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

E. H. Clayton[1], A. Priatna[2], B. D. Bolster, Jr.[3], and P. V. Bayly[1,4]
[1]Mechanical Engineering & Material Science, Washington University in St. Louis, St. Louis, MO, United States, [2]MR R&D Collaborations, Siemens Healthcare, St. Louis, MO, United States, [3]MR R&D Collaborations, Siemens Healthcare, Rochester, MN, United States, [4]Biomedical 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.

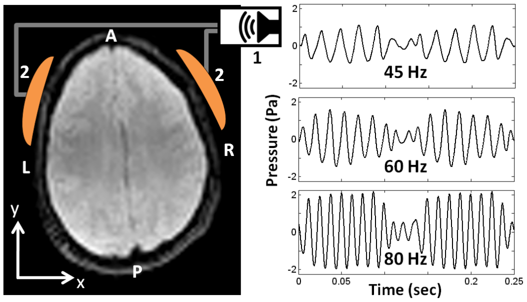

Figure 1: (Left) Passive actuator pads were positioned near left and right pterion (2). An active driver (1) produced acoustic pressure in the pads. (Right) Pressure was measured for all frequencies in the tubing connecting the active driver to the pads.

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 imaged by encoding spin phase. Clinical interest in MRE has largely been driven by the direct empirical relationship between tissue stiffness and health. However, the "raw" MRE data (3-D displacement measurements) and calculated strains can elucidate loading paths, anatomic boundaries and the dynamic response of the intact human head.

In this study, we use MRE to measure human brain tissue motion *in vivo* as the cranium is exposed to acoustic frequency pressure loading of known amplitude. The unique features of this study are knowledge of the external loading (pressure amplitude) and the quantification of the brain's response in terms of mechanical strain.

Methods: Acquisition: Studies were conducted at 1.5T on three human subjects, aged 21-30 years-old (mean: 23.7 yr) at frequencies of 45, 60, and 80 Hz. All procedures were approved by the institutional Human Research Protection Office Internal Review Board to ensure that the rights and welfare of the human research participants were protected. MRE data were collected using a MAGNETOM Avanto (Siemens) series whole-body clinical scanner equipped with a phased-array head coil. Tissue displacements were acquired with a specialized motion-encoding, gradient-recalled echo (GRE) NMR imaging pulse sequence. (TR/TE: 138/27.5 ms, flip angle: 25°, NEX: 1, resolution 3 mm^3 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 (u_1, u_2, u_3) 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 µm/rad 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, $\varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i})$, $(i,j = 1,2)$.

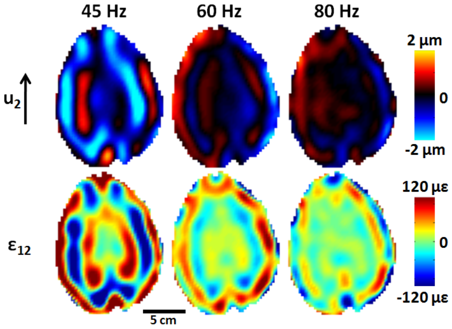

Figure 2: (Row 1) In-plane displacements (the imaginary part of the fundamental harmonic). (Row 2) In-plane shear strain fields reveal propagating shear waves due to acoustic pressure loading.

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. Mean regional RMS shear strains, normalized by input RMS pressure, are shown in Fig 3. At 45 Hz, the strain amplitude reaches 217 µε per Pa of applied pressure in the outer ring of this imaging plane; at 80 Hz the response is approximately 58 µε per Pa, reflecting reduced transmission.

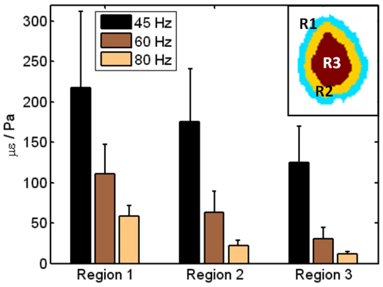

Figure 3: Mean regional RMS shear strain normalized by RMS excitation pressure, all subjects (n=3). Error bars signify one standard deviation. (Inset) Regions 1-3 shown as R1-3.

Discussion: When the skull exterior is subjected to symmetric acoustic pressure loading, concentric elliptical shear strain (ε_{12}) bands are produced in brain tissue. The quantitative (strain per Pa) and qualitative features of the response offer insight into brain attachment and the filtering effects of the skull to acoustic pressure loading. Spatiotemporally, shearing 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 relative 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.

References: [1] Holbourn, The Lancet, 1943, 242(6267):438-441; [2] Smith et al., J Head Trauma Rehabil., 2003,18(4):307-316; [3] Meaney, et al., J. Neurotrauma, 1995, 12(4):689-694; [4] McCracken et al., MICCAI, 2004, 1081-1082; [5] Sack et al., NMR Biomed., 2008, 21(3):265–271; [6] Green et al., NMR Biomed., 2008; 21(7):755-764; [7] Muthupillai et al., Science, 1995, 269:1854-57.