A computational approach to cumulative blast exposure in the brain for sequences of blast overpressure-orientation combinations

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Abstract. Blast pressure transmission into the brain, associated with traumatic brain injury (TBI), is a complex sequence of events. In this presentation (i) three-dimensional (3-D) nonlinear finite element computational simulations of the head to assess the sensitivity of internal brain pressures to individual blasts from different orientations and (ii) Monte Carlo simulations of random multiple blast sequences to assess cumulative exposure trends are discussed. The NRL high-fidelity 3-D human head finite element model is employed. This validated model, based on high resolution image data, accurately reproduces complex structures of the head and is implemented in the DoD Open Source multi-physics code CoBi. A hyper-viscoelastic model captures brain tissue behaviors with material parameters calibrated on dynamic loading data. The semi-empirical ConWep model generated transient blast from a free-field explosion in air that is nearly planar upon contact with the head model. The individual 3-D simulation results reveal that pressure patterns in the brain vary strongly with blast orientation and appear to highlight important influences of local skull curvature on blast pressure transmission. Regions of higher and lower skull curvature are associated with lesser and greater transmission of the incident blast wave. This appears to be associated with the relative phasing of the blast wave on contact with the head. Brain biomechanical injury is calculated using a spectrum of TBI thresholds associated with single and repetitive single injury. The Monte Carlo simulations, using a database constructed from the individual simulation results to analyse random sequences of blast orientations, were employed to tabulate a Cumulative Pressure Exposure Fraction (CPEF) metric versus number of blast exposures. Plots of 20 random orientation sequences of 200 blasts show the sequence dependent evolutions of the CPEF value for the brain, mean value and standard deviation CPEF convergence used to characterize early and late stage cumulative exposure.

1. INTRODUCTION

Blast pressure transmission into the brain is a complex sequence of events associated with traumatic brain injuries (TBI). In recent military operations, large numbers of service members have experienced repetitive concussion or sub-concussion exposures to explosive blast from improvised explosive devices (IEDs) [1]. Repetitive exposure to blast waves, in operational or training environments, can subject the warfighter to different ranges of pressures and incident directions of these waves. Military personnel having repeated exposures may experience neurological disorders, including concentration problems, blurred vision, irritability, headaches, sleep disorders and depression.

Current understanding of blast induced brain injury mechanisms is limited. In particular, conditions associated with cumulative head injury effects from repetitive blasts over a prolonged period of exposure are not well understood or quantified. Most effects of blast neurotrauma, resulting in structural, biochemical or electrical abnormalities in the brain, spinal cord or other nerves, are mild and difficult to detect with conventional neuroimaging. Research using controlled studies of induced mild traumatic brain injury (mTBI) is not possible with human subjects while the existing animal injury models cannot directly correlate with human injury. Three dimensional (3-D) computational analyses of blast wave biomechanics have the ability to establish relationships between the blast pressure on the head, internal biomechanical response and locations of induced brain injury. This insight can be useful in understanding injury mechanisms and designing improvement of protection systems.

The approach taken here is to quantify the biomechanical effects of individual blast events from different orientations at a fixed incident pressure using high fidelity 3-D computational simulations. The 3-D simulations track the internal response in the brain, such as stress, strain and strain rate, to each blast event and identify how the blast orientation affects the brain response. The maximum local pressures in the brain are used to track the global fraction of the brain exceeding the TBI thresholds. These detailed computational simulation results are compiled in a database covering the range of incident directions.

https://doi.org/10.52202/078352-0018

The 3-D simulation database was used to demonstrate a probabilistic Monte Carlo methodology for long random blast orientation sequences. The database is queried to calculate the cumulative exposures in the brain from the random sequences. The statistics of the internal brain pressure responses are analyzed to identify and quantify the initial variations of the mean values and standard deviation, early in the blast sequences, and the subsequent trend to convergence later in the blast sequences.

2. METHODS

2.1 Computational finite element model of human head

The 3-D human head finite element (FE) model was generated from in-vivo magnetic resonance imaging (MRI) scans with 1 mm isotropic resolution of a young adult. Figure 1 shows the human head finite element model subjected to the blast loading. The model consists of 29 material components including gray matter, white matter, ventricles, cerebrospinal fluid (CSF), skull, etc. Because of the complex geometry, a tetrahedral mesh was used for the discretization.

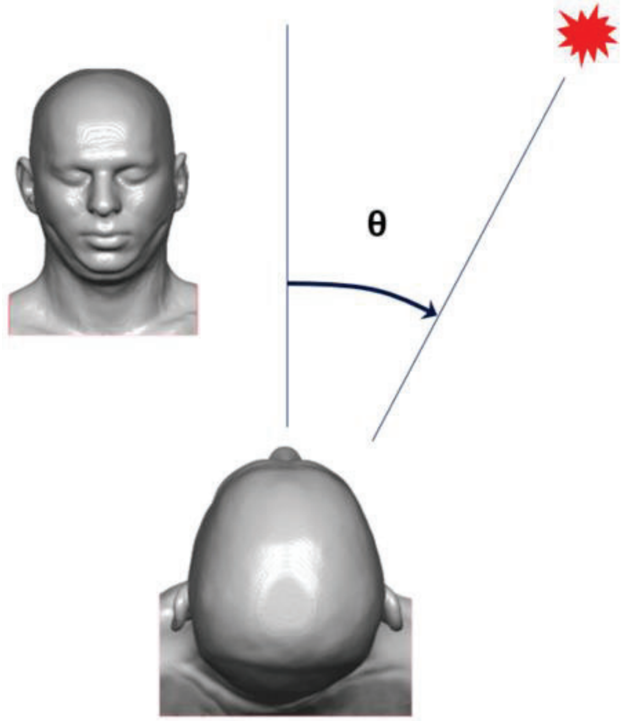

Figure 1. Finite element human head model subjected to blast loading

The multi-physics solver CoBi [2] is used for the simulation of blast-induced head biomechanics. The gray matter and white matter were modeled as hyper-viscoelastic materials. The CSF layer between the skull and brain and the ventricles inside the brain were modeled as the hyper-elastic solids with a very low shear modulus. The skull was assumed linear elastic. The full set of material models and corresponding parameters can be found in [3].

The ConWep model, incorporated in CoBi finite element solver, is used to apply the transient blast loading on the head resulting from a spherical free-field explosion in air (without the ground effect). A bare high explosive TNT charge of 1.03 kg is detonated at a distance of 2.7 m from the head surface at an angle θ relative to the middle sagittal plane of the head. The peak incident overpressure near the head is 15.0 psi (103.4 kPa). This value of overpressure is generally considered survivable in the operational environment. The angle θ ranges from 0 to 360 degrees with increments of 15 degrees, i.e. θ=0, 15, 30,…, 330, 345, 360 degrees, for a total of 24 angles.

The result of each finite element simulation with time duration of 2.5 ms produced spatially- and temporally-resolved pressure field data at each point in the 3-D brain model. These values can be compared to the minimum pressure thresholds for a critical pressure injury criterion to determine if TBI

 https://doi.org/10.52202/078352-0018

has occurred. As shown in Table 1, pressure-based TBI thresholds suggested in the literature [4-6] were used to assess different levels of blast TBI. (While the pressure threshold criterion is used here, other criteria can be appled as appropriate.) The criteria are simultaneously applied on an element-by-element basis to the brain at every time step in each analysis. If an element maximum pressure exceeds a given pressure threshold at any time during the analysis, the element is considered to have been "injured". The full set of 24 blast orientation simulations generated a database containing the local pressures in each element and whether those pressures exceeded any of the four TBI thresholds.

Table 1. Pressure based thresholds of traumatic brain injury [4-6]

Blast induced TBI Type	Repetitive mTBI	Single onset mTBI	Single moderate TBI	Single intermediate TBI
Threshold (kPa)	142	173	204	235

2.2 Monte Carlo simulation of repetitive blast sequences

To conduct the Monte Carlo simulation of repetitive blast sequences, the precomputed finite element database of pressure responses in the brain containing the 24 incident blast orientations is used. Random sequences S=20, each sequence N_{tot}=200 in length, are drawn from the set of 24 blast orientation simulations. Each blast n=1, 2, 3,…, N_{tot} in a random sequence refers back to the precomputed database for dynamic pressure responses in the brain.

The pressure exposure (PE) of an element e in the finite element model is denoted as PE(e, n) and initialized to be zero, i.e. PE = 0. If the pressure in the element e equals or exceeds the specified injury threshold pressure at any time during a blast simulation, PE = 1. V(e) is the associated element volume. The cumulative pressure exposure fraction CPEF(e, N) for each element e in the brain model after N blast events ($1 \leq N \leq N_{tot}$) is defined as

$$CPEF(e,N) = \frac{\sum_{n=1}^{N} PE(e,n)}{N} \quad (1)$$

and CPEF(E_{tot}, N) for the entire brain with E_{tot} elements is defined as

$$CPEF(E_{tot},N) = \frac{\sum_{n=1}^{N}\sum_{e=1}^{E_{tot}} PE(e,n)\times V(e)}{N\times\sum_{e=1}^{E_{tot}} V(e)} \quad (2)$$

The pressure exposure fraction (PEF) in the brain, defined for a single blast orientation, is equivalent to equation (2) with N=1 at an angle θ. Refer to [7] for further details.

3. RESULTS

The results of the individual and repetitive blast exposure analyses will be presented in terms of both local and global measures of brain dynamic response. Local measures associated with individual blasts include representative local pressure-time histories in the brain and spatial distributions of maximum pressures generated in the brain over the course of a blast analysis. Global measures associated with individual blasts include the pressure exposure fractions (PEF) versus orientation angle for a pressure injury threshold. Global measures for repetitive blast sequences are expressed in terms of the cumulative pressure exposure fraction (CPEF).

Figure 2 presents an example of data for the time history of pressure at three locations in the brain for θ=0 degrees, i.e. for a frontal blast wave, generated from an incident overpressure of 15 psi (103.42 kPa). The pressure waveform in the brain is significantly different from the incident blast wave because of wave convergence and divergence. The peak pressure at the frontal brain lobe is higher than the ConWep incident pressure and more comparable to the normally reflected pressure. The peak pressure is lower for interior brain points compared to the locations near the brain-CSF interface. Note that the peak pressure at the rear brain experiences a significant negative pressure at the early time when other parts of brain are in the positive pressures.

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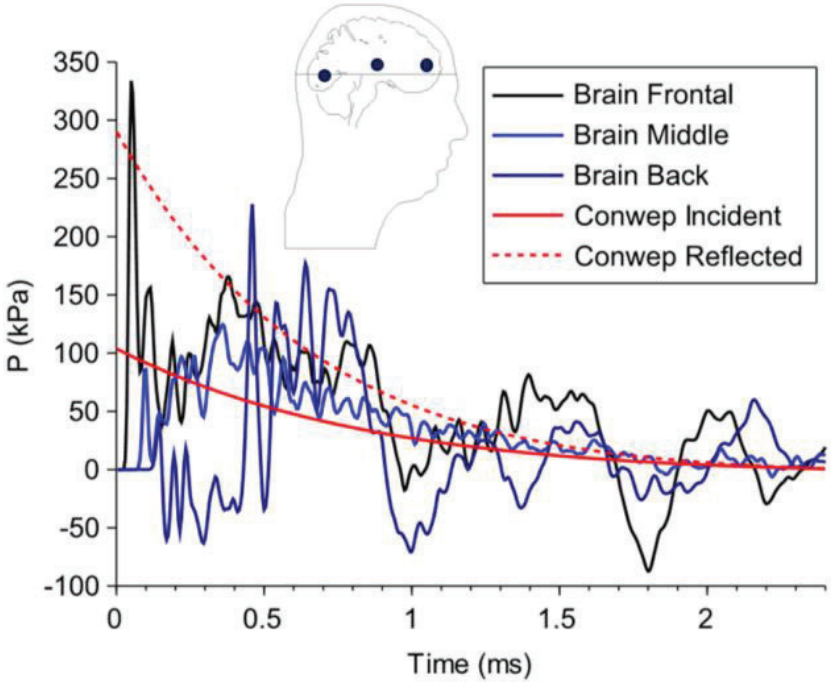

Figure 2. Time history of pressure in the brain for the frontal blast (θ=0 degrees)

The effects of different blast orientations (0, 75, 150, 180, -150 and -75 degrees) on maximum pressures experienced in the brain for a single blast are shown in Figure 3. The pressure distribution is generally symmetric for the blast orientation of 0 and 180 degrees. For 0, +/-150, and 180◦ blast orientations, the highest pressures reside in the region close to the coup and contrecoup. For +/- 75◦ blast orientation, the corresponding side of the brain incident to the blast experiences higher maximum pressures over a larger area and extending into deeper locations of the brain.

In Figure 4, the PEF parameter is plotted parametrically versus all 24 orientations and the four injury pressure thresholds for a single 15 psi (103.42 kPa) overpressure,. The plot quantifies how the PEF increases as the injury threshold decreases. It is broadly symmetric and features significant regions of both higher and lower PEF values. The slight asymmetry in the plot is caused by the natural asymmetry of the brain anatomy used to generate the model. Orientation intervals between (−120, −75) and (+75, +150) degrees have the highest CPEF values, while (−45,+45) degrees have the lowest values. The intervals between (−185, −120), (−75, −45), (+45, +75), and (+150, +180) degrees are the strong transition regions between the lowest and highest PEF values. Injury fractions of only 0.20 occur at +/−75 degrees for the higher 235 kPa injury threshold compared to 0.75 at +135 and -75 degrees for the lower 142 kPa threshold. It is clear that the side blast orientations produce much higher injury fractions in the brain compared to frontal or rear blasts.

Figure 5 shows an example of the change in PEF value relative to incident angle for the pressure injury threshold of 173 kPa in the cerebrum and cerebellum of brain, with further differentiation between grey matter (GM) and white matter (WM). The broad symmetry trend can again be observed. The PEF in the cerebrum is higher than that in cerebellum for the frontal blasts and lower for the rear blasts. Because the cerebellum is at the back of head, the PEF has the highest value in the cerebellum grey matter for the θ=180 degree blast orientations. The white matter of both cerebrum and cerebellum have a lower PEF because of the deeper interior locations compared to their respective grey matter.

It appears that the external curvature of the head, defined by the skull, is a significant factor affecting the levels of pressure infiltration into the brain. Figure 6 shows the surface curvatures of 3-D head finite element model. Both the Gaussian curvature and the mean curvature were calculated based on the triangular mesh defined by the head surface. An area on the side of the head exhibits lower curvatures compared to the forehead, back and top of the head. These low curvature areas on the right and left side of head, when aligned with the blast orientation, allow the nearly planar blast pressure wave to propagate more uniformly into the brain volume. As a result, the blasts at orientations of approximately +/-75 degrees produce the higher maximum pressures over a larger area of the brain as seen in Figure 3.

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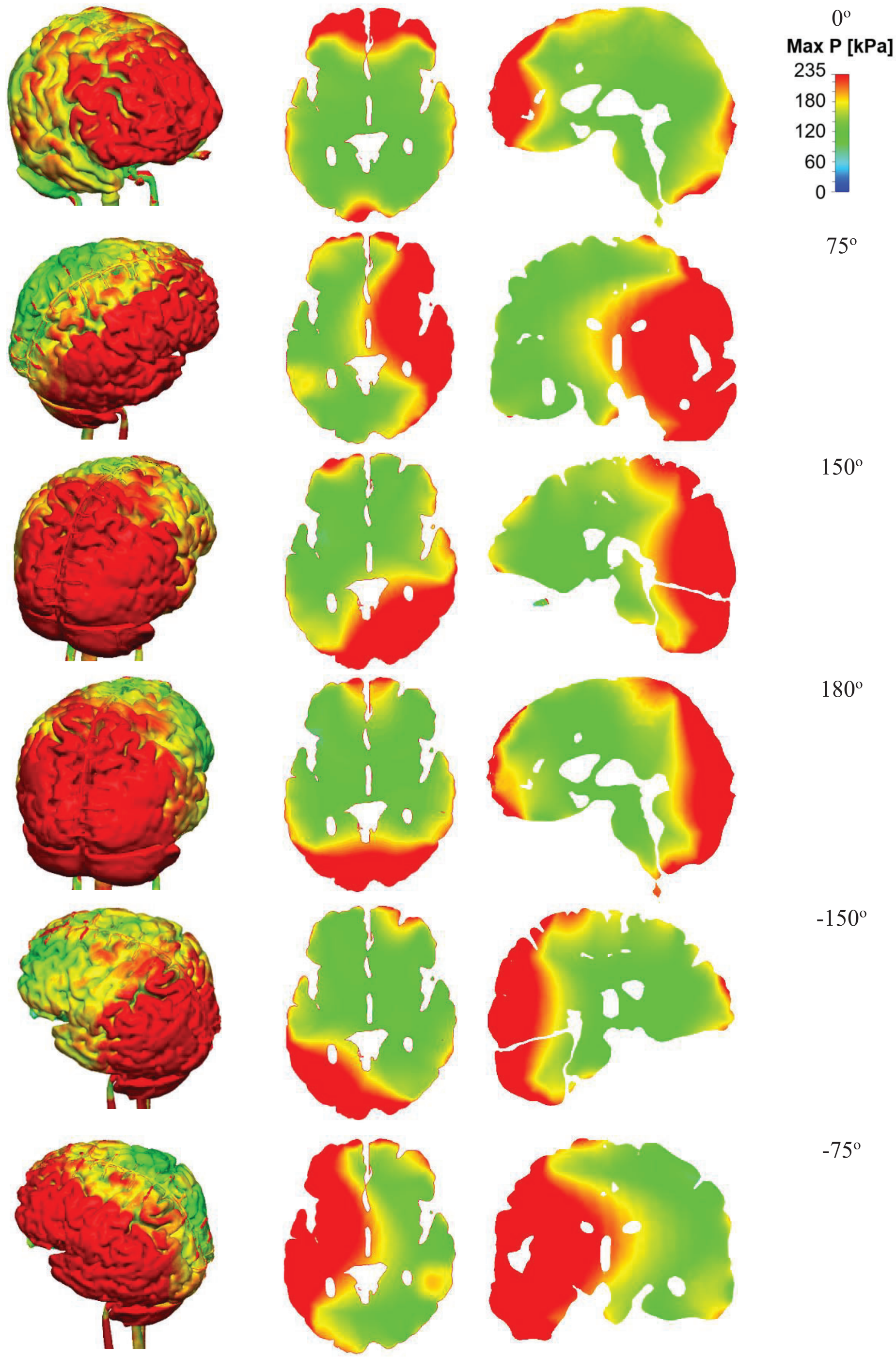

Figure 3. Maximum pressure in the brain during the blast for incident angles of 0, 75, 150, 180, -150 and -75 degrees at 15 psi (103.42 kPa) incident overpressure. Left graphic column shows contours on brain surface, middle graphic column shows contours on the transverse plane, right graphic column shows contours on the plane orthogonal to transverse plane along incident angle

https://doi.org/10.52202/078352-0018

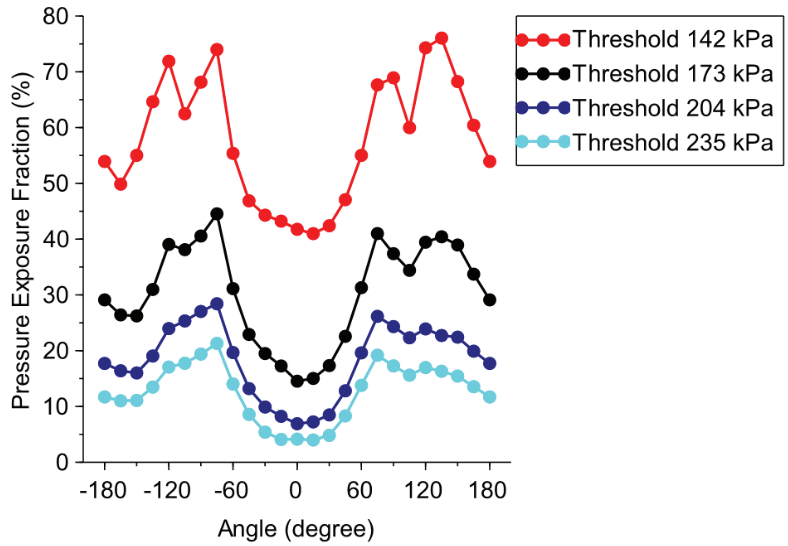

Figure 4. PEF vs. incident angle for four different pressure thresholds

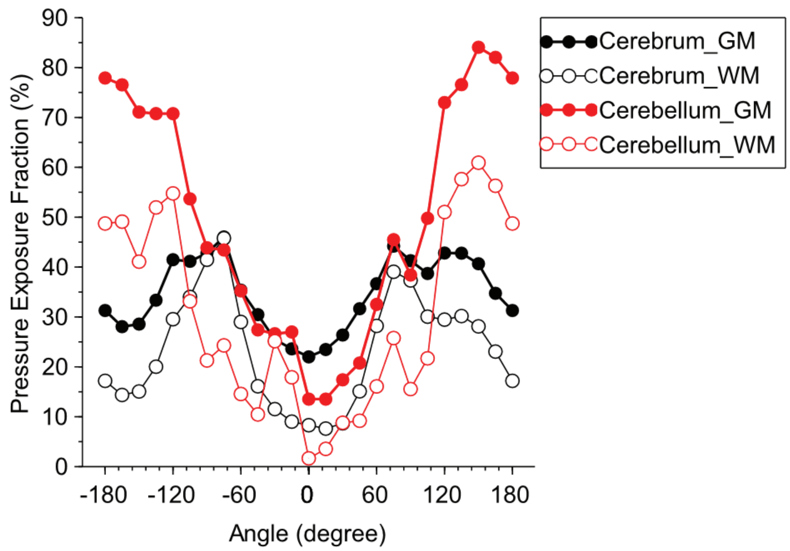

Figure 5. PEF vs. incident angle in cerebrum and cerebellum, parameterized by the grey matter (GM) and white matter (WM), for a pressure injury threshold of 173 kPa

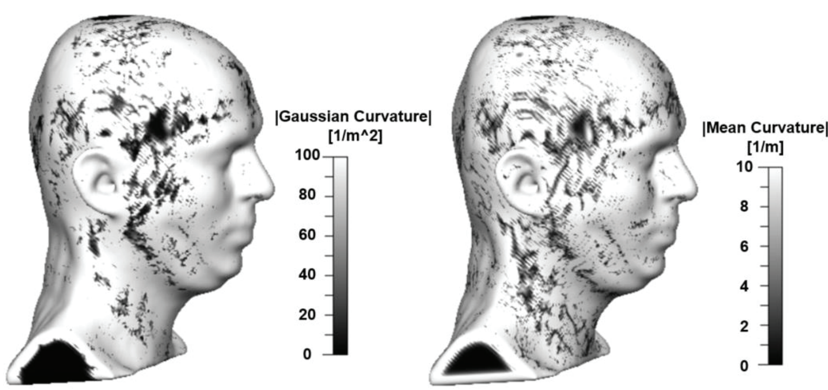

Figure 6. Surface curvatures of head finite element model

https://doi.org/10.52202/078352-0018

Using the database compiled from the individual finite element biomechanical analyses covering the 24 blast orientation angles, Monte Carlo simulations were conducted for 20 random sequences of N_{tot} = 200 blasts to generate cumulative response exposures statistics. Figure 7a through 7c shows the envelope curve for the 20 CPEF(E_{tot}, N) sequences exceeding the TBI thresholds of 142, 173, and 204 kPa in the brain. Also plotted are curves of the cumulative mean and cumulative standard deviation (SD), shown as red and black lines respectively. Figure 7d shows the semi-log plot of mean and SD with respect to number of blasts N. The CPEF parameter is sensitive to the direction of the blasts early in the sequence of 200 exposures, converging at approximately 40 blasts. The mean value of 0.59 is the largest, associated with the smallest TBI threshold of 142 kPa. The mean becomes much smaller, approximately 0.31 and 0.159 with the larger TBI thresholds of 173 and 204 kPa. The SD value converges at approximately 80, 70 and 40 blasts for the 142, 173 and 204 kPa injury threshold values, respectively. Analysis of the data suggests that while the mean value is associated with the scalar pressure dosing across the brain, the SD is associated with more complex geometric evolution of the CPEF patterns. When the SD converges, the patterns stabilize and do not change significantly from additional blasts.

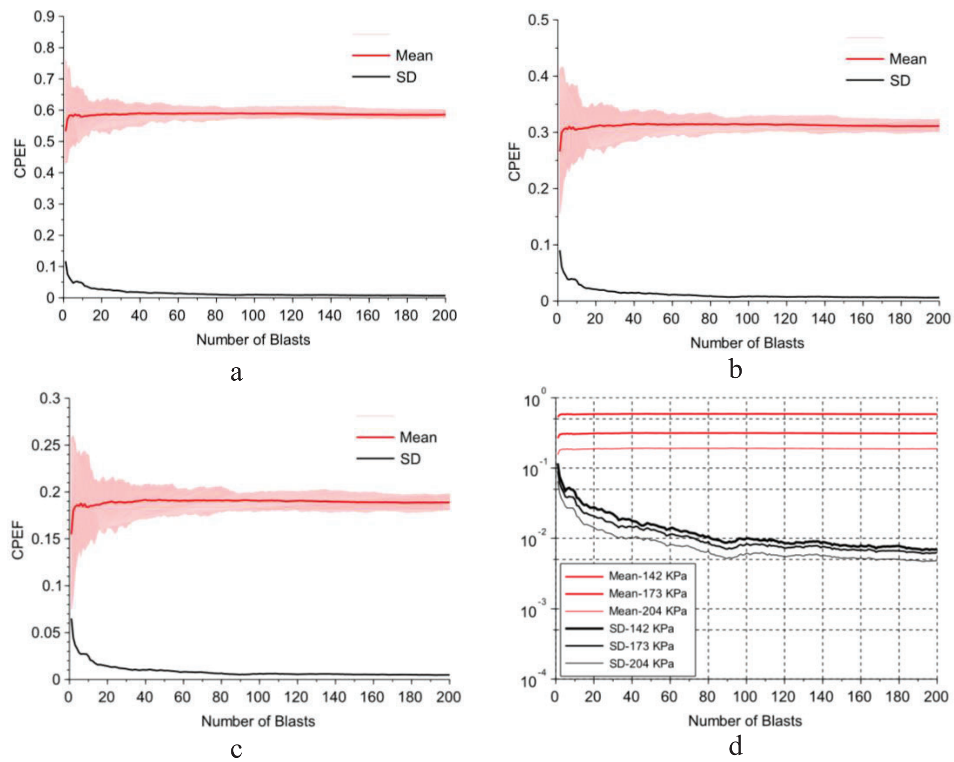

Figure 7. Three dimensional simulation Monte Carlo results for random blast sequences showing CPEF (E_{tot}, N) data for 20 blast sequences using TBI thresholds of (a) 142, (b) 173, and (c) 204 kPa. Each plot shows envelope curves (pink), cumulative mean value (red) and cumulative SD (black) for 20 blast sequences. Plot (d) is a semi-log plot of the cumulative mean and cumulative SD versus number of blasts N.

Comparison of these 3-D results with those of a prior study [7] that used a simpler transverse 2-D section along an axial plane of the 3-D human head model are useful. The 2-D study considered random blast sequences with the same 24 blast orientations while also considering four multiple blast overpressures of 7.5, 10.0, 12.5 and 15.0 psi (51.7, 68.9, 86.2 and 103.4 kPa). The effect of these overpressure-orientation combinations are shown in Figure 8 by CPEF plots for TBI thresholds of 142, 173, and 204 kPa generated from sequences of 200 random blasts. The CPEF mean values are approximately 0.17, 0.80, and 0.03 for the three injury thresholds, lower than the 3-D results due to the additional lower blast pressures. Figure 9 shows the CPEF versus number of blasts for TBI thresholds of 142, 173, and 204 kPa and a semi-log plot of mean and SD with respect to the number of blasts N. Qualitatively similar to the 3-D counterpart in Figure 7, the CPEF parameter shows the sensitivity for smaller numbers of blasts and convergence for larger numbers of blasts.

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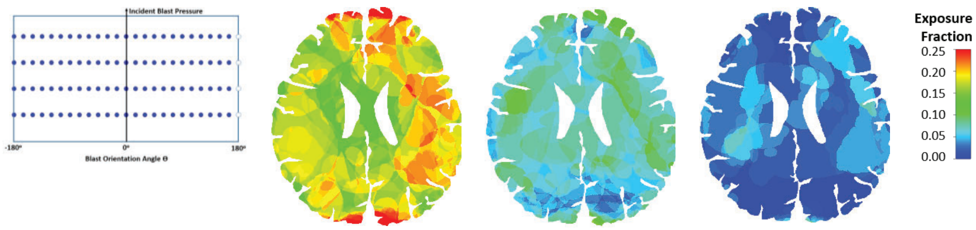

Figure 8. Monte Carlo simulations results from a two dimensions model. Uniform discrete distribution of the four blast pressures and 24 blast orientations used to construct 20 random blast sequences for N_{tot}=200, and three CPEF plots exceeding TBI thresholds of 142, 173, 204 kPa

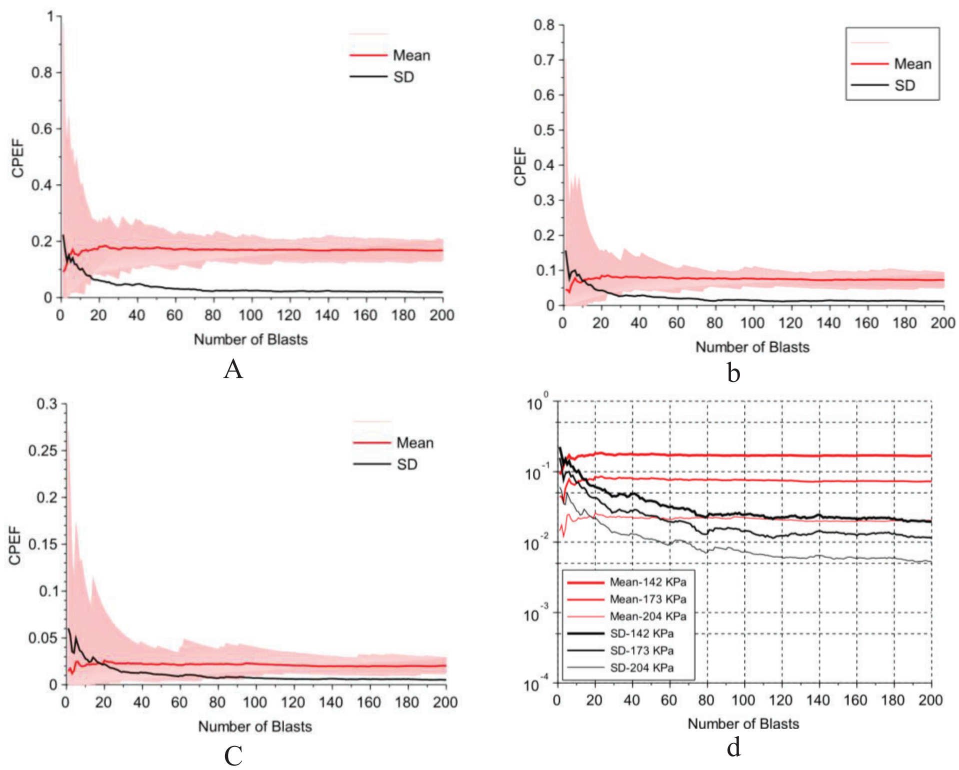

Figure 9. Two-dimensional simulation Monte Carlo results for random blast sequences showing CPEF (E_{tot}, N) data for 20 blast sequences using TBI thresholds of (a) 142, (b) 173, and (c) 204 kPa. Each plot shows envelope curves (pink), cumulative mean value (red) and cumulative SD (black) for 20 blast sequences. Plot (d) is a semi-log plot of the cumulative mean and cumulative SD versus number of blasts N.

4. DISCUSSIONS

The results presented above provide insight into the way individual blast events expose the brain to higher pressures exceeding TBI thresholds. This information is used to describe how multiple blast event exposures are accumulated by the brain. Different aspects of this and prior studies reinforce each other and quantify these trends.

From the individual blast simulations, the pressure versus time response across the brain is very heterogeneous. Pressure histories and pressure patterns vary strongly with blast orientation. Blast from the side, around +/-75 degrees, results in larger brain model injury areas than blast from other orientations. The maximum pressure encountered at each location in the brain from an individual blast creates complex patterns across the brain. These patterns include features beyond those at the typical coup and contrecoup locations associated with blast incident to the front or back of the head. For the side blast orientation the affected areas are much larger than these coup and contrecoup regions.

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The side blasts causing higher pressures in the brain can be related to the skull curvature. High skull curvature phases the contact of a planar or nearly planar blast wave normal to the head. The propagation of pressure into the head proceeds non-uniformly with a curved wave front, allowing a more phased dynamic response of the brain. Low skull curvature allows a normal blast wave to contact the head over a larger area nearly instantaneously, with propagation into the brain as a more linear wave front.

From the Monte Carlo studies of random blast sequences using the 3-D simulation data, the CPEF parameter tracks those portions of the brain exceeding a TBI injury threshold. CPEF tracks multiple blast exposures at each location in the brain and across the brain. It also captures the complex geometric overlay patterns that develop from different blast orientations (and overpressures), highlighting local regions of high and low cumulative exposure. The results confirm prior observations that the local low skull curvatures on the left and right sides make the brain more susceptible to blast injury. The CPEF itself is most sensitive, as shown by its fluctuations and range of responses, at lower values of N. The cumulative mean value is a more global measure of "dosing". Its convergence for the 3-D analyses at approximately 40 blasts means that in the range of 0 to 40 blasts each CPEF pattern in the brain model is likely to be significantly different and changing in geometry and in magnitude. The cumulative SDs converge between the first 40 and 80 blasts, depending on the TBI threshold, meaning that beyond this range the geometric patterns of exposure in the brain will stabilize and persist, total exposure will increase and average total exposure will remain the same.

5. CONCLUSIONS

A systematic, quantitative, and practical characterization of cumulative exposure of the 3-D brain model to repetitive blast events was developed using computational simulation of individual blast events and a Monte Carlo approach to random blast sequences. Results are generated in a computationally efficient manner for random blast sequences by constructing a detailed database, generated by a relatively small set of detailed finite element biomechanics simulations. This is followed by the Monte Carlo analysis that tracks cumulative exposure from multiple blast events utilizing the database.

The results highlight and quantify the likely role of blast orientations in random blast sequences on maximum pressure local values and spatial patterns across the brain. The associated mean values and SDs of the CPEF parameter, introduced to characterize the extent and repetition of high pressures exceeding different TBI thresholds, are tracked. Statistical convergence of the internal brain response metrics versus number of exposures quantitatively characterizes and highlights the cumulative effect in the repetitive blast environment.

These 3-D brain model results confirm the qualitative trends identified from prior analyses of a 2-D brain cross section model. 3-D simulations accounting for multiple blast pressures are planned. The significant variability in cumulative brain exposures in the early and intermediate portions of the repetitive blast sequences should be further analyzed and compared to the clinically observed range and severity of mTBI symptoms. The insights gained by this effort also complement and can maximize the utility of orientation data from blast sensors worn by the warfighter.

Acknowledgments

This study was supported by the Office of Naval Research (ONR) through the Naval Research Laboratory's Basic Research Program and the Department of Defense (DOD) High Performance Computing Modernization Program at the Army Research Laboratory, Air Force Research Laboratory and Army Engineer Research Laboratory DOD Supercomputing Resource Centers.

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https://doi.org/10.52202/078352-0018