FINAL REPORT

Blast and the consequences on Traumatic Brain Injury-Multiscale Mechanical Modeling of Brain

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Abstarct: A multiscale finite element analysis for the human head and brain injury analysis has been developed. At the continuum macroscale, the human head is subjected to shock loads from explosions and blasts. A multi-material ALE formulation is implemented to model the air-blast simulation. LS-DYNA as an explicit FE code has been employed to simulate this multi-material fluid–structure interaction problem. The 3-D head model is constituted of the detailed structure of the human head anatomy, including the brain, falx and tentorium, CSF, dura mater, pia mater, skull bone, and scalp. In various types of analysis, the impacts of many parameters such as the distance from the explosion site, the head orientation, neck stiffness, and the intensity of the explosive materials have been studied. At the microscale an algorithm utilizing finite element method for micromechanical characterization as well as analysis of axons and extracellular matrix (ECM) is developed to examine the Diffusion Axonal Injury (DAI) often causing the Traumatic Brain Injury (TBI). The material properties of both the axons and the ECM are assumed to have a viscoelastic behavior. The impact of parameters such as the undulations of axons as well as axon/ ECM volume fractions within different subregions of the brain has been examined.

Foreword: In this report the important subjects that have been covered in the project are briefly described. For detail information on each of these subjects in the sections/subsections, one should refer to the corresponding published papers (as listed in the list of publications of this project at the end of the report). For this purpose at each section, the publication numbers to be referred to are given prior to the brief description.

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14. ABSTRACT

A multiscale finite element analysis for the human head and brain injury analysis has been developed. At the continuum macroscale, the human head is subjected to shock loads from explosions and blasts. A multi-material ALE formulation is implemented to model the air-blast simulation. LS-DYNA as an explicit FE code has been employed to simulate this multi-material fluid?structure interaction problem. The 3-D head model is constituted of the detailed structure of the human head anatomy, including the brain, falx and tentorium, CSF, dura mater, pia mater, skull bone, and scalp. In various types of analysis, the impacts of many parameters such as the distance from the explosion site, the head orientation, neck stiffness, and the intensity of the explosive materials have been studied. At the microscale an algorithm utilizing finite element method for micromechanical characterization as well as analysis of axons and extracellular matrix (ECM) is developed to examine the Diffusion Axonal Injury (DAI) often causing the TBI. The material properties of both the axons and the ECM are assumed to have a viscoelastic behavior. The impact of parameters such as the undulations of axons as well as axon/ ECM volume fractions within different subregions of the brain has been examined.

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Contents

1: The Human Head Model, Head Constituents, Brain Materials

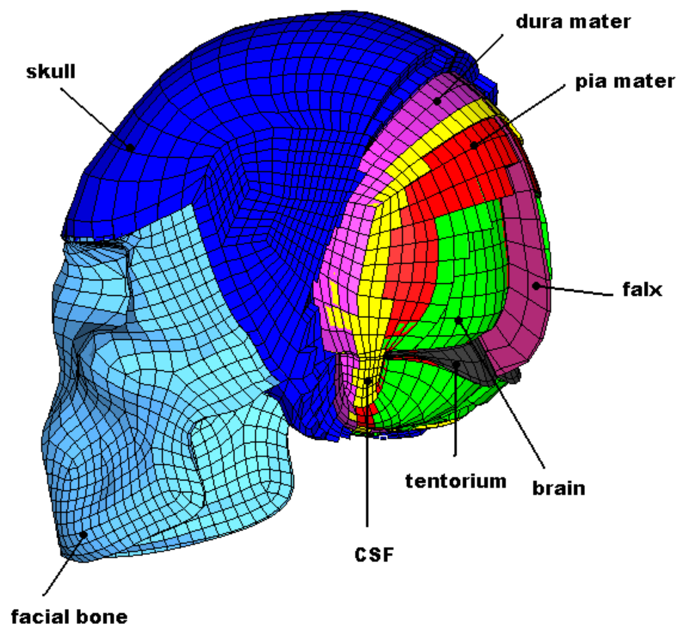
Publication #s: [9], [10], [11],

The head model used in the study contains all of the essential anatomical features of a 50th percentile male head, including the brain, falx and tentorium, cerebral spinal fluid (CSF), duramater, piamater, facial bone and skull. The geometry for this FE head model is attained from the magnetic resonance tomography (MRT) and computed axial tomography (CT) scan techniques. Figure 1 shows a prospective view of the head model used, as well as its FEM discretization. The overall model is composed of 24,933 elements and approximately 28,816 nodes.

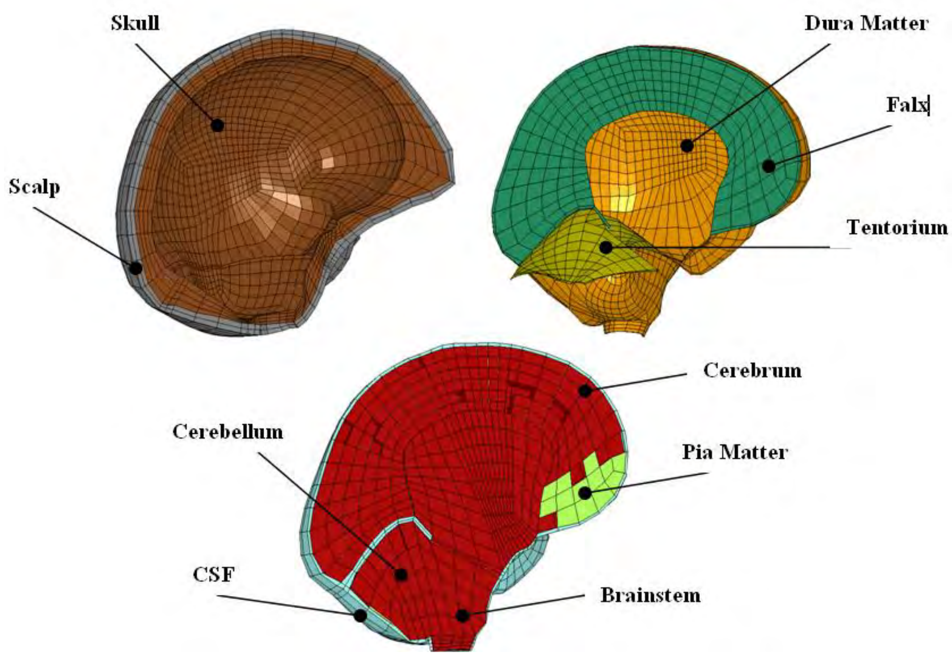
The geometrical data and anatomical structure of the human as well as the number of elements/nodes for each component is tabulated in Table 1.

Table 1. Tissue structure and the finite element model [11]

Tissue	Anatomical structure 50th percentile male	Constitutive model	Finite element model	# of Elements
Scalp	5-7 mm thick	Linear elastic	6 mm thick Solid element	4128
Skull	195 mm length, 155 mm breadth,225 mm height, 4-7 mm thick.	Linear elastic	Solid element	8256
Dura, falx, tentorium	1 mm thick	Linear elastic	1 mm thick membrane element	2609
Pia	1 mm thick	Linear elastic	1 mm thick membrane element	2786
CSF		1- Linear elastic with ‘fluid’ option 2- solid Element with low Shear and High Bulk Modulus 3- Viscoelastic	1.3 mm thick solid element	2874
Brain	165 mm length 140mm transverse diameter	Hyperviscoelastic	Solid element	7318



(a)



(b)

Figure 1. (a) A perspective view of the head model showing different regions and elements of the brain in discretized finite elements. (b) Sections of the head model; the right half of the head model is shown with the brain, the meningeal layers (dura mater with falx and tentorium) and the scalp and skull separated. [9,11]

1.1 Brain Interfacial Regions Modeling

Publication #s: [9], [10], [11]

The interfaces between the components are described by contact conditions. CSF is modeled as a layer of fluid separating the brain from the skull, and acting as a natural shock absorber for the brain and an interface enabling relative motion between the skull and the brain. It is modeled as a layer of eight-nodded solid elements with fluid-like property. This property, which allows brain relative movement during impact loading, does agrees with the impact experiments. The interface between the dura, tentorium and falx is defined as tied node-to-surface contact. These components are physically adhered to each other. Tied contact algorithm is suitable for the brain-membrane interfaces because it can transfer loads in both compression and tension, while only compression loads are transferred in penalty contact algorithm and a gap is created in the contrecoup region where tensile loading is possible in frontal impact. Also, tied contact algorithm with offset in between skull/dura, dura/CSF, CSF/pia and CSF/pia interfaces, was implemented.

1.2 Constitutive Materials of the Head and Brain Regions

Publication #s: [11], [9], [10]

In literature of biomechanics in modeling of the human head a wide range of material properties and constitutive laws (linear elastic to non-linear hyper-viscoelastic) has been assumed to model and characterize the material behavior of the brain tissue. Recent developments in experimental characterization of brain tissue points towards a hyper viscoelastic material type behavior. We assumed linear viscoelastic as well as hyper viscoelastic behavior for the brain in the modeling procedures. Linear elastic material behavior is assumed for skull, facial bone, dura mater, pia mater, falx, and tentorium membranes. Table 2 shows the material properties of the head and brain.

Table 2 [9]

a) Material characteristics for scalp, skull and membranes

Elastic Material Properties	Density ρ kg/mm^3	Young Modulus E (MPa)	Poisson's ratio, v
Scalp	1×10^{-6}	16.7	0.42
Skull	2.1×10^{-6}	15000	0.23
Dura, Falx and tentorium	1.13×10^{-6}	31.5	0.45
Pia Matter	1.13×10^{-6}	11.5	0.45

b) Hyperviscoelastic parameters for the brain [9]

Hyperviscoelastic parameters	C_{10} (Pa)	C_{01} (Pa)	G_1 (KPa)	G_2 (KPa)	β_1 (s^{-1})	β_2 (s^{-1})	K (GPa)
brain	3102.5	3447.2	40.744	23.285	125	6.6667	2.19

2. Validation of the Modeling of the Blast - Human Head Interaction

Publication #s: [10, [11]

A fluid-solid interaction algorithm has been implemented to model the blast, and generate the shock blast waves in interaction with the human head exposed to such a scenario. The overpressure shock waves created by the explosion has been compared with the experiments and have been verified. Figure 2 shows the finite element mesh generated for the explosion. Figure 3 shows the propagation of a shock wave in the air medium at times after the detonation of the high explosive.

In Figure 4 a close agreement of the experimental and the numerical overpressure created due to a blast is shown. In Figure 5, a schematic representation of the blast and human head model is shown. In this figure the head model is located in the free space, confronted to the blast waves at a distance from the high explosive blast. In the inset, the pressure contour on the entire model is shown at the instant when the blast wave, due to the blast, strikes the head. Fringe levels in the inset figure represents the pressure level. In Figure 6, a typical shear stress distribution of the entire brain in the head model on a sagittal section at distinct times after the blast-head impact is shown. Shear stress is a parameter to be monitored during any impact to the brain.

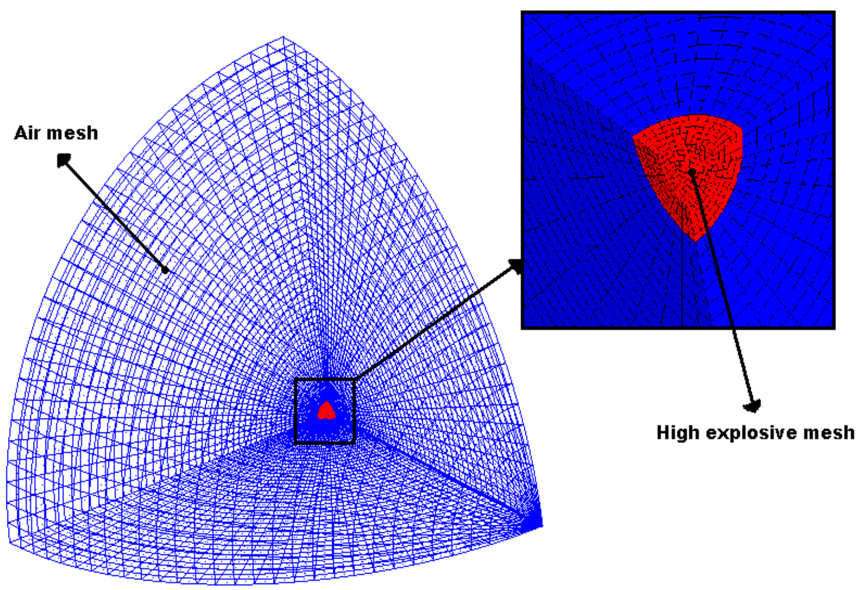


Figure 2. FE mesh of air and high explosive used in the study. Both the air and the high explosive are modeled in the form of a sphere, and the high explosive sphere is the small sphere shown in the inset. The radius of the sphere is 2.117 *cm* with a total of 485 elements. The radius of the air sphere is 695.733 *cm* and contains a total of 67,512 elements[10].

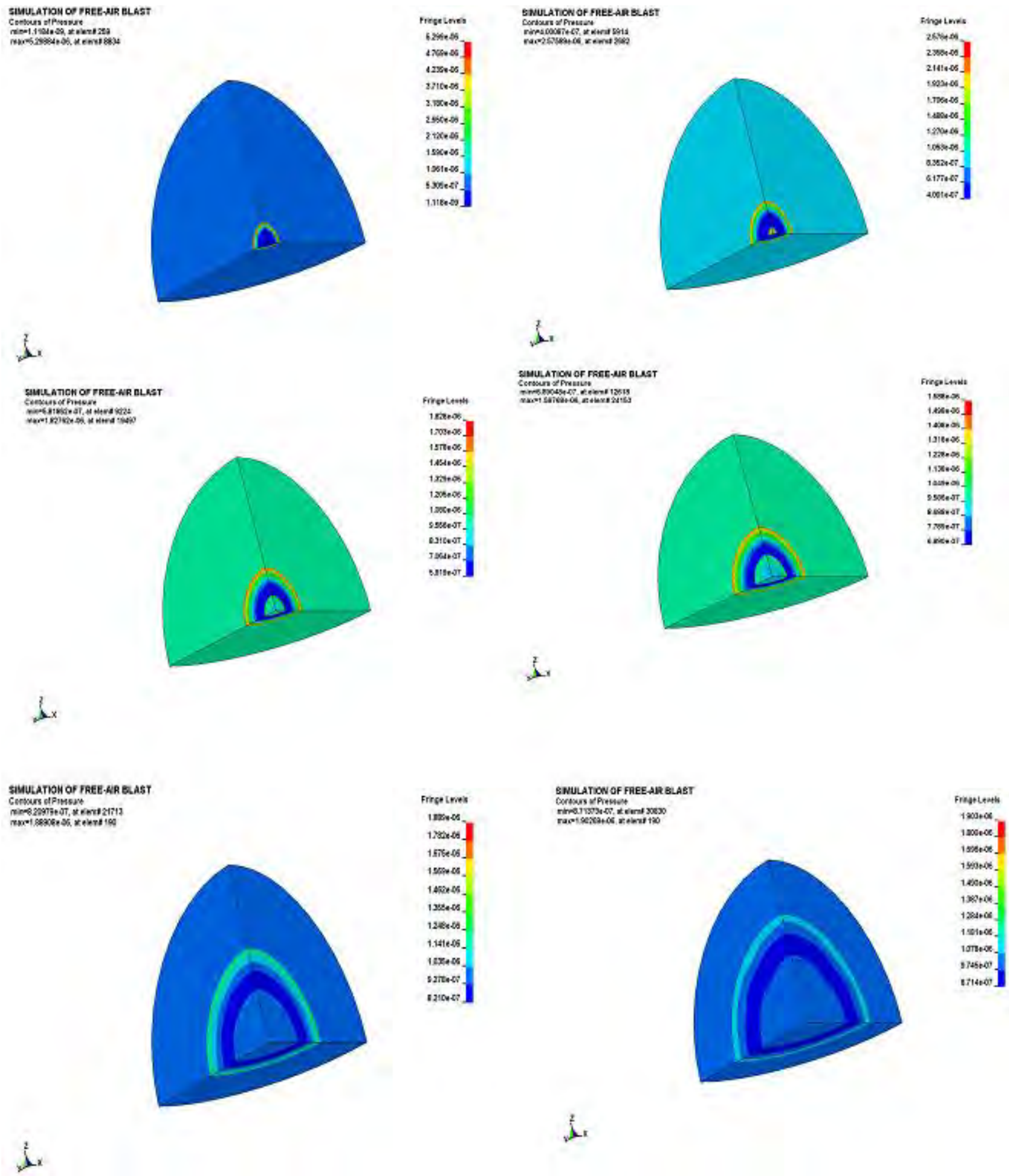


Figure 3. The propagation of a shock wave in the air medium at times after the detonation of the high explosive. The intensity of the blast used is 1 *lb* TNT and it is an open air blast model (i.e. surrounding medium is a open field) [10].

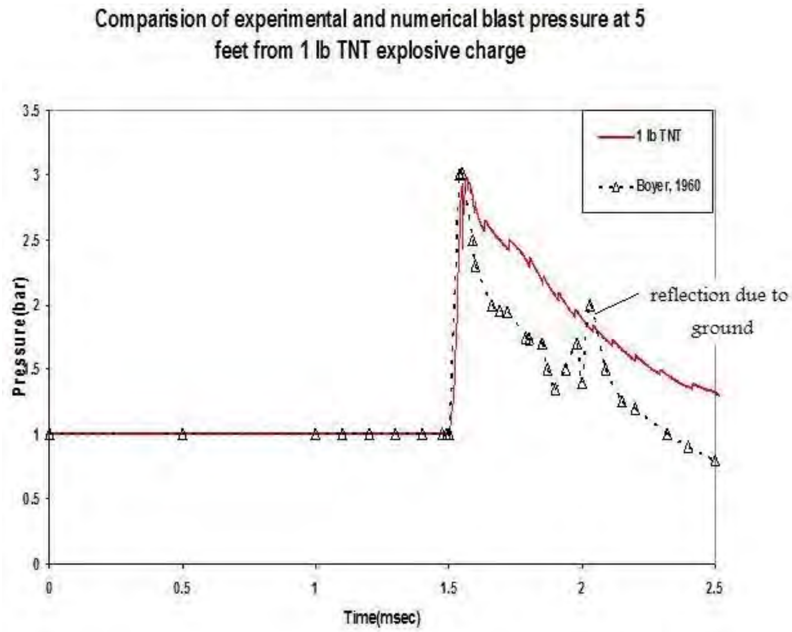


Figure 4. Comparison of experimental and numerical overpressure. The experimental curve presents a peak overpressure of 3.02 *bars* at approximately t = 1.5 *ms*. The numerical overpressure curve correlates well with the experimental results [10].

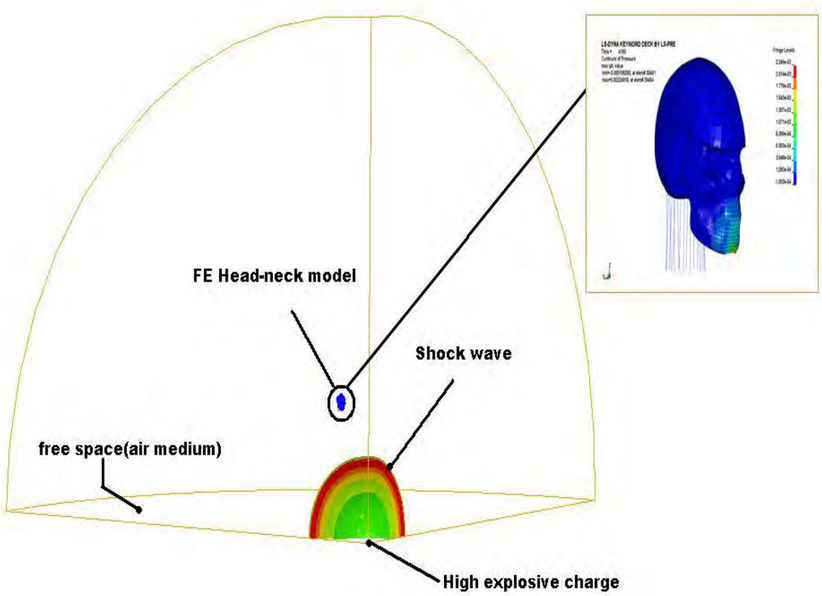


Figure 5. Schematic representation of the blast model. The head model is located in the free space, at a distance of 2 *m* from the high explosive material of 1 *lb* TNT. The blast wave produced from the high explosive material will strike the head model at around 4.1 *ms* of the simulation time. In the inset, the pressure contour on the entire model is shown at the instant when the blast wave, due to the blast, strikes the head. Fringe levels in the inset figure represents the pressure and it is represented in *Mbar* (i.e, 100*GPa*)[10].

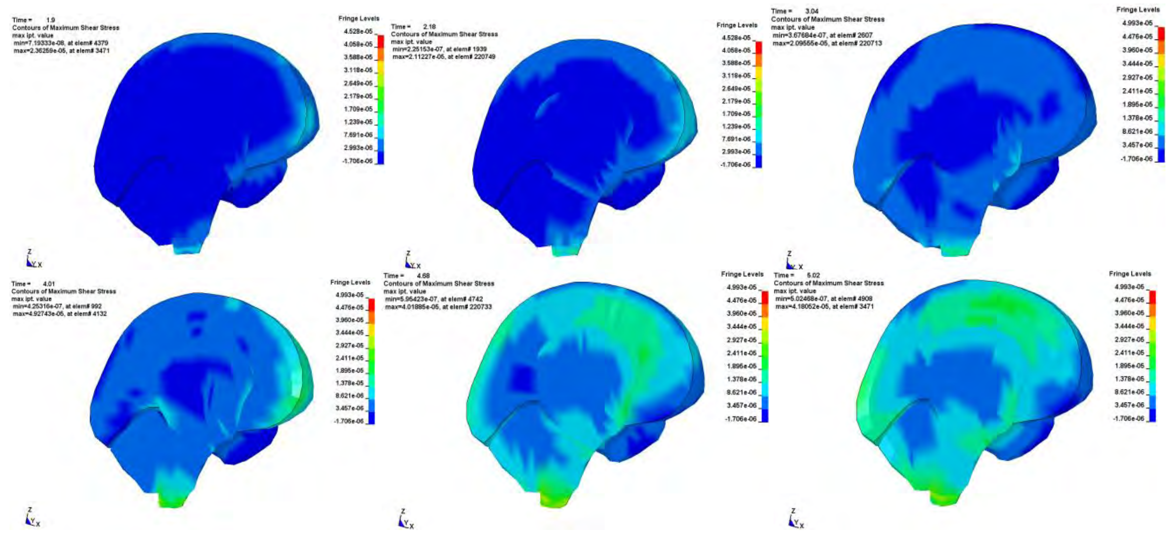


Figure 6. Typical maximum shear stress distribution of the entire brain in the head model on a sagittal section at distinct times (t=1.9,2.18,3.04,4.01,4.68,5.02 ms) after the blast-head impact[11]

3. Simulations under Impact Loading

Publication #s: [9], [13], [14], [41], [43]

Various simulations for head under impact loads have been carried out to verify the modeling procedure, and to study the influence of various conditions and assumptions related to material characteristics of the brain and other constitutive elements of the human head. For the validity of the algorithms the head is exposed to the Nahum head test scenarios.

4. Simulations under Blast Shock Waves

Publication #s: [9], [10], [11], [41], [43]

At many blast scenarios and under various conditions the head model has been exposed to shock waves due to blast. The response of the head and brain has been studied and the impacts of the following influencing parameters have been examined.

(a) intensity and the size of the explosive material. As a typical result Figure 7 shows the time-history of maximum principal strains at the corpus callosum and brainstem in the head for three explosive scenarios at a particular distant from the explosion. It is clear that increasing explosive material causes higher overpressure which in turn causes more severe injury to the head and brain.

(b) distance of the human head from the explosion center.

(c) Material property of the brain, In Figure 8, the resulting relative displacements for a cluster of the brain due to the air overpressures due to explosion are shown. In this figure the results for different material behavior assumption for the brain has been examined.

(d) orientation of the exposed human head. Figure 9 shows time-history of the average intracranial pressure of the brainstem, corpus callosum and cerebellum for three explosive scenarios with different head orientations.

(e) head with and without neck stiffness. This will be explained in more detail the next section.

(f) human head in open-space blast and in closed space. The head has been exposed to both open space explosion and explosions within barriers.

(g) time history of mechanical responses. The wave propagation and the response of the head is a time-dependent type problems. In all the analysis carried out the data have been gathered from the time span in aftermath of the blast explosion.

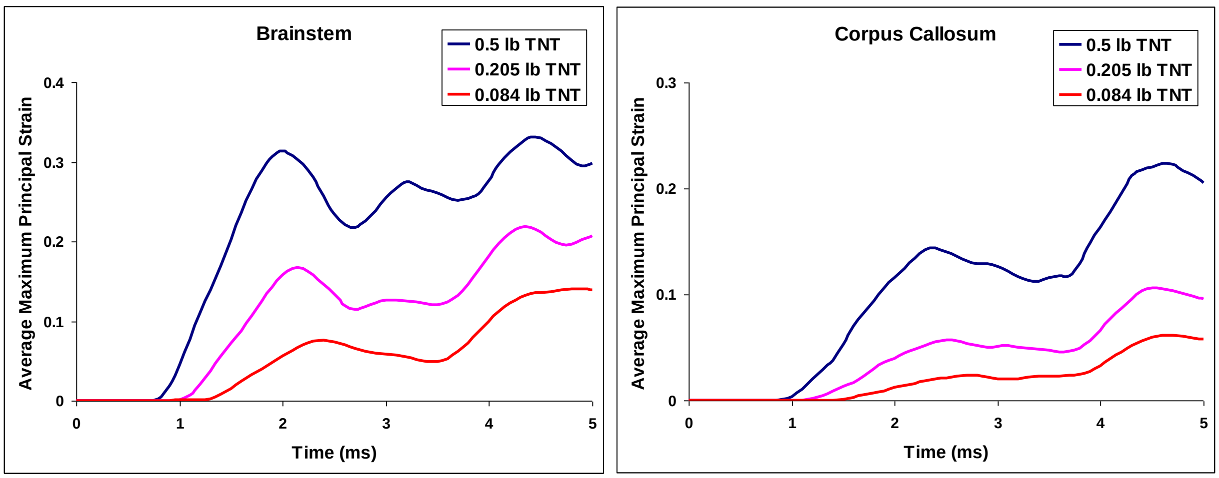


Figure 7. Time-history of maximum principal strains of the distinct brain regions (corpus callosum and brainstem) in the head model for three explosive scenarios[43].

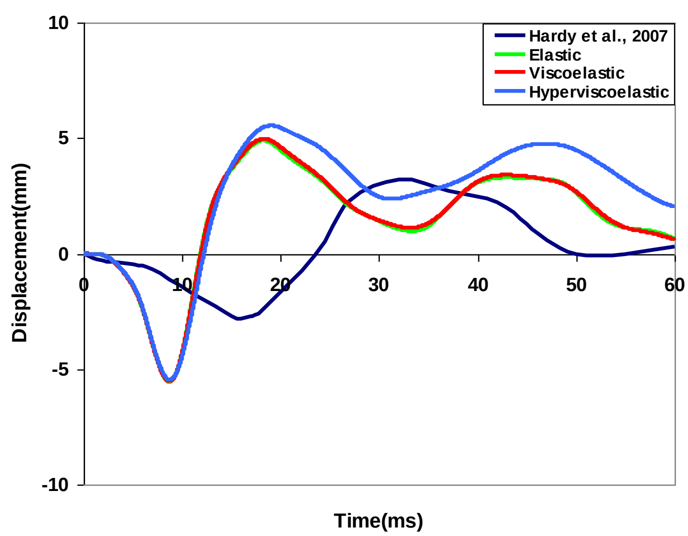
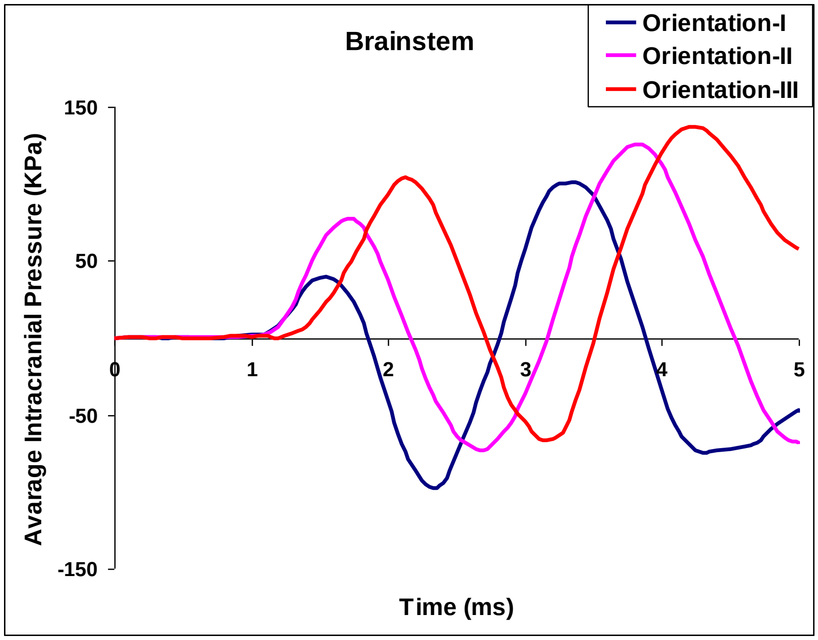


Figure 8. Relative displacement-time histories for two clusters of a particular test with brain material as linear, linear viscoelastic and hyperviscoelastic behavior assumption [43].



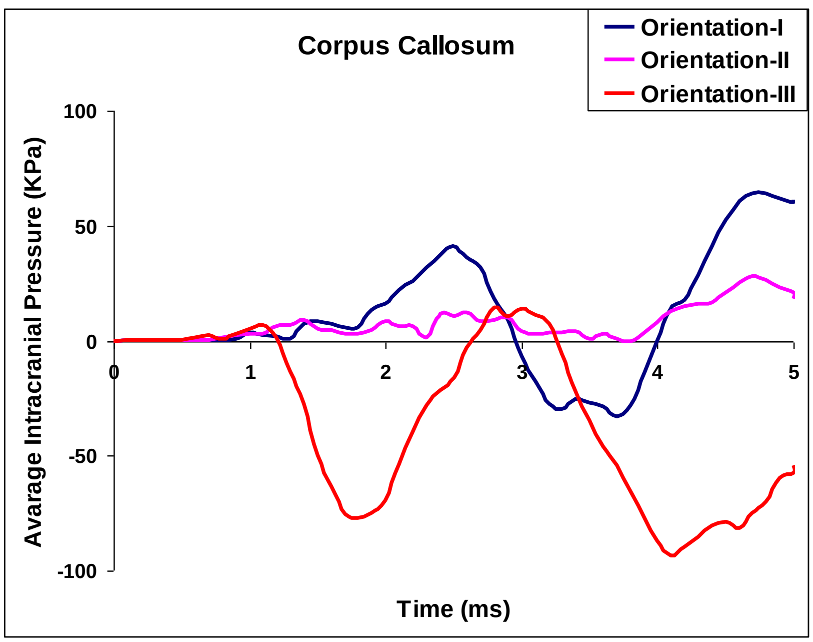


Figure 9. Time-history of average intracranial pressure of the brainstem, and corpus callosum for three explosive scenarios with different head orientations [43].

5. Biomechanics Study of Influencing Parameters for brain under Impact

5.1 The Impact of Cerebrospinal Fluid Constitutive Properties

Publication #s: [9], [43]

In modeling of the human head the role of CSF is dominant and should be included in any type of analysis. A comprehensive parametric study was carried out to examine the sensitivity of CSF properties on the brain dynamic response under impact loading. A fluid-like property for the CSF provides a good correlation to the cadaver experiments. In Figure 10, the results for different values for a fluid-like CSF are plotted in comparison with the experimental values on cadaver.

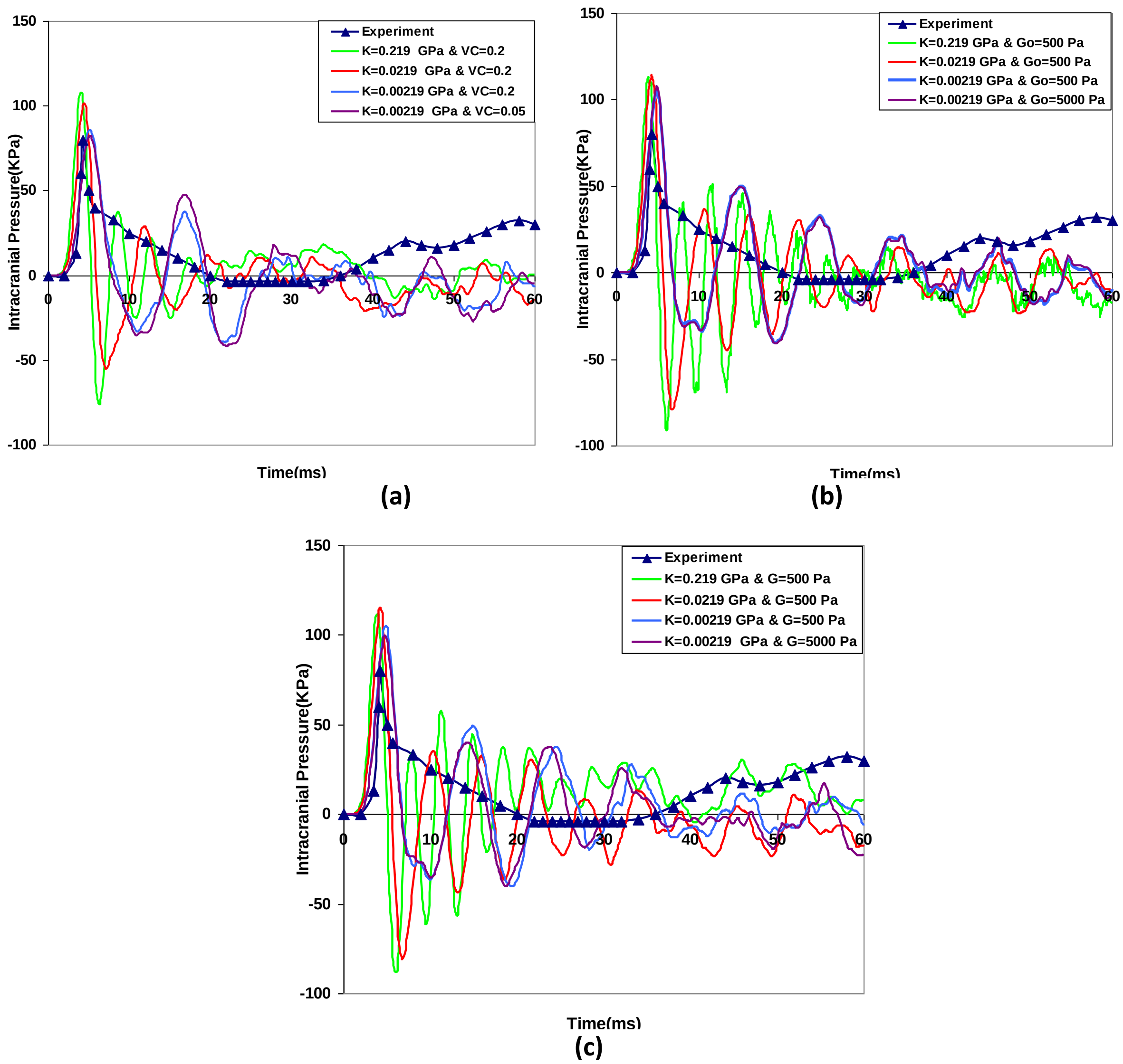


Figure 10. Comparison of the intracranial pressure-time history. CSF was modeled as,

(a) fluid-like elastic behavior material with different values for bulk modulus and viscosity,
(b) viscoelastic material behavior with different values for bulk and shear modulus, and
(c) elastic material with low shear modulus and high bulk modulus for different values of bulk and shear modulus [9].

5.2 The Impact due to Neck Stiffness

Publication #s: [13], [14], [41]

The impact of the rest of the body and in particular the neck is important on the response of the head and brain under insult. A Kelvin-Voigt viscoelastic material model has been assumed for the neck material. To determine the stiffness of linear elastic springs and the damping coefficients of the dash pots, various studies on material properties of neck ligaments, cervical discs, hybrid manikin III necks, and human cadaver spines were examined. Based on the experimental data regarding the stiffness values of human cadaver spines, hybrid III manikin necks, neck ligaments and cervical discs, four different neck stiffness values (K) were selected, ranging from a model with no neck stiffness to a neck with very high stiffness. The values of total stiffness (K) for the considered scenarios therefore, were assumed to be in the range of 1.8, to 1800kN/mm. Also non-linear viscous behavior dampers were employed to present the damping properties of the neck. The damping coefficient value (*C)* of each damper in the neck was assumed to be less than the damping coefficient value of rubber. The damping coefficient values of each damper in the neck for the three scenarios were chosen to be 0, 0.05, and 0.2 *(kN.ms)/mm*), respectively (Figure 11).

In Figure 12 and 13, the time histories of the coup and conter copu intracranial pressures, for different neck damping coefficients during impact load have been plotted. These curves are plotted based on the occurrence of coup/contercoup pressures in the brain. The coup pressure occurs in the frontal lobe of the brain, as shown in the inset. The coup pressure is plotted, therefore, from the frontal region of the brain. In Figure 14, shear stress distribution on the sagittal section of the brain for different simulations at 8.1 ms, after the impact load is plotted for different values for the neck stiffness and damping coefficient.

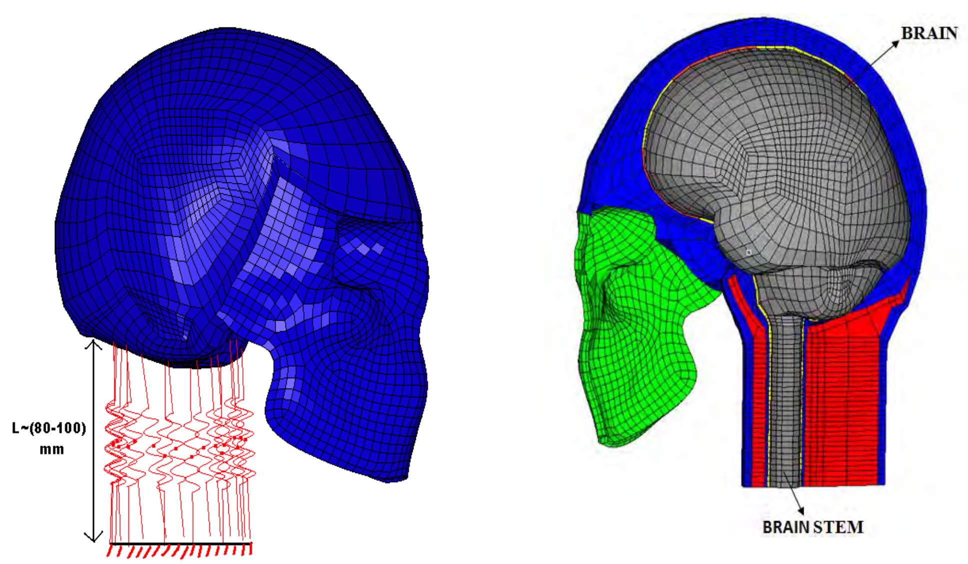


Figure 11. Schematic representation of side view of the FE model with the neck modeled as stiffened spring (a) and (b) as modeled as a continuum stiffened tissue [41].

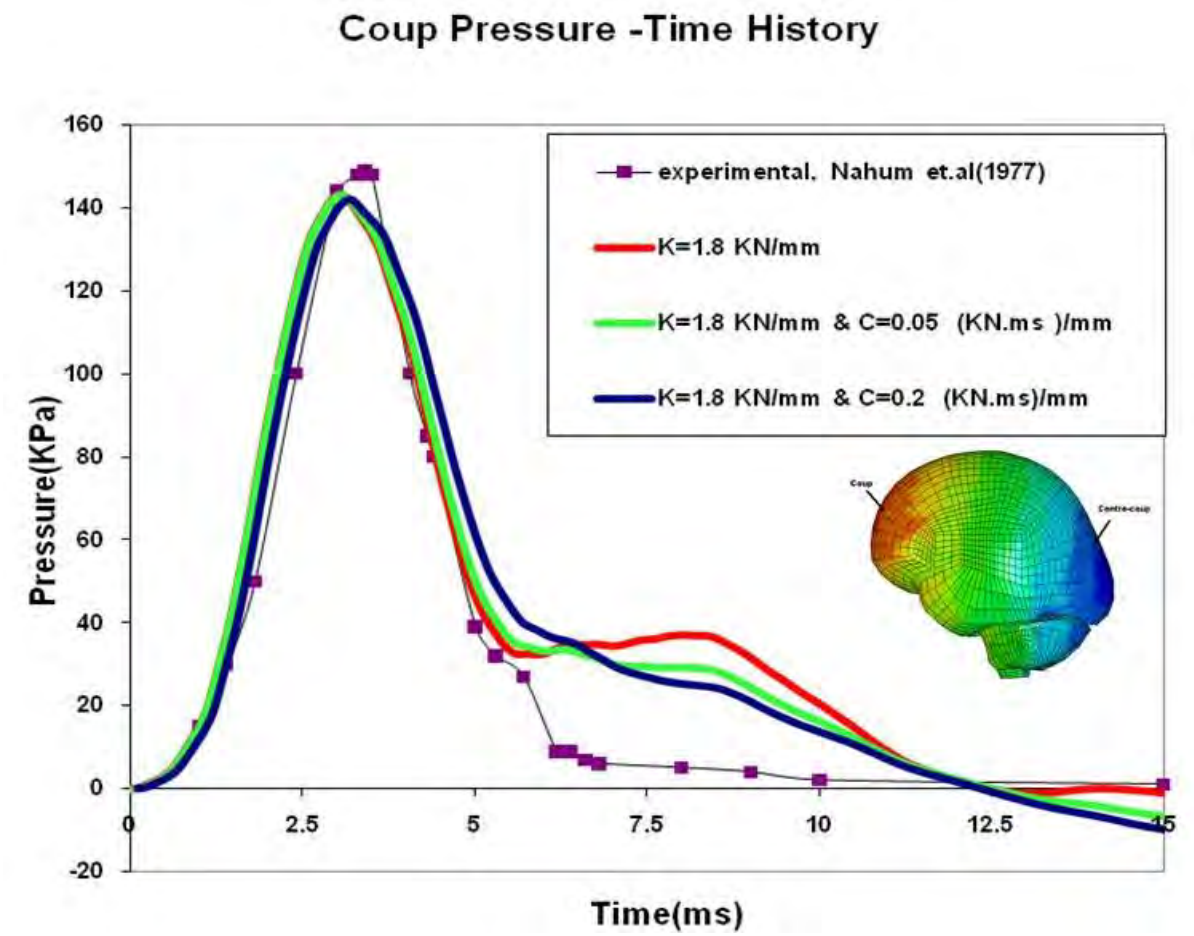


Figure 12: Time histories of the coup pressure, for different neck damping coefficients during impact load. These curves are plotted based on the occurrence of coup pressures in the brain. The coup pressure occurs in the frontal lobe of the brain, as shown in the inset. The coup pressure is plotted, therefore, from the frontal region of the brain[14].

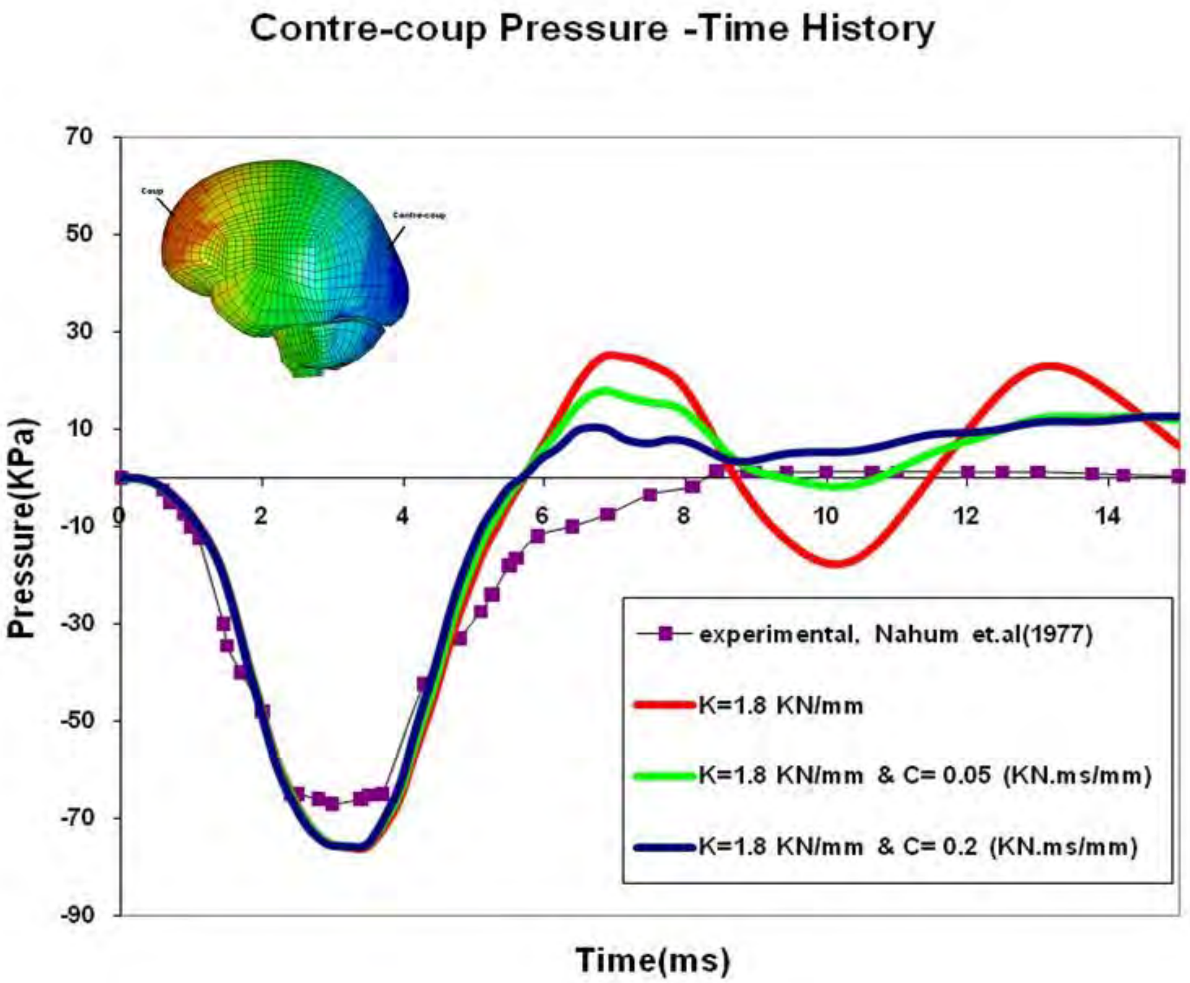


Figure 13: Time histories of the contre-coup pressure, for different neck damping coefficients during impact load. These curves are plotted based on the occurrence of contre-coup pressures in the brain. The contre-coup pressure occurs in the occipital lobe of the brain, as shown in the inset. The contre coup pressure is plotted, therefore, from the occipital region of the brain [14].

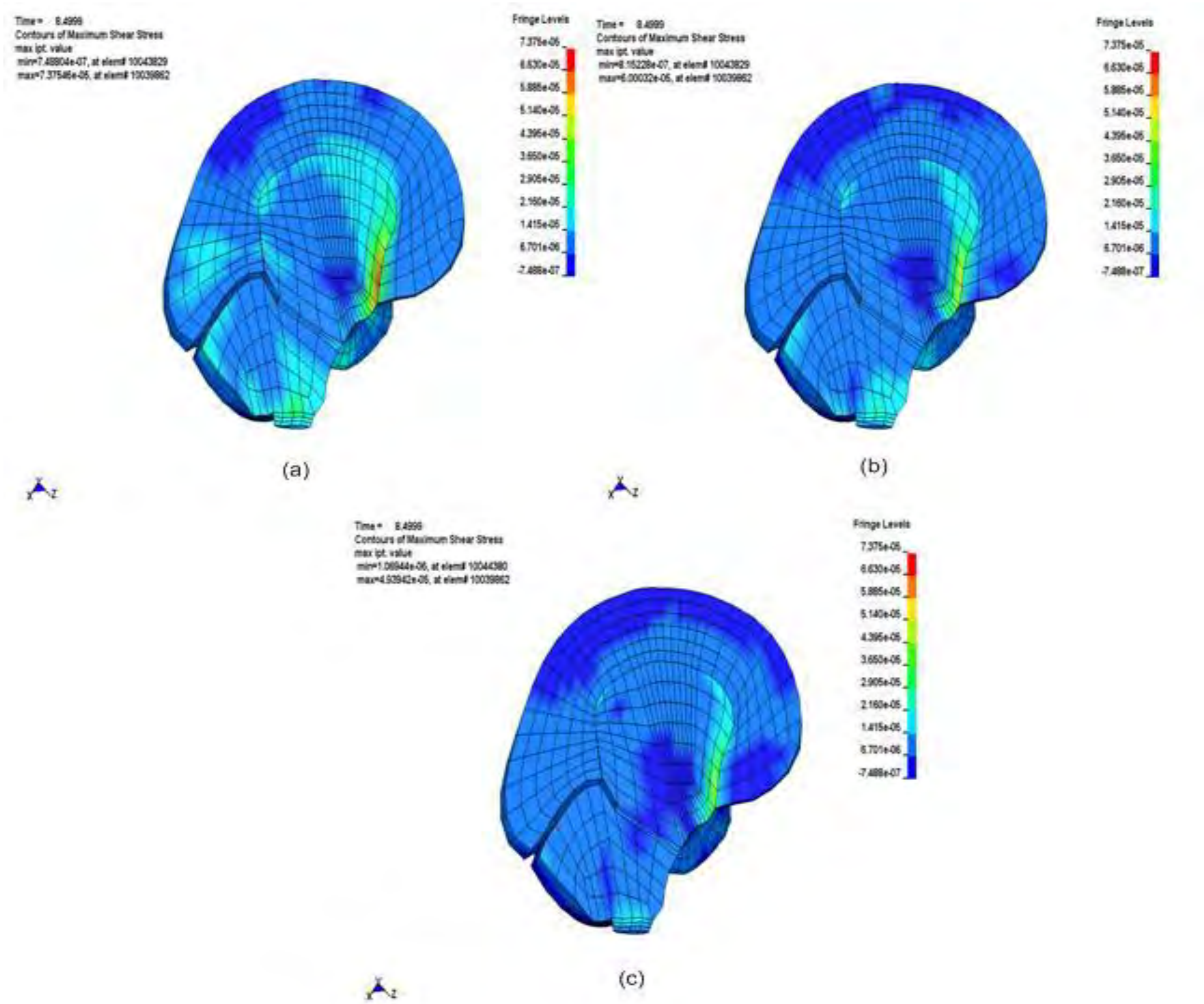


Figure 14 Shear stress distribution on the sagittal section of the brain for different simulations at 8.1 ms, after the impact load is applied. Fringe levels in this figure represent the shear stress, and the units for fringe levels are GPa. Maximum and minimum values of fringe levels in above figures are set to equal, to better distinguish the behavior of the brain.

(a) Model without any dampers, neck is modeled with only springs, K =1.8 *kN/mm.*
(b) Model with dampers K = 1.8 *kN/mm* and C = 0.05 *(kN.ms)/mm*.
(c) Model with dampers K = 1.8 *kN/mm* and C = 0.2 *(kN.ms)/mm*.[41]

5.3 The Brain Injury in Open Air Blast or Closed Area Blasts

Publication #s: [10], [11]

The impact of any barrier to shock wave propagation should be studied and consequently examine the impact on the brain exposed to such situations. The validated numerical air blast model can be thus considered as a tool to get the response of a human head under various blast scenarios. This has been done and the impact of walls in front of explosions was studied. As shown in Figure 15, one can see if there is a wall in front of the shock waves, the trend in the overpressure distribution will change depends on the close vicinity of the wall to the explosion center.

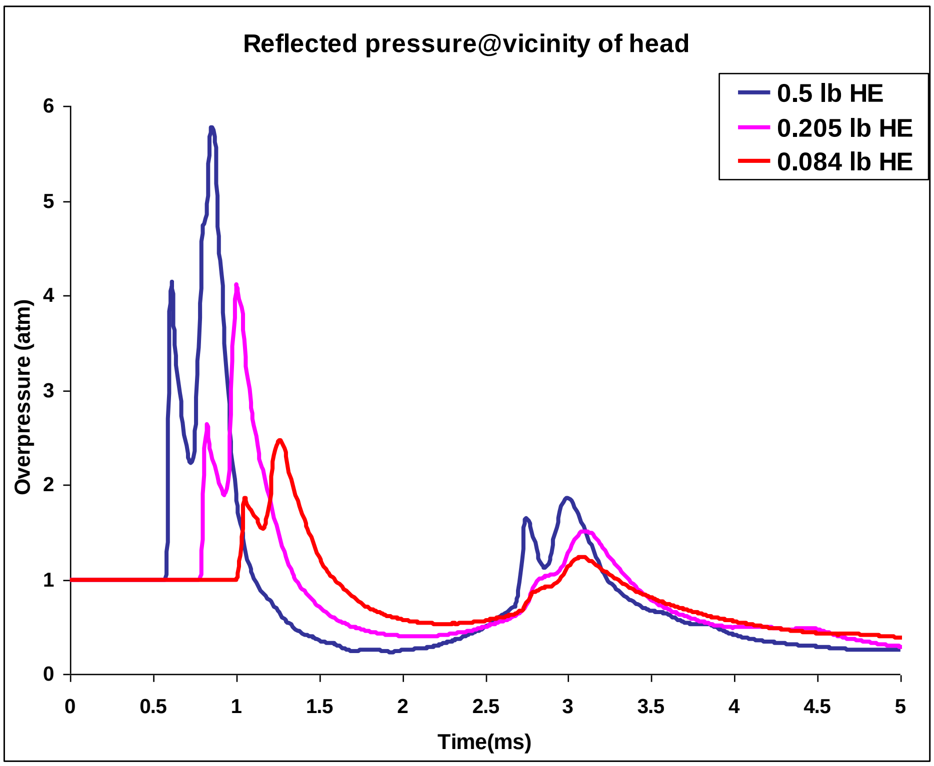


Figure 15. Resulting air overpressure of an element at the vicinity of the head for the various blast scenarios [10].

6. Micromechanics Modeling of the Brain Tissue

Publication #s: [6], [7], [12], [22], [23]

Diffuse axonal injury (DAI) is a devastating type of brain injury. DAI is characterized by microscopic damage to axons throughout the white matter of the brain and focal lesions in the corpus callosum and rostral brainstem. Damage to the white matter, as a consequence of brain and spinal cord injury, is the largest contributor to a poor neurological outcome in survivors of brain and spinal cord trauma. Microscale understanding of such injuries needs in-depth knowledge of brain material characteristics and brain microstructure response to different mechanical loadings. Mechanical properties and characterization of brain at macroscale and in bulk has been a subject of many medical as well as engineering investigations. But at microscale analysis, the subjects needs in-depth investigation.

In this project, a finite element micromechanics algorithm analysis for a brain made of heterogonous matter was developed. In the characterization procedure the material properties of the axons and the extracellular matrix (ECM) has to be primarily found as input data. Both axons and the matrix are assumed to have linear viscoelastic behavior. The results of the modeling have been validated with some experimental data. The influences of parameters such the undulations of the axons as well as the volume percentage within the subregions of the white matter were examined. Different unit cells composed of wavy geometries and with various volume factions were exposed to the loading scenarios. The results showed that the stresses and strains in the axons and ECM under loading will be impacted by undulation change. With increase in undulation the matrix suffer higher stresses when subjected to tension, whereas axons suffer higher stresses in shear. The axons always exhibit higher stresses whereas matrix exhibit higher strains. The evaluated time-dependent local stress and strain concentrations within a repeating unit cell (RUC) of the material model are indicative of the mechanical behavior of the white tissue under different loading scenarios.

6.1 The Unit Cell Modeling of Brain White Matter

Publication #s: [6], [7], [12],[22], [23]

In Figure 16 (a), a histology slide is shown which represents the axonal distribution inside the brainstem. The conventional hexagonal packing of the axons within the composite tissue is used to represent the repetitive distribution of axons inside the extracellular matrix. The hexagonal distribution of axons for a unit cell of the composite tissue is shown in Figure 16(b). Although for analysis different volume fractions of axons were considered to study the effect of volume fraction on the overall behavior of the composite tissue, however 53% volume fraction was considered to do most of analysis. The undulations of the axons were considered to be a major parameter where the undulation ratio was defined as the ratio of length of sinusoidal curve to the wavelength.

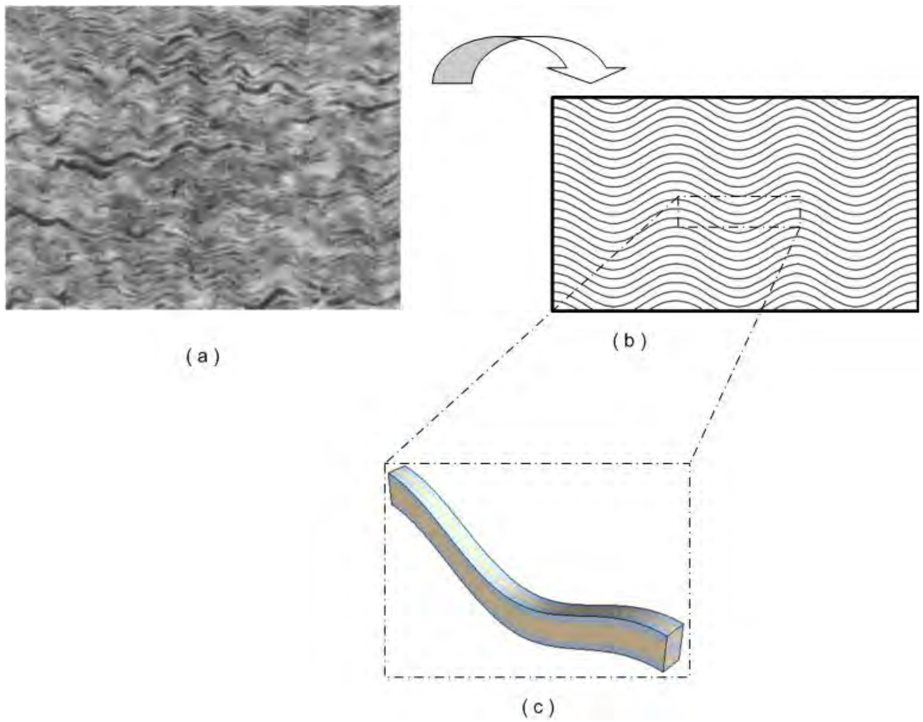


Figure 16. Slides of guinea optic nerve microstructure with the distribution of undulated axons inside the extracellular matrix, (b) simulated periodic sinusoidal wavy distribution of axons, with the corresponding periodic unit cell, and (c) RUC representing wavy periodic microstructure of the composite tissue [6]

6.2 Axonal Injury and ECM Interface Modeling

Publication #s: [6], [7], [12],[22], [23]

The response of the tissue composed of ECM and axon subject to stretch has been examined. In Figure 17, the composite with different values of axonal concentration (V_f) due to a uniaxial stretch in the axon direction. The Lagrangian stresses are compared with experimental results for the corpus callosum. In Figure 18, the contour stresses for tensile stresses in an undulated repeated unit cell of the tissue under the stretch are plotted in the ECM, axon and the composite tissue for a specific value of undulation.

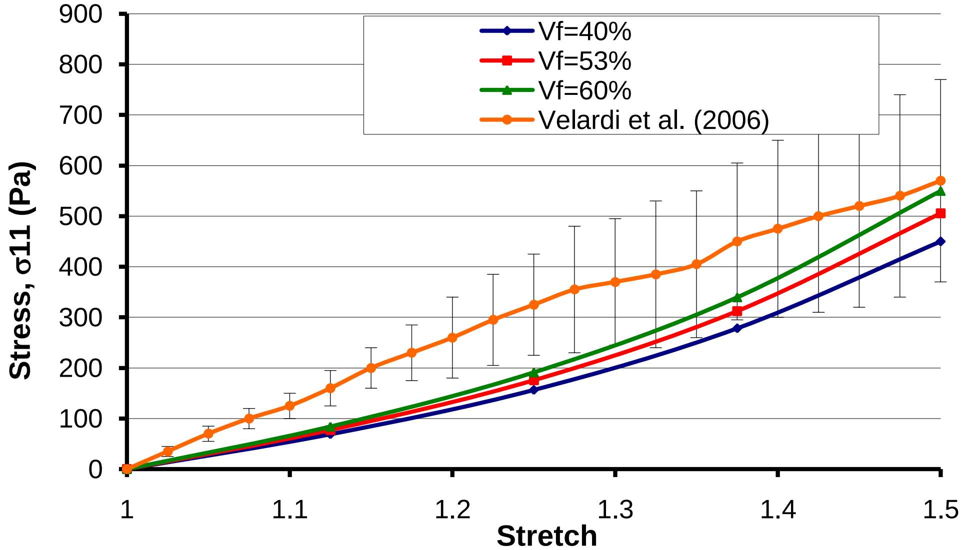


Figure17. The response of the composite with different values of V_f to a uniaxial stretch in the axon direction. Stresses are given in terms of Lagrange stresses as compared with the experimental results for the corpus callosum (Velardi *et al*. (2006) [6].

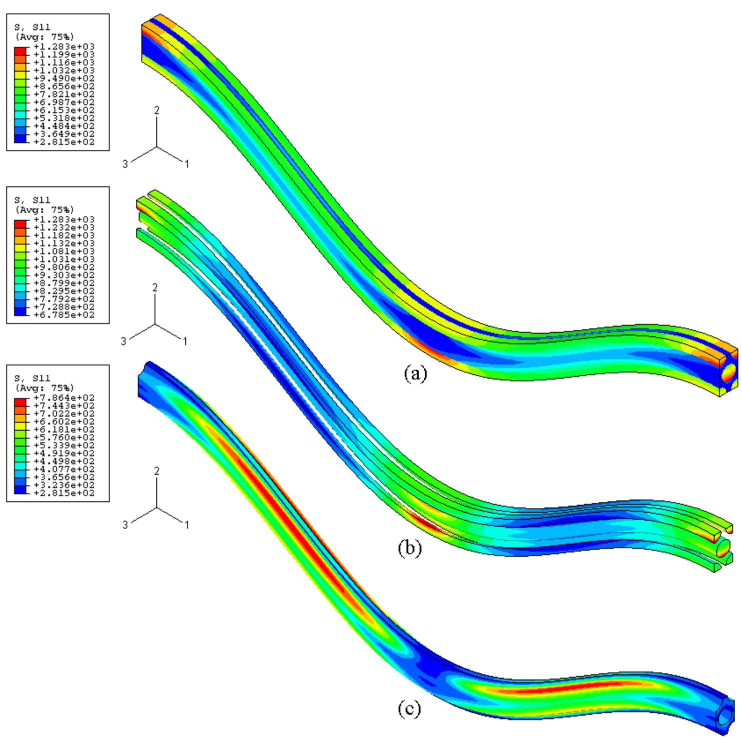


Figure18. Contour stress plots showing the tensile stresses in an undulated RUC that is stretched in the direction of the longitudinal axis of the axon. The composite (a), the axon (b), and the matrix (c) are shown for *U3* at a stretch of 1.5 [6].

6.3 Cellular Modeling under Impact Loading

<u>Publication #s: [5], [18],</u>

Cell injury happens due to deformation and stresses under mechanical loadings. In this project a unit living cell is formulated and analyzed under impact loading. The influences of the cell constituent elements mechanical properties have been examined. The unit cell is composed of cytoplasm, nucleus and membrane and the pre-stressed cytoskeleton. A three-dimensional finite element algorithm is employed to simulate the biomechanical behavior of this individual cell. As shown in Figure 19, the cell is composed of a combination of the continuum and microstructural (tensegrity system). The response of the model is studied with, and without, the inclusion of the microstructural system. The influence of the tensegrity infrastructure system on load transferring properties of the cell has been studied. Viscous behavior of the components of the unit cell in the tensegrity microstructure (microfilament and microtubules), as well as in the continuum part of the model were examined in detail. It has been shown that the viscose microtubules do not influence much on the deformation of the system. The elastic stiffness of the nucleus has also been examined. A typical dynamic response of the unit cell under different viscous properties of microfilaments and microtubules are shown in Figure 20.

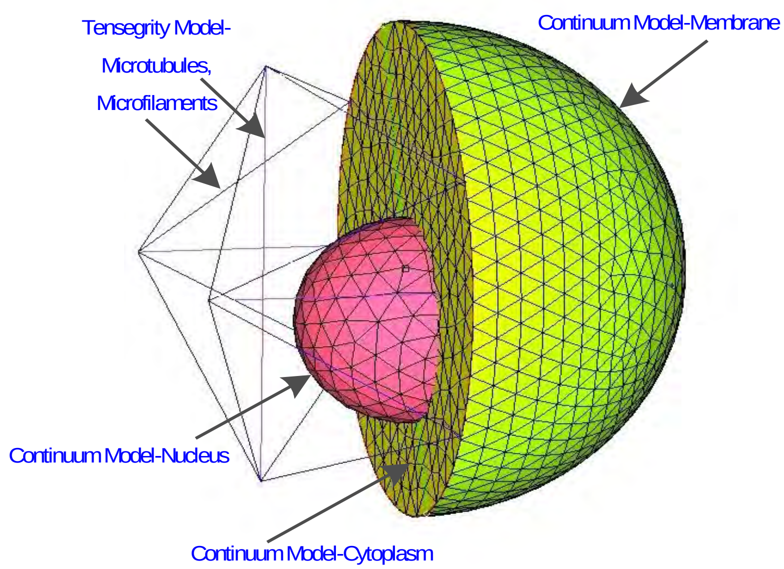


Figure 18. Continuum model with cytoplasm and the nucleolus [5]

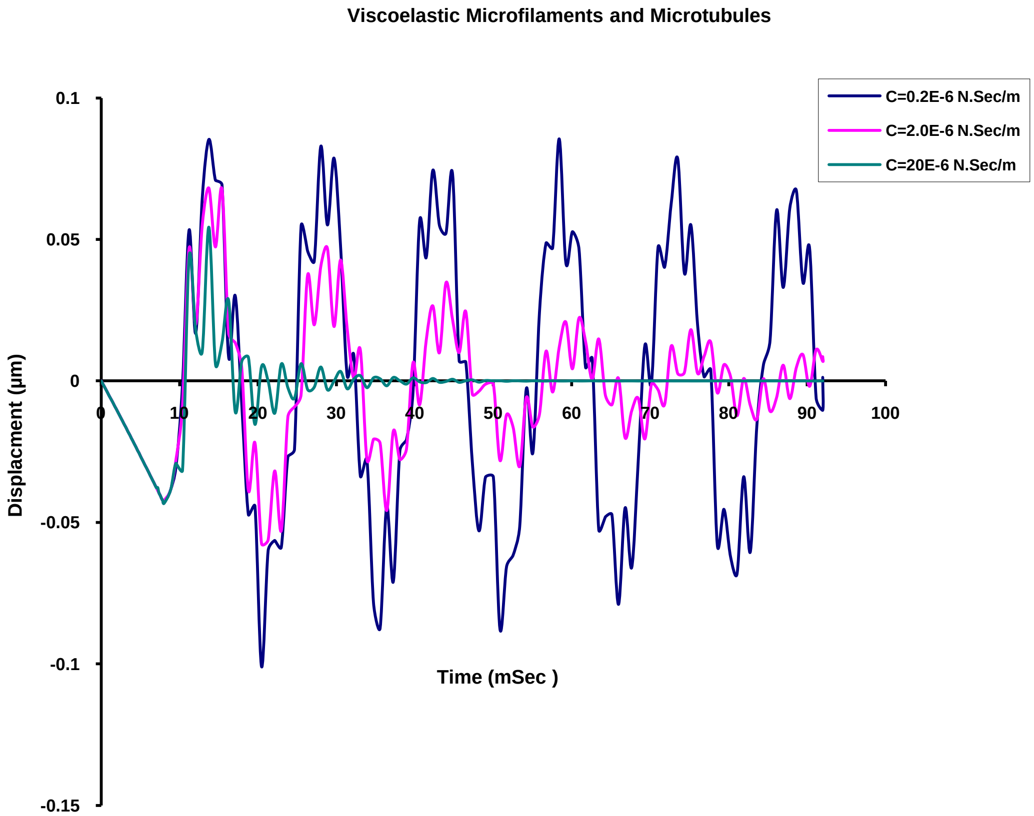


Figure 19. Dynamic response of the tensegrity system with assigning both microtubules and microfilaments as viscose materials [5]

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