to track changes.
- **The Measurement Issue:** Measures of viscoelasticity acquired on animal systems are challenging to replicate on traditional human systems given frequency and signal quality limitations.



Cortical tissue changes in murine brain slices post injury are characterized via AFM [a,b,d] and immunofluorescence [c,e], demonstrating regional changes in stiffness, including severe softening of glial scar tissue. Reproduced from Figure 2 of Moeendarbary et al., 2017 [9].



Schematic representation of the changes in principal structures in mechanical lattices yielding changes in viscoelastic parameters μ and α (derived from collection of the complex modulus across a frequency span fit to the springpot model). Reproduced from Figure 5 of Sack et al., 2013 [8].



Demonstration of the improved or maintained signal quality (OSS-SNR) of MRE at high frequencies in both a phantom[left] and human [right] made possible with acquisition on a high-performing gradient system.

- **The High-Frequency Challenge**: Actuation frequencies above 60 Hz generate shorter acoustic wavelengths ideal for mapping fine structural borders. However, they dissipate rapidly, causing severe signal loss on traditional human scanners.
- **Maximizing Signal Retention**: Improved retention from compressed echo times and increased efficiency at high frequencies (60-80 Hz) maximizes shear strain signal quality (OSS-SNR) to better differentiate anatomical interfaces and enable quality Multi-frequency MRE.

IMPACT & SIGNIFICANCE

Differentiating TBI Subtypes:

Detailed examination of viscoelastic properties enabled by high-performance gradients provides the potential to compare microstructural changes occurring with blast-induced and impact-based forms of TBI, as well as at different stages of TBI progression– informing the currently unclear cycle of influence between biochemical and biomechanical effects of injury states

Pre-Symptomatic Neurodegeneration Detection:

Longitudinal evaluation using this tool enables the identification of chronic microstructural tissue remodeling and early neurodegeneration, potentially before clinical symptoms physically emerge or show up on structural scans

Objective Return-to-Duty Metrics:

This technique has the potential to provide military clinicians with concrete, longitudinally trackable, and objective measures of brain tissue health to support high-stakes return-to-duty decisions

DEVELOPMENTAL STATUS

Operational Readiness:
MRE is a validated imaging technique, and the MAGNUS gradient configuration is fully mature and commercially available from GEHC. The unified platform is ready for immediate military population studies.

Future Forward Screening:
Population studies using high-performance gradient systems will help to identify and better characterize viscoelasticity-based biomarkers.

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