Comparison of the Brain Response to Blast Exposure Between a Human Head Model and a Blast Headform Model Using Finite Element Methods

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Abstract

Impact induced traumatic brain injury (TBI) has been studied by physical testing using various surrogates, including cadavers, animals, and crash test dummies and by computer modeling including Finite Element (FE) models of human, animal and crash test dummy head. The blast induced TBI research and evaluation of a protective device call for a head model which can mimic wave propagation phenomena through different parts of the head. For proper investigation of head responses and resulting brain injuries due to primary blast exposure, the characteristics of a physical test headform including details of brain/skull anatomy and material properties of the head tissues must be critically designed. The current study was undertaken to numerically evaluate the blast performance of an anatomically realistic headform constructed with existing skull/brain simulant materials in comparison with human head model responses in order to propose a future headform which could be used for testing equipment in blast loading conditions. Quantitative biomechanical response parameters such as pressure, strain and strain rates within the brain were systematically monitored and compared between the blast anatomical headform and the FE human head model. The results revealed that the blast anatomical headform resulted in an average of about 20% over prediction of the biomechanical response parameters in the brain. The results imply that the plyometric based thermoplastic, polycarbonate, polymethylmethacrylate, and polyoxymethylene can be the suitable surrogate skull materials for simulating head responses under blast exposure.

1. Introduction

Impact induced traumatic brain injury (TBI) has been studied by physical testing using various surrogates, including cadavers, animals, and Anthropometric Test Dummy (ATD) and by computer modeling including Finite Element (FE) models of human, animal and ATD/crash test dummy heads. The common physical surrogate head models include the Hybrid III dummy head designed for automotive crash tests and various headforms such as the National Operating Committee on Standards for Athletic Equipment (NOCSAE) headform and ISO headform designed for standard helmet performance test. These headforms recently have been used in blast testing (Yang et al., 2009; Dionne et al., 2004; Makris et al., 1997, 2000; Fournier et al., 2007).

It is well known that blast wave produced by detonation of high explosives is characterized by an extremely high peak overpressure and short duration. The human head is a very complex structure in which to initiate wave propagation in various parts of the head. There are marked differences in densities, material properties, and propagation velocities within various extra- and intracranial tissues, in addition to complex geometrical configurations. This wave propagation phenomenon cannot be assessed correctly by the current dummy head/headform due to the lack of proper material compositions and brain structure. To proper evaluate effectiveness of devices for blast injury protection a physical blast headform model must be capable of predicting wave propagation phenomenon within the skull/brain.

A literature survey revealed that none of the existing headforms represent the realistic geometrical and anatomical features for skull/brain/flesh of the human head. With modern molding techniques and 3D printing technology, it is possible to manufacture the physical headform with accurate geometric details for major components. One of the critical stages also lies in selection of the type of materials under given loading condition, that can best simulate the mechanical responses of the human head. The choice of skull simulant materials must approximate the skull mechanical behaviors such as elastic compressive and tensile strength. Polymeric materials (thermoplastic), polycarbonate, polymethylmethacrylate, polyoxymethylene and composites such as polyester resin have been proposed to simulate the skull bone material under mechanical loadings (Zhang et al., 2009; Alley et al., 2010; Plasmans, 2000; Bosch, 2006). Recently, a skull simulant based on polymeric foams has been used in blast experiments (Hossain, 2010). The silicone Sylgard Gel (Sylgard 527 A&B) has been used as brain simulant to study blunt impact injury and gunshot wounds in physical models as well as in FE models (Brands et al., 1999, 2000; Zhang et al., 2005, 2010). This substance was reported to have similar dynamic modulus to that of the brain tissue and behaved as a linearly viscoelastic solid for strains up to 50% at loading frequencies up to 460 Hz (Brands et al., 1999, 2000). These skull/brain simulant materials along with existing 3D human head FE model made it possible to design and test a new blast headform numerically before making the prototype for physical testing.

Previously, an anatomically detailed, validated FE human head model has been applied to investigate the blast wave effect on the brain in open-field blast exposure and shock tube blast test (Zhang et al., 2001,2013). The current study was carried out to numerically design and evaluate the blast performance of an anatomically realistic blast headform in comparison to a human head model under a range of blast exposures. The study may help in the design of a biofidelic blast headform that will lead to development of improved military helmet designs.

2. Materials and Methods

2.1 Human Head and Blast Headform Models

FE Human Head Model

The sophisticated validated FE human head model, Wayne State University Head Injury Model (WSUHIM), developed previously (Zhang et al., 2001) was used for this study. This anatomically inspired, high resolution FE model features fine anatomical details of the human head (Figure 1), including the scalp, sandwiched skull, dura, falx cerebri, tentorium, sagittal sinus, transverse sinus, bridging veins, arachnoid, cerebral spinal fluid (CSF), pia mater, hemispheres of the cerebrum with distinct white and gray matter, cerebellum, brainstem, lateral and third ventricles, facial bones nasal cartilage, teeth, temporal mandibular joints, ligaments, flesh and skin. The entire head model is made up of over 330,000 elements. The model has been subjected to rigorous validation against available experimentally measured intracranial pressure, ventricular pressure, brain/skull relative motion, and facial impact responses obtained from cadaveric blunt impact tests (Zhang et al., 2001; Viano et al., 2005). More recently, the model has been validated against intracranial pressure changes due to blast overpressure loading in shock tube experiments (Sharma, 2011; Zhang et al., 2013).

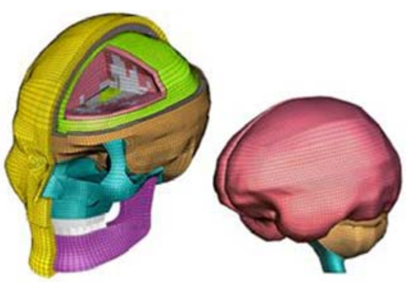


Figure 1: FE model of the human head

FE Headform Model

To develop this anatomically realistic blast headform model, the geometry and mesh of the skull, brain, face and flesh of the human head model was adopted for the headform model. For the headform, a single-layered skull and a homogenous brain were chosen as opposed to an inhomogeneous brain and layered skull bones defined for the human head model. This was done so that the structure of an actual physical headform can be kept simple yet detailed enough to capture pressure wave transformation.

Material Properties

The skull simulant materials proposed must approximate the human skull mechanical behaviors such as elastic compressive and tensile strength. The material properties defined for the skull of the headform were taken from the average value of published data (Zhang et al., 2009; Alley et al., 2010; Plasmans C., 2000). Table 1 lists the material properties of the skull for the headform model together with the skull properties of the human head model.

The brain is a complex structure with neural tissues, membranes, fluids and blood vessels. A practical approach in designing a physical model (headform) is to treat brain as a single homogenous material. The reported silicone Sylgard Gel (527 A and B) material properties were used to represent the brain properties of the blast headform. Most studies reported similar values for Sylgard gel in terms of the density, bulk and elastic moduli (Brands et al., 1999, 2000; Zhang et al., 2009). Table 2 shows the brain material data adopted for the blast headform and defined for the different brain components in the human head model.

Table 1: Material properties of the skull defined for headform and human head models

Components	Density ρ (kg/mm^3)	Elastic Modulus E (GPa)	Bulk Modulus K (GPa)	Shear Modulus G (GPa)	Poisson's Ratio ν
Headform-Skull	1.2 x10^{-6}	4	3.33	1.53	0.30
Head model-Skull_Cortical	2.2 x10^{-6}	10	5.94	4.099	0.22
Head model-Skull_Spongy	0.99 x10^{-6}	1.293	0.77	0.53	0.22

Table 2: Material properties of the brain defined for headform and human head models

Components	Density ρ (kg/mm^3)	Elastic Modulus E (kPa)	Bulk Modulus K (GPa)	Shear Modulus (kPa)		Decay Constant β (ms^{-1})
				Short Term G_0	Long Term G_∞	
Blast Headform Brain	9.7 x10^{-7}	82.5	1	25.5	0.22	0.45
Human head-Grey Matter	10.6 x10^{-7}	10	2.19	10.0	2.5	0.1
Human head -White Matter	10.6 x10^{-7}	12.5	2.19	12.5	2.5	0.1
Human head-Brainstem	10.6 x10^{-7}	22.5	2.19	22.5	4.5	0.1
Human head-Ventricles	10.6 x10^{-7}	1	2.19	1.0	.01	0.1

2.3 Blast Simulation

Open Field Blast Simulation

The levels of overpressure and associated pulse durations of a forward blast loading were selected from Bowen's iso lung damage threshold curve (Bowens et al., 1968) for a 70 kg unarmored human. Four levels of the peak overpressure ranged from 0.27 to 0.66 MPa with associated durations from 1 to 3 ms were simulated to produce the blast wave in open-field scenarios. The net weight of TNT explosives and the stand-off distances required to achieve these four blast overpressure-pulse profiles were calculated first and then verified by the MMALE model simulation. These levels of blast profiles were utilized in our previous study to characterize blast wave interaction with the head model and subsequent intracranial responses due to various blast conditions and head orientations (Zhang et al., 2013).

FE Models of TNT and Air

The FE models of TNT and air (Figure 2) and their material property definitions were the same as those in our previous study (Zhang et al., 2013). Basically, the detonation and expansion of the TNT explosive materials were described using the Jones-Wilkins-Lee (JWL) equation of state (EOS) along with a high-explosive material property definition. The JWL equation is described as:

$$p = A\left(1-\frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1-\frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega E}{V}$$

Where V is relative volume. E is specific internal energy. A, B, R_1, R_2, and ω are JWL fitting parameters (Dobratz et al., 1985). The models of both the head and blast headform were positioned forward with respect to the center of the charge at various stand-off distances. The blast wave propagation in air, interaction with the head model and the subsequent structural response in the brain of various anatomical structures were simulated and analyzed using the coupled multi-material Lagrangian-Eulerian and fluid-structural interface method in LS-DYNA® 971 (LSTC, Livermore, CA).

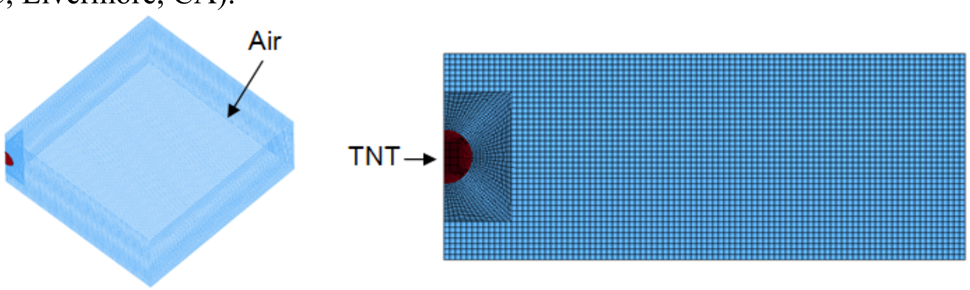


Figure 2: FE mesh of TNT and Air model in iso and side views

Comparison of Brain Response Parameters

The biomechanical response parameters within the brain tissues and brain simulant, including the intracranial pressure (*ICP*), maximum principal strain (ε), maximum principal strain rate ($d\varepsilon/dt$) and the product of strain and strain rate ($\varepsilon \bullet (d\varepsilon/dt)$) were computed and compared between the human head model and the blast headform model.

Among different skull simulant materials reported in literature (Zhang et al., 2009; Alley et al., 2010; Plasmans, 2000), an average elastic modulus was 4 GPa which was used in the current study (baseline case). To assess the sensitivity of brain responses to pressure wave transmission due to material properties of the skull from various simulant materials, a parametric study was conducted on blast a headform by varying skull elastic modulus from 4 GPa to 2 and 6 GPa for one blast loading condition (350 kPa-2ms). The model predicted responses for *ICP, ε,* and *ε•(dε/dt)* were compared to those of the baseline case.

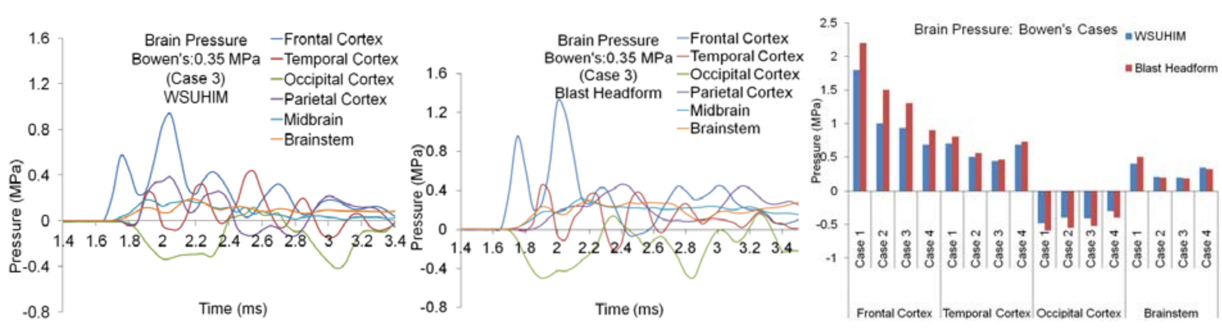
3. Results

3.1 Head and Headform Response to Air Blast

Intracranial Pressure Response

Figures 3a and 3b show the intracranial pressure-time histories predicted by the two models (human head vs headform) at various cortical regions, the midbrain, and lower brainstem of the brain for Case 3 (350kPa-2ms). The blast wave impinged on the brain at about 1.65 ms with an initial peak of 0.6 MPa as predicted by the human head model (WSUHIM) (Figure 3a), whereas this peak was about 0.9 MPa as predicted by the blast headform model (Figure 3b). Both peak positive and negative pressures sustained at the frontal and occipital cortex increased to 1.3 from 0.93 MPa and to -0.5 MPa from -0.41 for the headform model. As depicted in the figure, the ICP in the headform followed the trend of the ICP in the head model except the overall magnitudes predicted by the headform were higher than those by the head model. In addition, the pressure gradients in the headform model did not diminish as quickly as in the head model.

For all the Bowen's cases, the ICP magnitudes in the two models varied by regions and were related to the incident overpressure and pulse duration of the waves (Figure 3c). The peak coup pressure in the head model ranged from 1.8 to 0.68 MPa whereas in the headform model it ranged from 2.4 to 0.8 MPa, which was about 30% higher than that by the head model. The peak contrecoup pressure in the headform model ranged from -0.4 to -0.59 MPa, which was nearly 20% higher than that by the head model. The structures in the core region of the brain, including the thalamus, midbrain and brainstem sustained lower pressure than the cortical tissues. The ICP difference in the brainstem was the least (<10%) between the two models in all blast exposures. Despite the differences in peak ICP magnitudes the overall ICP at the corresponding cortical and central brain locations/regions showed similar trends between the two models.



(a) (b) (c)

Figure 3: Pressure time histories predicted in the brain of various regions by (a) human head model, and (b) blast headform. (c) Comparison of peak ICP between the two models for all four exposures

Brain Strain and Strain Rate

Figures 4a-4b compare the peak magnitudes of the maximum principal strain as well as the product of strain and strain rate predictions at various brain regions between the head and headform models from all blast exposures. In the head model, ε ranged from 0.015 to 0.12, whereas in the headform, ε was about 20% higher. The highest ε was located chiefly in the brainstem as compared to the other regions in the cerebral hemisphere from all cases. Among all exposures, for both models exposed to Case 1 blast produced the highest ε than other three cases.

Similar to the ε response, the brainstem sustained the highest $\varepsilon \bullet (d\varepsilon(t)/dt)$ except for the Case 1 blast the frontal cortical (coup) region sustained higher $\varepsilon \bullet (d\varepsilon(t)/dt)$ than the brainstem and other cortical regions. In comparison to the head model, $\varepsilon \bullet (d\varepsilon(t)/dt)$ predicted by the headform was generally at an average of 15% higher magnitudes for all cases. The highest $\varepsilon \bullet (d\varepsilon(t)/dt)$ was 30 s^{-1} in the headform and was 25 s^{-1} in the head model due to Case 1 exposure.

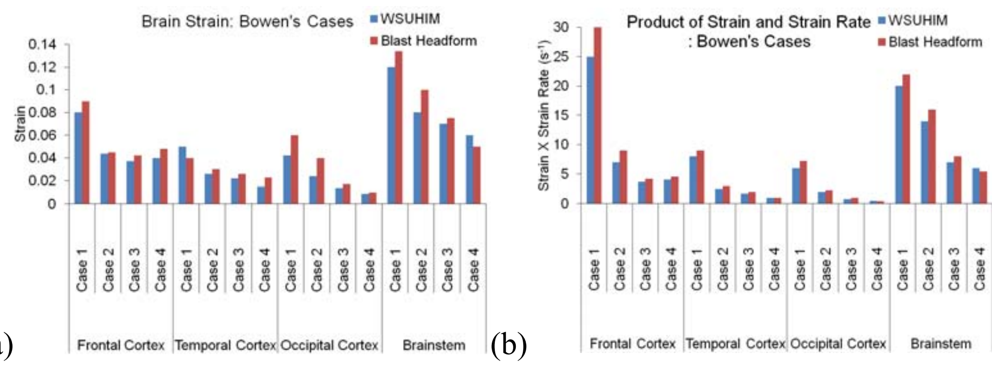
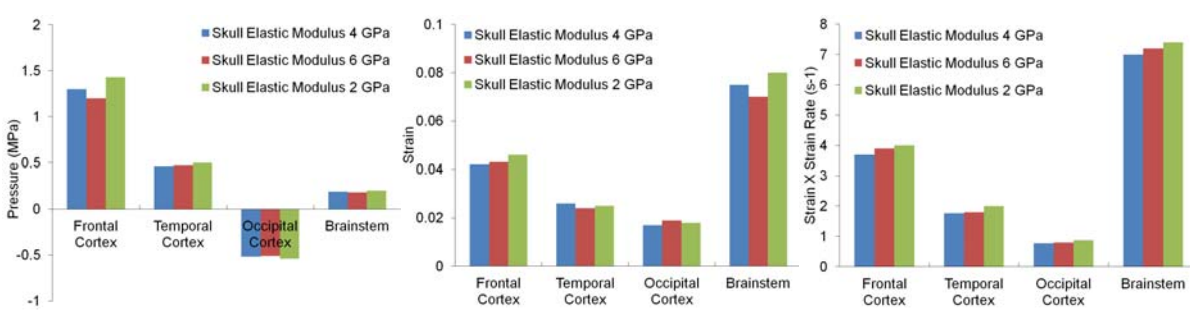


Figure 4: (a) Peak magnitudes of maximum principal strain (b) Product of strain and strain rate at various brain regions between the two models: human head model (WSUHIM) and blast headform model

Parametric Study

Figure 5 shows the effect of the varying elastic moduli of the skull simulant material on the resulting brain pressures, brain strains and strain rate from one blast exposure. Using elastic moduli of 6 GPa (upper bound) and 2 GPa (lower bound) for the skull, model prediction showed an average of 5-11% change in the brain in terms of ICP, ε*, and* $\varepsilon \bullet (d\varepsilon(t)/dt)$ as compared to the skull defined with an elastic modulus of 4 GPa. Interestingly, both brainstem strain and coup pressure decreased as the skull elastic modulus increased. This may imply some protective effect of a rigid skull which limited the direct pressure transmission, leading to less tissue deformation in the central core region of the brain.



(a) (b) (c)

Figure 5: Effect of changes in skull material property on brain responses (a) intracranial pressure (b) maximum principal strain (c) product of strain and strain rate

4. Discussions and Conclusion

The FE analyses were conducted to assess the feasibility of designing a new physical blast headform that represents the anatomically accurate geometries of the skull-brain structures constructed with simulant materials. The simulation of blast waves of different intensities (overpressure and pulse duration) and wave interaction with headform were performed and the brain responses were compared to those calculated from an anatomically accurate human head model. The results revealed that the blast anatomical headform resulted in an average of about 20% over prediction of the biomechanical response parameters (intracranial pressure, brain strain, and strain rate) in the brain. Since the geometrical and structural details were the same between the human head and blast headform models, the variation in brain responses were likely attributed to the difference in material properties between the brain tissue and brain simulant material, particularly the instantaneous shear moduli. Among the model predicted results from all four Bowen's blast exposures, a residue brain pressure and strain were presented in the brain of the blast headform model after 4 ms due to slow decay of stress wave in the brain simulant material.

The Sylgard gel is the most widely used brain material simulant in blunt impact conditions under dynamic rate lower 100/s. Blast waves produced by high explosives are a short duration loading event (<and strain rates resulted from blasts can be even higher than in ballistic events (Zhang et al., 2008). There is a lack information on the rate sensitive shear properties of the Sylgard gel and brain tissues (animals or human) at high rate relevant to blast loading conditions.

The skull serves as the main load transmission pathway for the shock waves before entering the brain. The sensitivity study of the skull simulant material properties indicated that only less than 10% changes in brain responses resulted from either increase or decrease in elastic moduli of skull from 4 to 6 or to 2 GPa, suggesting the blast wave was insensitive to the variation of elastic moduli of the same order. The findings imply that the plyometric based thermoplastic, polycarbonate, polymethylmethacrylate, and polyoxymethylene can be the suitable surrogate skull materials for simulating head responses under blast exposure. Future study will be fabricating the blast headform along with the pressure sensors and tested under blast loadings. Eventually a biofidelic blast headform may help improve the blast-mitigating performance of the military helmet design.

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