



US DEPARTMENT OF DEFENSE

# BLAST INJURY RESEARCH PROGRAM COORDINATING OFFICE

## Mechanics of Head Injury

### Transparent, Tunable Polymer Models for Experimental Modeling of Blast-induced Brain Injury

Variation in neurological tissue properties due to age, gender, and species limit the usefulness of animal and cadaver studies in understanding the mechanisms of primary blast-induced traumatic brain injuries (bTBI). Biofidelic materials that simulate cranial tissues are needed to produce readily reproducible models for blast studies. Transparent materials could also enable high speed optical measurements during a blast experiment. Using such tissue simulants, it may be possible to compare post-blast results with post-mortem diagnostics of observed injuries in military Service members that sustained bTBI from an improvised explosive device. Researchers at the San Antonio Military Medical Center Department of Neurology (San Antonio, TX), the New Mexico Tech Department of Chemical Engineering (Socorro, NM), and Michigan State University Department of Mechanical Engineering (East Lansing, MI) have developed such materials, by exploring the use of transparent tunable polymers as cranial tissue simulants for bTBI experiments. These materials match physical properties of mammalian tissue and are transparent for high speed optical imaging during blast. They are either physically (natural gelatins) or chemically (polyacrylamide) gelled with the adjacent material to provide a more realistic cohesive material model. Of particular interest are separate material formulations to represent white, grey, and vascular tissue and a molding technique which provides a non-slip boundary between these materials. Mechanisms that are identified from these studies may ultimately be used to inform the design of protective gear to mitigate blast injuries.

Several natural and synthetic transparent gelatins were mechanically tested to find optimal formulations to represent white matter, grey matter, and vasculature. Bovine skin derived gelatin, bovine bone derived gelatin, and polyacrylamide gelatins, at varying weight-to-volume ratios, were used to achieve density values reported for human grey and white matter. The gels were tested for physical properties, including: elastic modulus, a measure of how much the material stretches in response to a force; fracture strength, a measure of how much force per unit area will tear the material; and shear modulus, a measure of how a material deforms when pulled different directions.

Choosing the ideal mix to represent tissue is complicated because material property data for human tissue in the literature are sparse and vary widely in terms of the methods and measurements achieved; however, there are broadly accepted values and good agreement on some relative parameters, such as that white matter is 20–30 percent stiffer than grey matter. Uniaxial tensile and compressive elastic moduli and shear modulus for brain tissue have been reported as roughly 5 kPa in tension, 14 kPa in compression, and 0.4–1.9 kPa in shear at comparable strain rates to these studies. Those values were well matched by polyacrylamide gels, at low strain rates, although at high strain rates the shear modulus





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is larger. Natural gelatins, on the other hand, had too large elastic and shear moduli at the weight to volume ratios tested.

Having selected formulations, the group made simulated brains for testing. Formulations that matched tissue properties were used to fabricate 30 cranial objects that were tested in a blast tube at two peak pressures and in two orientations (head-on, side-on blast). The materials were cast into 3D-printed molds in successive steps forming a test object with geometry representing the gross structure of the brain: the central sulcus, simplified gyri, sulci, ventricles, and vasculature. In each object, either natural or synthetic materials were used in conjunction to provide coupled material boundaries, such that adjacent grey and white matter material mimics adhered. Larger fluid vessels of about 4–5 mm were fabricated with polyacrylamide using a higher weight to volume ratio to represent vascular tissue. Smaller fluid filled vessels were made by leaving an empty cylinder when casting the gelatin, to represent smaller vessels of about one to three mm. The entire object was submerged in a cerebrospinal fluid mimic composed of normal saline and albumin (35 mg/dL) and enclosed by a 3D-printed case, with a simplified skull geometry and acrylic side windows for illumination and imaging. Care was taken to ensure that ventricles and vessels were fully perfused with fluid, with no bubbles in the sealed skull mimic before subjecting it to blast testing. Material boundaries and particles are readily observed through the model, allowing visualization of material motion and calculation of displacement at high temporal resolution. In a subset of fabricated cranial test objects, cavitation nuclei (microbubbles or phase-change nanodroplets) were embedded into gelatins to lower the energy threshold required for cavitation, making it possible to observe potential cavitation events and the resulting damage (Figure 1).

Three rounds of blast testing, each with ten test models, were carried out. The first round used gelatins derived from bovine skin and bone to model white and grey matter; the second round used polyacrylamide gels of varying density for grey and white matter and for large blood vessels. The third round used a different set of polyacrylamide densities to further match the material properties observed from biological measurements. In all tests, optical imaging data were collected for calculation of displacement and strain, pressure transducers were placed to monitor blast pressure, and photographs of the model before and after the blast were compared and analyzed.

All the test objects remained intact after blast exposure. No gross structural damage was observed; this result is consistent with medical imaging results of Soldiers exposed to improvised explosive device (IED) blasts. At high blast pressures (around 75 psi), gas coalescence was observed in the periventricular region of two objects containing cavitation nuclei, suggesting that the fluid-gel boundary may be more susceptible to injury. Early results show maximization of model tissue deformation at the brain surface and gray matter. These regions also are preferentially scarred in human subjects after blast injury and such a finding may provide insight into possible mechanisms of this scarring pattern.

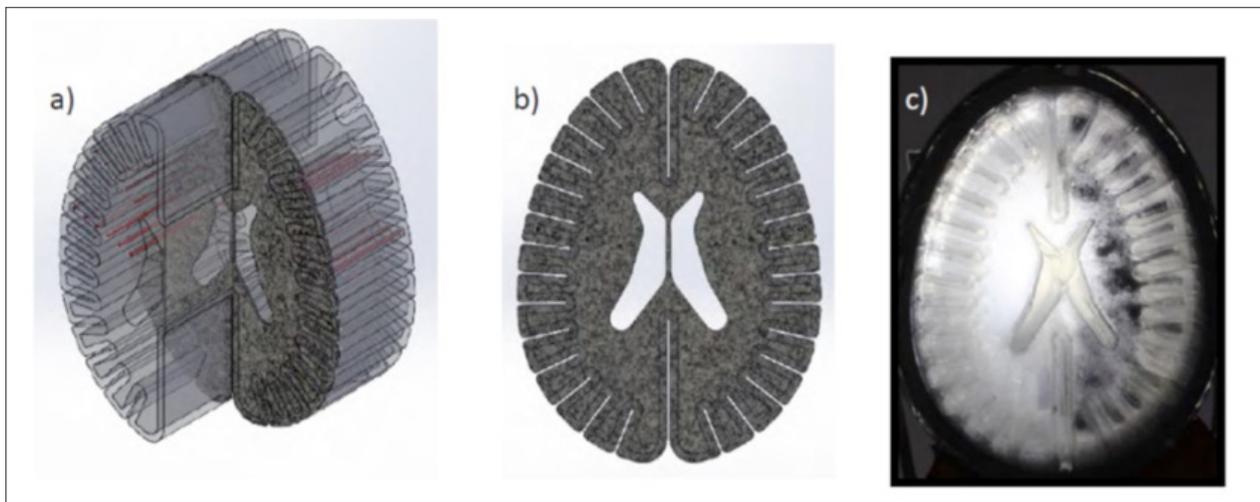




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This project is the first to fabricate blast test objects using natural and synthetic gelatin materials in an effort to capture the material property differences at various tissue boundaries composed of grey/white matter, vascular tissue, and cerebrospinal fluid. The data collected can inform the validation of simulations in which a blast wave interacts with tissue. A limitation of the approach is imperfect matching of the total strain and maximum strain rates observed with typical materials characterization techniques between human tissue and mimetic materials. Characterization of microbubble and phase-change nanodroplets properties in these materials is underway to develop a diagnostic for the forces experienced by the material during blast. This project is ongoing, and this knowledge will be harnessed to modify current combat helmets with the goal of reducing brain deformation during blast and perhaps providing improved protection for Service members.

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**FIGURE 1:** Figure tracks material deformation, showing transverse layers of particles deposited in the brain phantom. A) shows the intermediate layer in the midplane of the phantom; B) is a representation of how the particle plane would be seen through the transparent material of the phantom when using back illumination; and figure C) shows an axial view of a real phantom using back illumination. (Figure used with permission from the authors).

