Full-Field 4D Measurements of Acceleration-Induced Deformation in the Living Human Brain

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Traumatic brain injury (TBI) arises from rapid acceleration of the skull and can induce symptoms ranging from momentary loss of consciousness to chronic disabilities. Experimental measurements of brain-skull displacement are fundamental to quantifying the biomechanics of acceleration-induced TBI. We have previously applied tagged magnetic resonance imaging (MRI) to extract measurements of brain deformation at low accelerations in humans in vivo. This information can be used to bridge the knowledge gaps in the mechanisms between deformation-induced disruptions in neuronal tissue at the cellular level, and macroscopic deformation patterns during head-brain acceleration. Using MRI-based deformation measurements, two-dimensional measurements of in-plane strain on slices spanning the whole brain can be computed [1]. However, experimental constraints, such as the need to repeat head motion during MRI acquisitions during a limited scan time, restrict the resolution and consistency of tagging data. Thus, the collection of image slices, on its own, is insufficient to define a complete quantification of deformation (the strain tensor) across three-dimensional space and time.

This research introduces novel data collection and processing strategies for deriving accurate, four-dimensional (4-D), full-field measurements of displacement and strain. The acquisition strategy includes specialized hardware, triggering strategies, and pulse sequences for obtaining tagged MRI in human volunteers. Image processing consists of harmonic phase analysis with finite element models (HARP-FE), which enforces mechanical regularization on the results to reduce artifacts and produce a smooth strain field. The analysis pipeline was applied to images from healthy volunteers during non-injurious rotational and linear accelerations, spiking between 2-4 g in magnitude. The resulting displacement fields exhibited patterns consistent with the direction of the acceleration pulse. However, the principal deformation direction (first principal strain axis) exhibited different patterns, including a concentric rotation-like arrangement immediately after the acceleration peak. Maximum shear strains ranged between 2-4%.

These preliminary results demonstrate the extraction of dense, full-field, 4-D motion estimates of in vivo brain tissue under acceleration, and underscore the importance of the constitutive and anatomical relationships between the brain and the skull. The presence of rotation-like deformation patterns in the brain may be due to the internal features of the skull and the meningeal connectivity between the skull and brain. Further application of this measurement technology will elucidate the biomechanical response of different brain structures. These data can be used immediately for the validation of computational models of TBI.

[1] Bayly, et al. Annu Rev Biomed Eng. 2012; 14: 369–396.