Primary blast waves induced brain dynamics influenced by head orientations

Yi Hua¹ · Yugang Wang² · Linxia Gu^{1,3}

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Abstract There is controversy regarding the directional dependence of head responses subjected to blast loading. The goal of this work is to characterize the role of head orientation in the mechanics of blast wave-head interactions as well as the load transmitting to the brain. A three-dimensional human head model with anatomical details was reconstructed from computed tomography images. Three different head orientations with respect to the oncoming blast wave, i.e., front-on with head facing blast, back-on with head facing away from blast, and side-on with right side exposed to blast, were considered. The reflected pressure at the blast wave-head interface positively correlated with the skull curvature. It is evidenced by the maximum reflected pressure occurring at the eye socket with the largest curvature on the skull. The reflected pressure pattern along with the local skull areas could further influence the intracranial pressure distributions within the brain. We did find out that the maximum coup pressure of 1.031 MPa in the side-on case as well as the maximum contrecoup pressure of -0.124 MPa in the back-on case. Moreover, the maximum principal strain (MPS) was also monitored due to its indication to diffuse brain injury. It was observed that the peak MPS located in the frontal cortex region regardless of the head orientation. However, the local peak MPS within

each individual function region of the brain depended on the head orientation. The detailed interactions between blast wave and head orientations provided insights for evaluating the brain dynamics, as well as biomechanical factors leading to traumatic brain injury.

Keywords Blast wave · Head orientation · Traumatic brain injury · Finite element modeling · Stress transfer

1 Introduction

Blast-induced traumatic brain injury (TBI) has been gaining increased attentions for designing better diagnostic and protection measures [1]. Current protective armors have demonstrated its efficacy against blunt impacts, shrapnel or projectiles, but they are not designed for protection against blast waves, leading to an increased incidence of blast-induced TBI [2, 3]. Specifically, the head orientations could affect the level of TBI subjected to impact or inertial loading [4–6]. However, little is known about the directional dependence of head responses under blast loading conditions. Taylor and Ford [7] simulated three different human head orientations with respect to the oncoming blast wave, i.e., head facing blast, head facing away from blast, and right side of the head exposed to blast. They found that the head orientation had negligible impact on the orbito-frontal regions and the posterior fossa (cerebellum and brain stem). From the numerical study by Zhang et al. [8], the peak coup pressure was found when the right side of the head was exposed to the blast, and the peak contrecoup pressure was observed when the head faced the blast. This contradicted the findings of Taylor and Ford [7]. Rat models [9, 10] were also utilized to investigate the role of head orientation in brain dynamics. Both studies stated that

✉ Linxia Gu
lgu2@unl.edu

¹ Department of Mechanical and Materials Engineering,
University of Nebraska-Lincoln, Lincoln, NE 68588-0656,
USA

² China JiLiang University, Hangzhou 310018, Zhejiang,
China

³ Nebraska Center for Materials and Nanoscience, Lincoln,
NE 68588-0656, USA

the peak intracranial pressure (ICP) was measured when the head faced the blast. In addition, for all these studies regarding the role of head orientation, the detailed characterizations of the blast wave-head interactions and load transfer mechanism into the brain were less characterized.

In this work, we delineated the effect of head orientation on the mechanics of the blast wave-head interactions as well as the load transfer to the brain through the finite element (FE) method. A three-dimensional (3D) human head model with anatomical details was reconstructed from computed tomography (CT) data. It was then positioned in three different orientations with respect to the oncoming wave direction; head facing blast, head facing away from blast, and right side exposed to blast. The intensity of blast overpressures that exerted at the vicinity of the head was monitored. The brain responses in terms of ICP and maximum principal strain (MPS) were also computed.

2 Finite element modeling

A human head model was reconstructed from CT data, which consisted of 73 axial scans of 512^2 pixels taken at 3 mm intervals in an adult male head. The image data were segmented into three different tissue types of the head, i.e., skull, cerebrospinal fluid (CSF), and brain (Fig. 1). The segmentation was realized using the 3D image analysis algorithm implemented in Mimics® (Materialise, Inc., Leuven, Belgium). The skull included most of the anatomical structures such as the frontal, occipital, and temporal bones as well as the eye sockets. Followed by segmentation, the head model was imported into HyperMesh® (Altair Engineering, Inc., MI, USA) through an STL file and discretized into 159,621 10-noded modified quadratic tetrahedron elements (C3D10 M). It was then subjected to a planar blast loading mimicking the in-house shock tube as described in our previous work [11]. Briefly, the measured incident pressure

history with peak value of 0.22 MPa was used as the pressure boundary condition at the inlet of the Eulerian domain ($400 \times 400 \times 1000$ mm) filled with air. It consisted of 1,300,000 brick elements with appropriate mesh refinement near the region of the human head to capture the effect of fluid–structure interaction. The velocity perpendicular to each face of the Eulerian domain was kept zero to avoid escaping/leaking of air through these faces. This would create a planar blast front traveling along the incident direction without lateral flow. The head model with a fixed bottom was immersed in the Eulerian domain and their interaction was enforced through a penalty contact algorithm with frictionless tangential sliding and hard contact normal behavior. The blast wave-head interaction model, governed by partial differential equations of conservation of mass, momentum and energy along with the material constitutive equations and boundary conditions, was solved in ABAQUS/Explicit analysis software (Simulia, Inc.).

The skull was modeled as a homogeneous linear elastic isotropic material and the Young's modulus and Poisson's ratio were assumed as 5.37 GPa and 0.19, respectively [6]. The brain was assumed to be linear viscoelastic with a short-term shear modulus of 41 kPa and a long-term shear modulus of 7.8 kPa [12]. The CSF was modeled as an incompressible fluid using the linear Mie–Grüneisen equation of state, which related the blast velocity and fluid particle velocity to the pressure inside the CSF [13]. The air was modeled as an ideal gas equation given by

$$P = (\gamma - 1) \frac{\rho}{\rho_0} e$$

where P was the pressure, γ was the constant pressure to constant volume specific heat ratio (1.4 for air), ρ_0 was the initial air mass density, ρ was the current mass density, and e was the internal volumetric energy. The Mach number of the blast front measured in our previous experiment was approximately 1.4. Hence, ideal gas equation of state

Fig. 1 Finite element model of the human head subjected to blast loading (midsagittal view)

Table 1 Material properties used in the finite element simulation

(a) Elastic material properties				
Material	Density (kg/m ³)	Young's modulus (MPa)	Poisson's ratio (/)	
Skull	1710	5370	0.19	
Brain	1040	1.314	0.4999	
(b) Viscoelastic material properties				
Material	Short-term shear modulus (kPa)	Long-term shear modulus (kPa)	Decay constant (ms)	
Brain	41	7.8	700	
(c) Incompressible fluid EOS parameters				
Material	Viscosity (N s/mm ²)	Sound speed (mm/s)	Hugoniot slope coefficient (/)	Grüneisen's gamma (/)
CSF	1×10^{-8}	1.48×10^6	0	0
(d) Ideal gas material parameters for air				
Material	Density (kg/m ³)	Gas constant (J/kg·K)	Temperature (K)	
Air	1.1607	287.05	300	

assumption is valid, as the ratio of specific heats do not change drastically for this Mach number. A summarization of the material properties is illustrated in Table 1.

3 Results

The computational framework has been validated against our experimental work [11]. Briefly, repeated shock tube tests were conducted on a surrogate head, i.e., a water-filled polycarbonate shell located inside the shock tube. The ICP histories at three different locations were measured. Results show that the major features of the measured pressure profiles, including the peak pressure, nonlinear decay, and small peaks and valleys were captured by the simulation. The maximum deviation of the peak pressure in the brain was only 8.31%.

To examine the influence of head orientation on the mechanics of blast wave-head interactions, we monitored the reflected pressure histories at four different locations around the head (Fig. 2). Locations R1–R4 represent the frontal bone, eye socket, occipital bone, and temporal bone, respectively. In the front-on (head facing blast) case, the maximum reflected pressure of 0.67 MPa was observed at location R2 (eye socket). Compared to the incident pressure of 0.22 MPa, the reflection factor Λ (ratio of the reflected pressure to the incident pressure) was calculated as 3.0. As the blast wave traversed the head, the reflected pressure

decreased from locations R1 ($\Lambda = 1.8$) to R3 ($\Lambda = 1.6$), and the minimum reflected pressure was observed at location R4 ($\Lambda = 1.1$). In the back-on (head facing away from blast) and side-on (right side exposed to blast) cases, the maximum reflected pressures were observed at locations R3 ($\Lambda = 2.0$) and R4 ($\Lambda = 2.1$), respectively. However, both of them were smaller compared to the reflected pressure measured at location R2 ($\Lambda = 3.0$) in the front-on case.

The intracranial wave propagations under different head orientations are illustrated in Fig. 3. All three head orientations exhibited typical coup and contrecoup pressure patterns throughout the brain while the blast wave front passed through the head as shown in the first two snapshots of the ICP distributions. Once the blast wave front passed over the head, complex ICP pattern developed due to the wave reflection and skull flexure as depicted in the last two snapshots. The peak coup pressures were 0.380, 0.529, and 1.031 MPa and the peak contrecoup pressures were -0.084 , -0.124 , and -0.069 MPa in the front-on, back-on, and side-on cases, respectively (indicated by the dashed circle).

The role of head orientation in the peak MPS was also obtained at four critical regions of the brain (i.e., frontal cortex, superior cortex, occipital cortex, and brainstem) as shown in Fig. 4. In the frontal cortex region, the peak MPS subjected to the front-on or side-on orientation were 37.4 and 34.8% higher than the one in the back-on case. In the superior cortex region, the peak MPS occurred in the case of side-on ordination (0.017). In the occipital cortex region,

Fig. 2 Comparison of the reflected pressure histories at four locations around the head for **a** front-on, **b** back-on, and **c** side-on cases

the peak MPS was observed in the cases of back-on or side-on orientations (~ 0.014). In the brainstem region, the peak MPS (0.003) was observed in the front-on case.

4 Discussion

A 3D FE human head model was developed to investigate the role of head orientation in transmitting blast waves to the brain. The detailed blast wave-head interactions as well

as the ICP and MPS responses in the brain were characterized. As the blast wave front hit the head, the incident wave pressure was amplified due to the local fluid–structure interaction (Fig. 2). This pressure amplification behavior can be attributed to the aerodynamic effects in which the high-velocity particles of the wave front are brought to rest abruptly, leading to an amplified reflected pressure acting on the solid surface of the head. The reflection factor can vary from 2 to 8, depending on several factors such as the incident blast intensity, fluid medium in

Fig. 3 Snapshots of intracranial pressure distributions for front-on, back-on, and side-on cases. The red line represents the location of blast wave front. The red dotted circle highlights either the peak coup (positive) or contrecoup (negative) pressure. (Color figure online)

which blast wave travels, angle of incidence, mass and geometry of the object [11, 14, 15]. Our results show that the maximum reflected pressure occurred at the eye socket (location R1, $\Lambda = 3.0$) in the front-on case due to the concave shape of the eye socket. In contrast, the peak reflected pressures in the back-on and side-on cases were located at the occipital bone (location R3, $\Lambda = 2.0$) and temporal bone (location R4, $\Lambda = 2.1$), respectively. This is expected since the curvature of the skull surface impacted by the wave front was positively correlated with the reflected pressure [16].

The reflected pressure exerted on the skull resulted in different ICP patterns within the brain under various head orientations. In all three head orientations, the peak positive pressure (compression) was observed at the coup site and the peak negative pressure (tension) was at the contrecoup site (Fig. 3). The maximum coup pressure of 1.031 MPa was found in the side-on case while the minimum one of 0.380 MPa was in the front-on case. This is consistent with the reflected pressure pattern on the skull, i.e., the maximum reflected pressure was at the temporal bone (location R4, $\Lambda = 2.1$) in the side-on case and the minimum one was at the frontal bone (location R1,

$\Lambda = 1.8$) in the front-on case. All these observations could be attributed to the skull geometry. Compared to the frontal bone, the temporal bone has a relatively flat contact surface and a relatively larger span. As a result, the skull will experience more loading in the side-on case, leading to a larger coup pressure in the brain. Although the maximum reflected pressure occurred at the eye socket in the front-on case, the relatively small area interacted with the blast wave resulted in minimal ICP in this case. The computational work by Mao et al. [17] demonstrated a similar trend in the rat brain, i.e., higher pressure for a lateral blast loading compared to a frontal one. However, the experimental work by Chavko et al. [10] showed that rats experienced higher brain pressure in the frontal loading compared to that in the side-on one. The discrepancy between computations and experiments remain interesting, while it should be noted that the accurate blast experiments are still lacking because of the complexity in collecting data at super high-rate blast events. Our results also showed that the back-on case led to the maximum contrecoup pressure. This is consistent with the clinical observation that the patients who suffered from a back impact usually have contusions in the frontal lobe [18]. However, our

Fig. 4 **a** Four regions in the midsagittal plane where the peak maximum principal strain was measured, and **b** comparison of the peak maximum principal strain for front-on, back-on, and side-on cases

observations were different with the published computational work [8], in which the contrecoup pressure in the back-on case was equivalent to that in the front-on case, and both of them were larger than that in the side-on case. This could be attributed to the difference in material properties.

The peak MPS at four functional regions of the brain were extracted from our numerical results (Fig. 4) since the brain MPS was speculated to be correlated with the diffuse brain injury [19–21]. It was observed that, regardless of the head orientation, the peak MPS was generally larger in the frontal cortex region than in other regions. This is attributed to the relatively rough features of the frontal skull. Moreover, the local peak MPS within each individual function region of the brain depended on the head orientation. Specifically, in the frontal cortex region, the peak MPS was observed in front-on and side-on cases, while in the occipital cortex region, the peak MPS was obtained in the back-on case. These could indicate that the frontal cortex were prone to TBI especially in the front-on and side-on cases, while the occipital cortex was the vulnerable one in the back-on case. This clearly shows that head orientation results in different brain dynamics, which is also region-specific. This observation is contradictory to Taylor's work [7], which observed that no difference among three head

orientations. This could be attributed to the adopted boundary conditions at the head. Specifically in their work, the head was free from any constraints, which resulted in a 1 mm displacement of the head during the 2 ms simulation. This could explain why they did not observe the difference between head orientations.

In this work, we validated the head model against pressures rather than brain motions. As a result, the prediction of brain strain is not backed up by sufficient validations. However, the lack of brain motion validation is mostly due to the fact that there are no blast-induced human brain motion data available yet. In addition, only the head bottom was constrained and the head-neck junction was not considered [22]. The skull was also simplified as homogeneous and isotropic material. More realistic models considering heterogeneous skull properties could alter the brain dynamics. Despite these simplifications, the present work demonstrated the importance of head orientations on estimating the blast-induced TBI.

Compliance with ethical standards

Conflict of interest The authors declare that there is no conflict of interests regarding the publication of this article.

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