Quantitative Measurement of Brain Deformation Caused by Pressure Loading of the Skull

E. H. Clayton¹, A. Priatna², B. D. Bolster, Jr.³, and P. V. Bayly⁴

¹Mechanical Engineering & Material Science, Washington University in St. Louis, St. Louis, MO, United States, ²MR & D Collaborations, Siemens Healthcare, St. Louis, MO, United States, ³MR & D Collaborations, Siemens Healthcare, Rochester, MN, United States, ⁴Biomedical Engineering, Washington University, St. Louis, MO, United States

Introduction: Traumatic brain injury (TBI) due to explosive blast may lead to permanent cognitive impairment, though the mechanism of injury remains poorly understood. In blast, the mechanical insult is an external pressure wave interacting with the outside of the skull; mechanical strain is likely the key kinematic parameter for injury. The relationship between extra-cranial forces and internal brain tissue response has been a topic of research since the early 1940’s [1-6], yet little remains known about strain amplitudes and patterns that result from specific external forces. Computer simulations of injury mechanics offer enormous potential for diagnosis and prevention of TBI, but their validation requires direct comparison with experimental data. Magnetic resonance elastography (MRE) is a non-invasive imaging technique to visualize tissue motion in vivo and estimate material properties [7]. Externally applied forces are used to excite propagating waves in tissue, and displacements are acquired with a specialized motion-encoding, gradient-recalled echo (GRE) MRE imaging pulse sequence. (TR/TE: 138/27.5 ms, flip angle: 25°, NEX: 1, resolution 3 mm³ isotropic) A single transverse-oblique slice of motion encoded data was acquired for each subject through the central (I/S) cerebrum. The procedure was repeated three times with different motion-encoding, magnetic field gradient orientations to record each displacement component (u₁, u₂, u₃) relative to the imaging plane. The absolute peak motion-encoding gradient amplitude was 25 mT/m and spin-phase was accrued over a single gradient cycle. All data were acquired with a temporal resolution of four points per actuation cycle. Motion was induced in the brain using an acoustic actuation system (Resoundant™, Resoundant Inc.) modified slightly so that a single active driver could power two passive drivers with equal amplitude and phase. Each passive actuator was positioned near the left and right pterion and affixed with an elastic bandage. The actuation system was configured to transmit a 4, 6, and 8 cycle pressure-wave train synchronized with the MRE sequence at 45, 60 and 80 Hz, respectively. Imposed acoustic pressure loads were measured with the PCB Piezotronics model 103B01 dynamic pressure sensor. Data processing: Phase-contrast images were obtained by complex division of positive and negative polarity phase images, and converted to displacements using sensitivities of 5.63, 7.66, and 10.6 um/v per Pa for 45, 60, and 80 Hz data, respectively. The fundamental temporal harmonic was extracted from each displacement component by Fourier transform. Data were filtered with a 3 x 3 kernel median filter and circular, 4th-order Butterworth bandpass filter (high cut: 2.14 cm, low cut: 40.0 cm). Displacement gradients were observed to be small for all experiments performed, therefore the 2-D infinitesimal strain tensor was calculated, \( \epsilon_{ij} = \frac{1}{2} (u_{ij} + u_{ji}) \) (ii = 1,2).

Results: The root-mean-squared (RMS) acoustic pressure supplied to each actuator pad was 0.54, 0.76, and 1.2 Pa at 45, 60, and 80 Hz (Fig. 1). Example displacement and shear strain fields are shown in Fig. 2, and regional RMS shear strain, normalized by input RMS pressure, are shown in Fig. 3. The strain amplitude reaches 217 \( \mu \) per Pa of applied pressure in the outer ring of this imaging plane; at 80 Hz the response is approximately 58 \( \mu \) per Pa, reflecting reduced transmission.

Discussion: When the skull exterior is subjected to symmetric acoustic pressure loading, concentric elliptical shear strain (\( \epsilon_{ij} \)) bands are produced in brain tissue. The quantitative (stress per Pa) and qualitative features of the strain response offer insight into brain attachment and the filtering effects of the skull to acoustic pressure loading. Spatiotemporally, shear strains that propagate inward from the skull boundary towards the center of the brain predominate; however, we also observe motion emanating inward from the anterior and posterior falx. We believe this behavior can be attributed to reflections from interior structures (the falx cerebri between the brain hemispheres, and the tentorium between cerebrum and cerebellum). These results highlight the importance of understanding skull transmissibility and brain boundary conditions in the response to blast.

Conclusion: MRE-based displacement measurements and input pressure data, provide new insight into the study of blast biomechanics. Symmetric acoustic pressure excitation of the human skull leads to propagation of shear waves in the brain. The magnitude and phase of these oscillations related to known pressure excitation can be used to validate computer models and to illuminate fundamental mechanical properties of the skull, brain, and associated intracranial anatomy in vivo. Future work will investigate the response to alternative loading locations, and will include acquisition of data from multiple contiguous slices of brain. This will permit through-image-plane derivatives to be calculated, allowing all components of the 3-D strain tensor to be calculated.