Experimental Characterization of Brain Deformation and Injury Mechanisms in Biofidelic Phantom during Blast Loading

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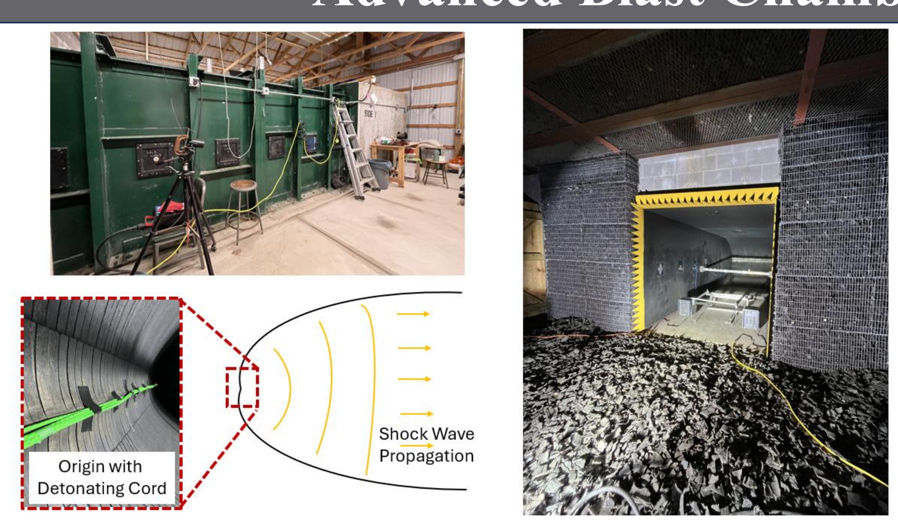
Introduction

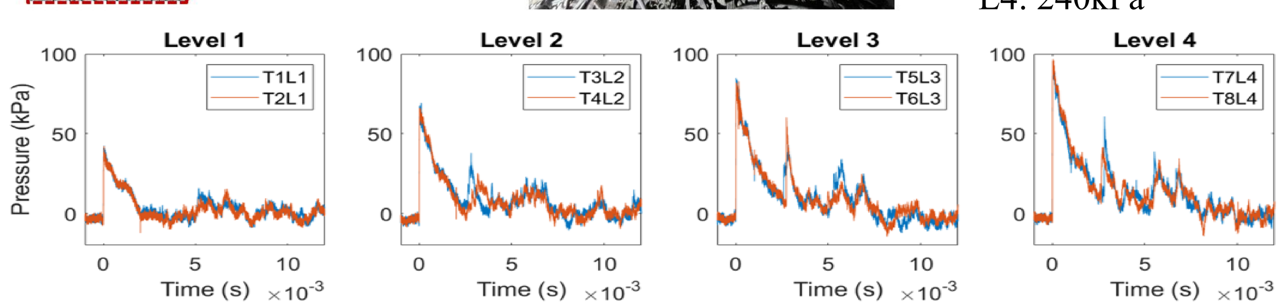
- Blast-induced traumatic brain injuries (bTBI) represent the signature wound of recent conflicts with nearly 70% of injuries to Service Members are blast-related.
- The impact of blast-wave exposures on brain tissue deformation and associated injury mechanisms remains poorly understood.
- Current bTBI studies rely on post-blast imaging to assess gray/white matter atrophy histologically, while existing approaches for measuring in vivo brain deformation are invasive, computationally intensive, or lack sufficient spatial resolution.
- Due to this, biomechanical injury thresholds in response to blast exposure has not been well defined.

Advanced Blast Chamber

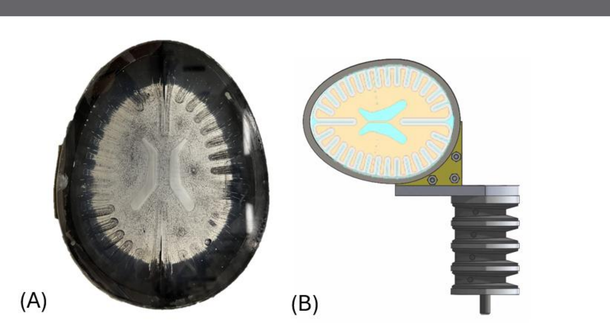


2.03m x 2.03m cross-section and driver section with PETN to initiate blast wave.

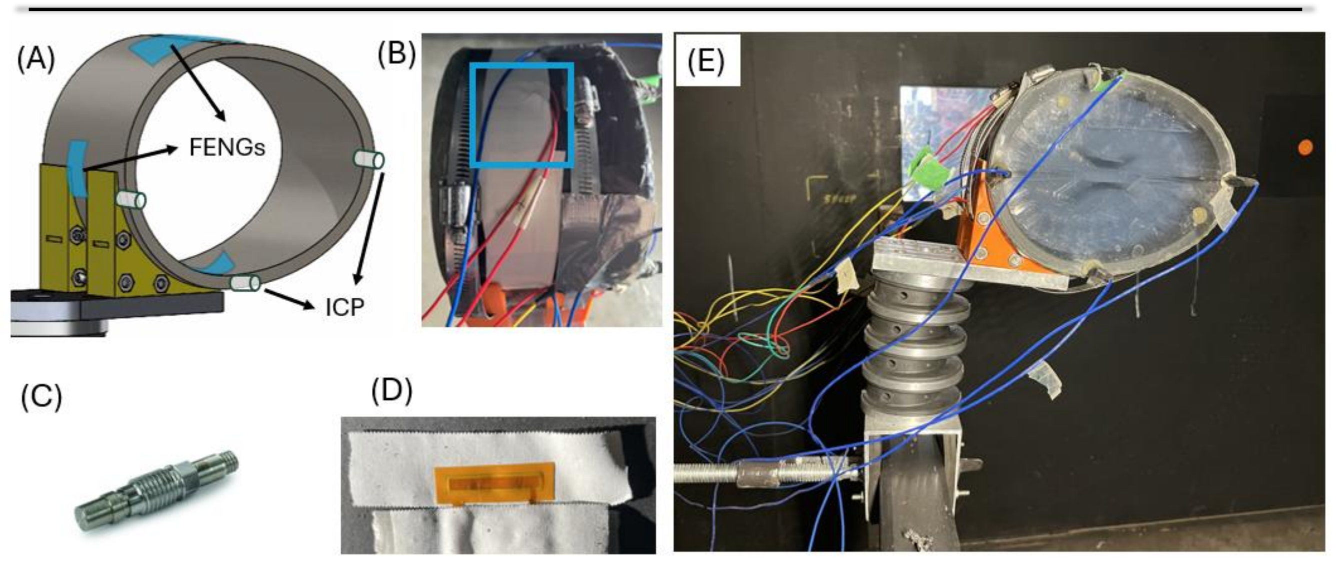
Delivered impacts of reflective pressure:
L1: 100kPa
L2: 140-160kPa
L3: 185kPa
L4: 240kPa



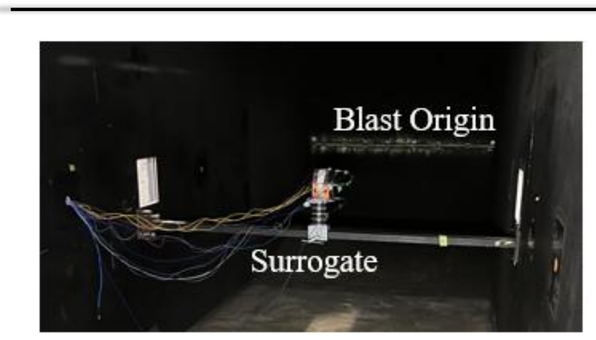
Biofidelic Model



Anthropomorphic Neurologic Gyrencephalic Unified Standard (AGUS) at glance. (A) Real image of dual-layer fabricated model with embedded speckle pattern. (B) Schematic of head-neck assembly utilized in this work.

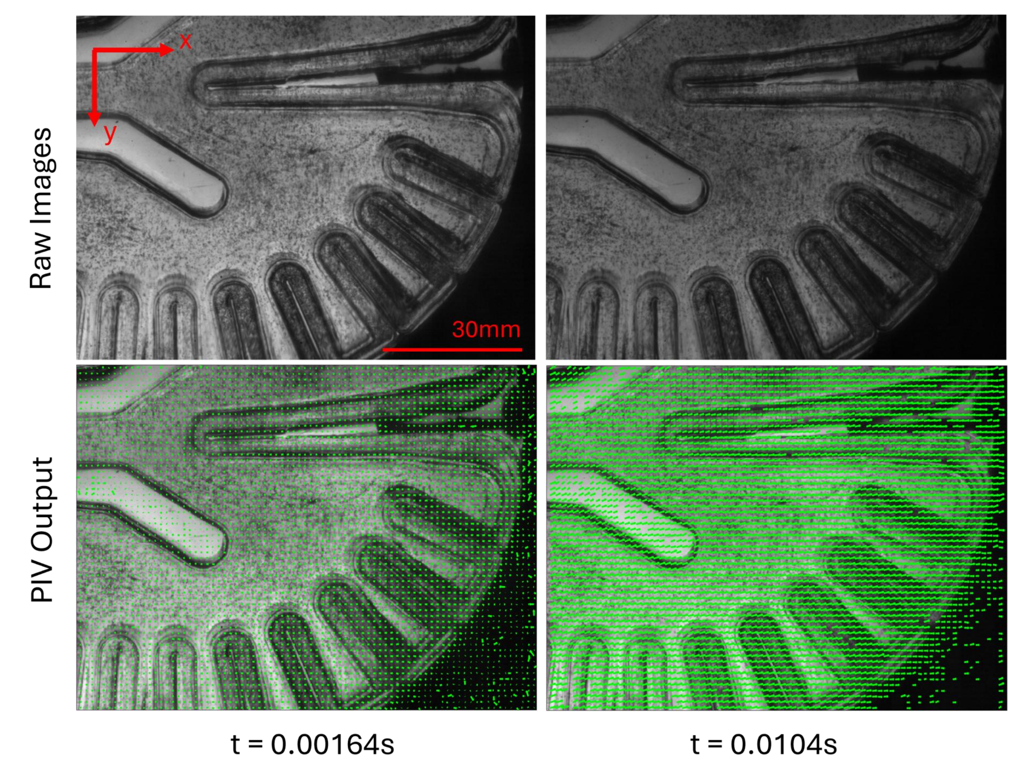


(A) Schematic of sensors locations on skull. (B) Kinesiology tape attaching ferroelectric nanogenerator (FENG) flexible sensor. (C) Pressure transducers for intracranial pressure (ICP). (D) Real view of FENG sensor. (E) Full head surrogate assembly inside blast chamber.



Back view from inside the chamber with subject in the center. Left chamber windows allowed recording of brain tissue deformations using high-speed imaging.

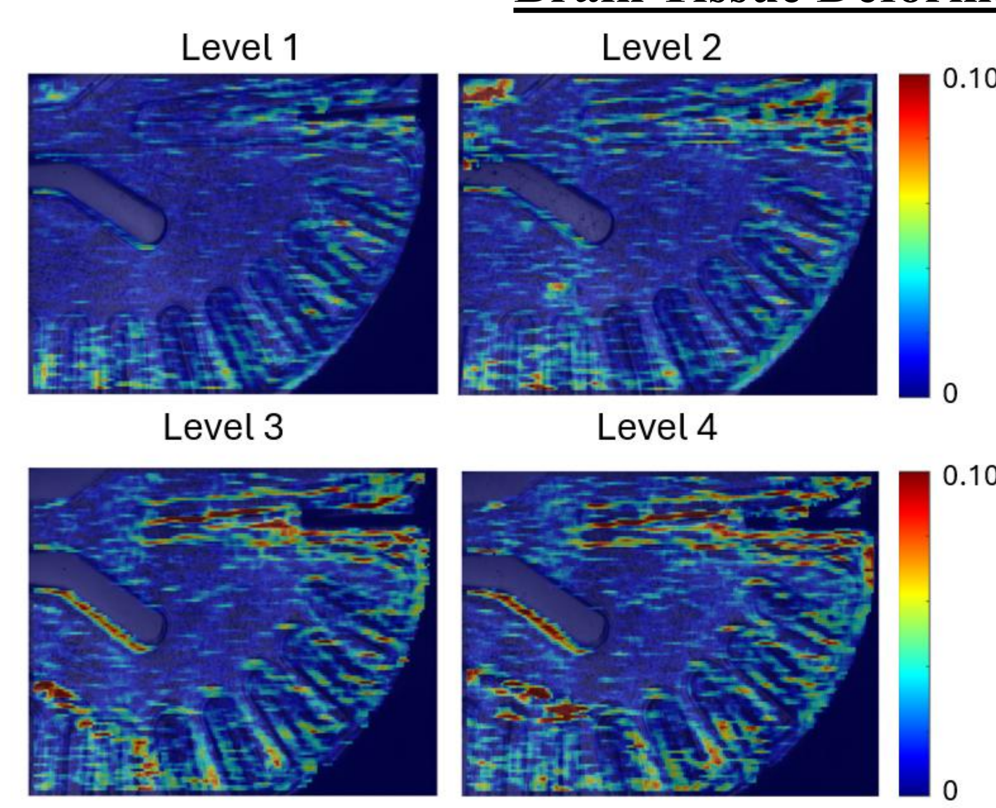
Results

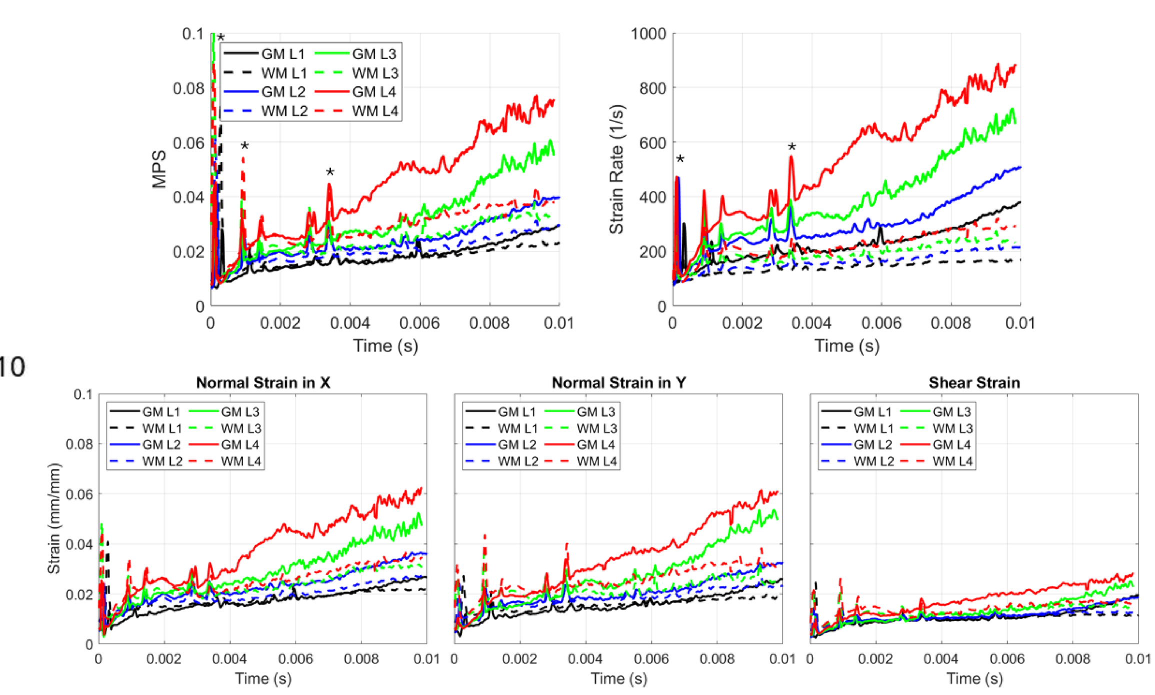


Example of images and process of Test 8, Level 4.

- Particle Image Velocimetry was used to obtain local displacement and velocity vectors from the high-speed images recorded at 70,000 fps.
- Least-square method was applied to obtain 2D displacement/velocity field and gradients.
- Parameters needed for approximating Maximum Principal Strains (MPS) and Maximum Principal Strain Rate (MPSR).

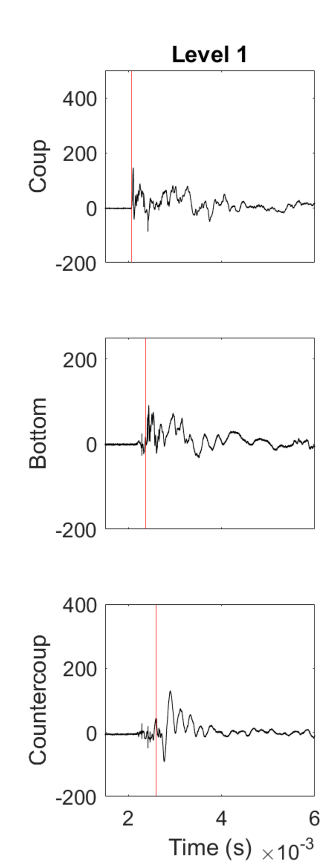
Brain Tissue Deformation Mechanics During Blast

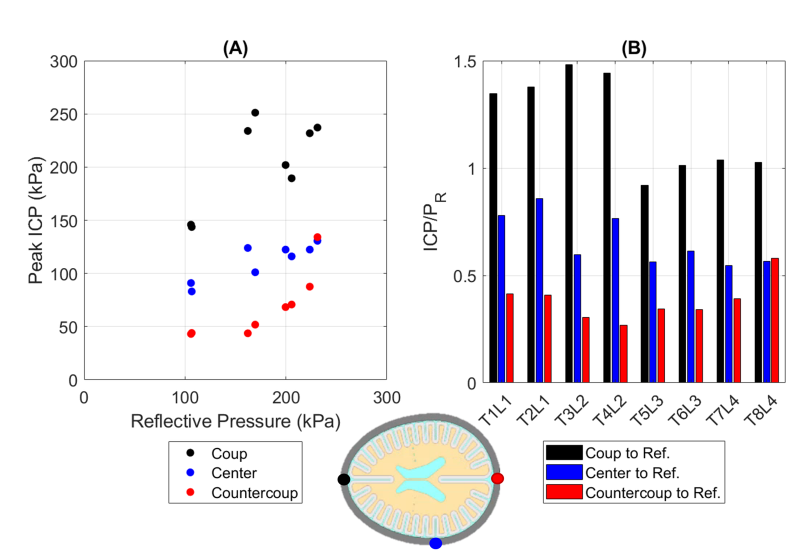




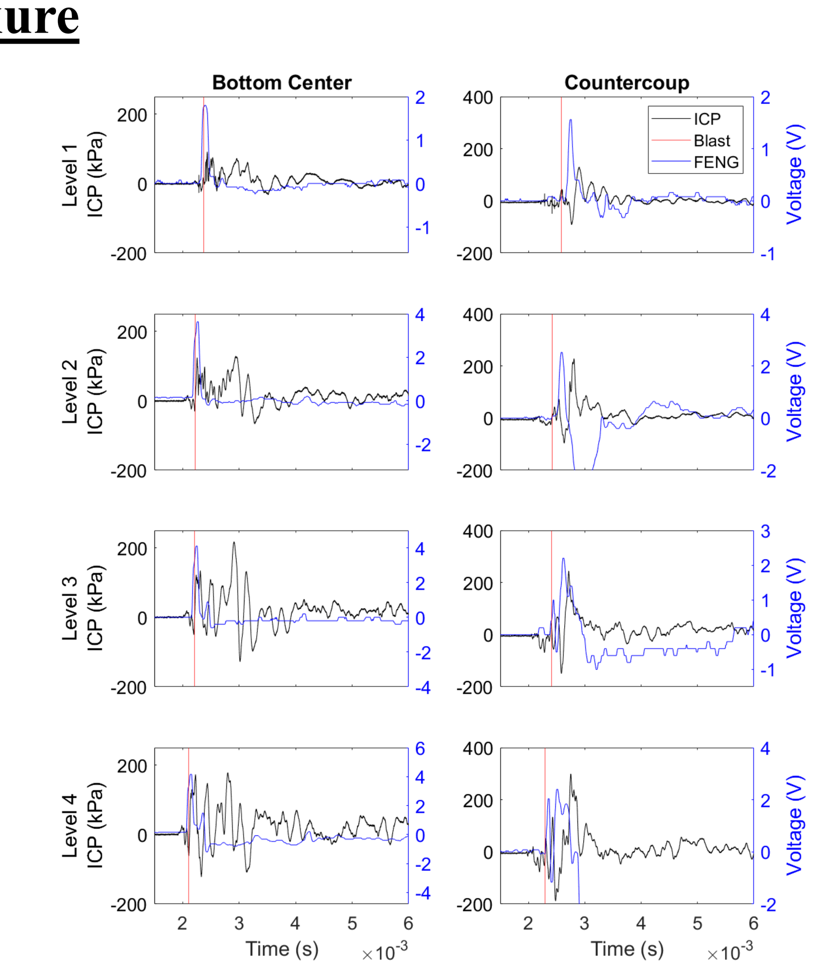
Left: MPS, ε_2, after 10ms of blast impacts. Results through levels show an increase in location and magnitude of MPS. Right: Progression of 95th percentiles for multiple deformation mechanics parameters in the gray- and white-matter during blast impact. The * indicates visual disturbances from reflective waves within the chamber; deformation not occurring in the brain tissue.

ICP and Skull Flexure





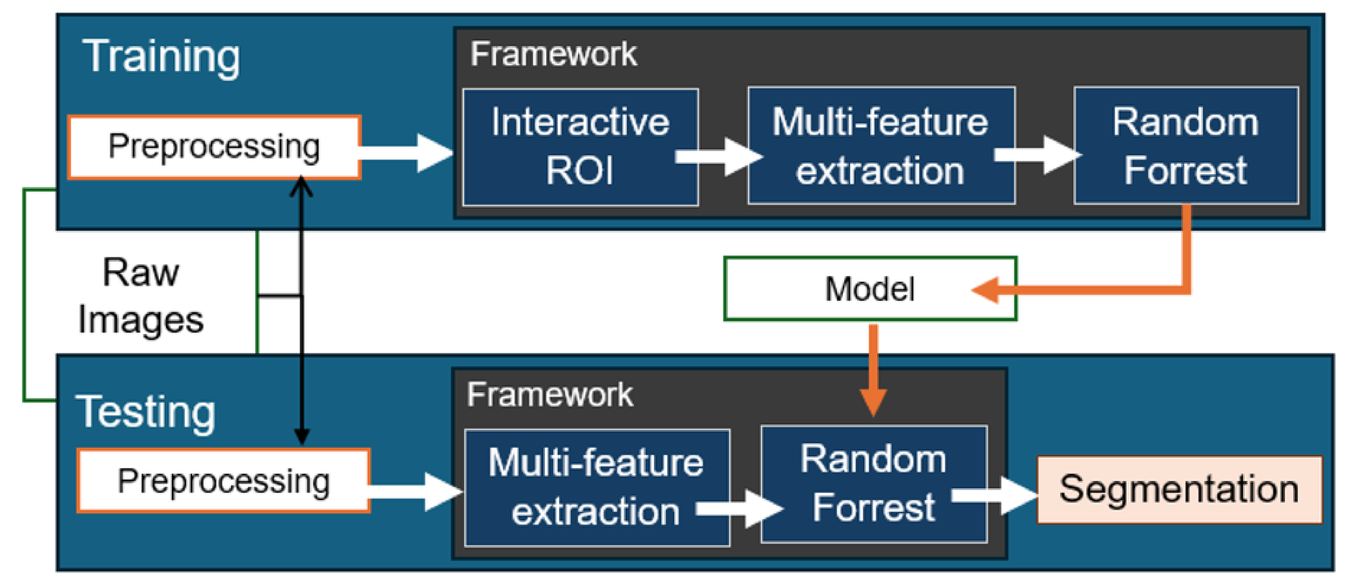
Left: Global ICP in ANGUS for Test 1, Level 1. Top: Summary of all levels, (A) showing peak ICP from direct cranial transmission, and (B) showing ratio of ICP with respect to incoming reflective pressure.



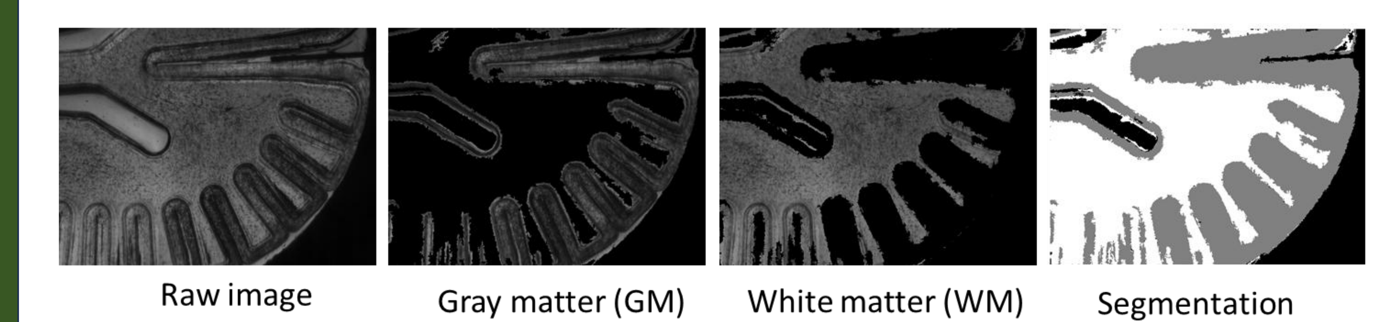
Example of FENGs response to blast impacts for potential skull deformation along with ICP traces at the bottom center and countercoup locations.

These results show a multitude of possible injury mechanisms during blast loading. Changes in ICP involve transmission through skull and subsequent skull deformations.

Machine Learning Based Image Segmentation



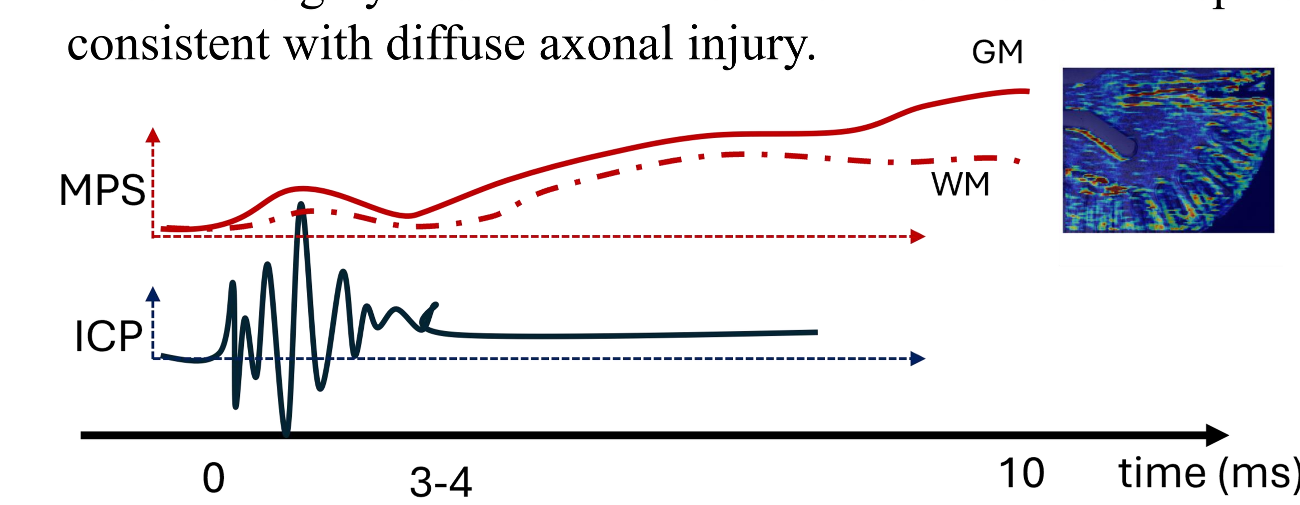
Overview of workflow for the use of ML-based image segmentation in ANGUS images.



Example of ML-based image segmentation for blast impacts to ANGUS. From left to right: raw image, image showing only gray matter, image showing only white matter, and image showing segmentation by joining masks.

Discussion

- The described approach establishes a validated quantitative platform for characterizing tissue deformation mechanics and differentiating brain injury response.
- The results identify a sequence of injury mechanisms during the first milliseconds of blast overpressure, with elevated strain rates at the gray and white matter interface and sulcal depths consistent with diffuse axonal injury.



Proposed sequence of injury mechanisms in the first 10ms post blast impact. There are drastic ICP fluctuations and once these stabilize, the gray- and white- matter tissue perceive an increase in strains and strain rates.

- Levels 3 and 4 produce strains and strain rates two- and three-fold, respectively, in the gray matter compared to the white matter.
- Establishing tissue-specific biomechanical mechanisms is critical for evidence-based return-to-duty standards for blast-exposed warfighters.

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