HONOR PLEDGE

"I pledge on my honor that I have not given or received any unauthorized assistance on this assignment."

Investigating Traumatic Brain Injury: Correlating External Pressure Distributions to Internal Injury

TEAM BLAST

Blast Localization and Sensing Technology

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I. ABSTRACT

Development in military protective equipment has lead to decreased soldier mortality as a result of better protection from the effects of explosive blasts without providing protection from closed-head Traumatic Brain Injury (TBI). In this study, we expand upon the current methods of blast-induced TBI detection. We hypothesize a correlation exists between the static pressure over the surface of the skull and the responses of brain tissue. We will use physical simulations of scaled-down blast waves to observe the pressure distribution over the surface of a headform. A computer model will simulate the material responses of brain tissue during simulated blast events. Our conclusions can be used in the production of functional models to diagnose blast-induced TBI.

II. INTRODUCTION

A. Background

During World War I, 80,000 officers and soldiers were diagnosed with mental disabilities resulting from their service in the military [1]. At the time, doctors were unaware of the cause of this phenomenon and termed the soldiers' condition "shell shock" [2]. Soldiers diagnosed with shell shock experienced amnesia, difficulty concentrating, headache, dizziness, sensitivity to loud noises, ringing in the ears, and uncontrollable shaking. As hospital treatment did not alleviate the patients' symptoms, doctors believed that the soldiers had become insane due to their war experiences [3]. However, as scientific research progressed, medical insight revealed that shell shock is the result of internal head injuries caused by pressure waves produced by an explosion [2].

The scientific community has determined that battlefield explosions caused by Improvised Explosive Devices (IEDs) can harm soldiers by generating blast waves, which are high energy pressure disturbances consisting of highly compressed air molecules (see Appendix B) [4]. When a person is impacted by a blast wave, the energy from the blast wave propagates through their body tissues [5]. The propagation of the pressure waves can cause brain deformation as well as damage to organ systems such as the vascular system. Brain injuries resulting from blast wave exposure are forms of Traumatic Brain Injury (TBI) [6].

Many soldiers have been affected by blast waves while in service. According to the Centers for Disease Control and Prevention, approximately 5.3 million Americans live with disabilities that are a result of TBI [7]. The Defense and Veterans Brain Injury Center estimates that about 10-20 percent of soldiers who have fought in Iraq or Afghanistan acquired some form of TBI [6]. Moreover, IEDs and roadside bombs have caused about half of all the American combat casualties in Iraq and about 30 percent of combat casualties in Afghanistan.

B. Our Research

Team BLAST aims to research blast wave interactions with the human skull in order to further the scientific community's understanding of blast wave-induced TBI. Currently, scientists do not fully understand how changes in pressure around the skull correlate to the conditions inside the skull when exposed to blast waves. Our research intends to find a correlation between the external pressure and internal pressure, acceleration, and strain rate of brain tissue. By connecting external pressure to internal conditions, medical professionals would be able to better understand soldiers' injuries and provide proper treatment.

Our research is important because the number of American soldiers suffering from TBI is significantly increasing as IEDs become more prominent in the battlefield [8]. The goal of our research is to add to the medical community's understanding of primary blast injuries so that in the future, diagnosing blast-related TBI may be improved and fewer soldiers would sustain permanent brain injuries. Between January 2003 and February 2005, Walter Reed Army Medical Center observed that 60 percent of soldiers who have endured a blast were diagnosed with TBI [7]. The medical community continually strives to gain a better understanding of TBI with the hope of better protection and treatment for those serving their country.

In addition to the medical community, helmet manufacturers would also benefit from our research. The conclusions we draw from our data analysis could be used to create new helmet monitoring systems, which could be used in the military, mining, and construction environments.

Furthermore, our research could be used in helmet evaluation systems by determining which helmets best protect from TBI.

C. Team BLAST Research Questions

We aim to answer the following research question:

“What is the relationship between the pressure distributions measured over the surface of the skull and the blast wave-induced strain rate, internal pressure, and acceleration of brain tissue?”

D. Team BLAST Research Hypothesis

We hypothesize that different static pressure distributions measured over the surface of the skull can be correlated with the specific strain rates, pressures, and accelerations in brain tissue during a blast event. This correlation will suggest avenues to allow future researchers to develop predictive models capable of extrapolating data gathered by helmet-bound pressure sensors to internal injury sustained by brain tissue.

III. LITERATURE REVIEW

A. Blast waves

Blast waves are created by a gas that expands faster than the speed of sound. The wave can be split into different components (see Appendix B) [4]. The highly compressed air at the edge of the wave is called the shock front. Following the shock front is the blast wind, a fast moving wind created by the low pressure behind the shock front [9]. Blast waves inflict primary injury on the body because of the large pressure differences they induce in the ambient air. The large spike in ambient pressure induces pressure waves which structural damage to sensitive organs, such as the brain.

The four types of blast-related injuries are primary, secondary, tertiary, and quaternary. Primary blast injuries result from blast wave propagation through the brain, which creates extreme pressure differences between brain tissues. Pressure differences create shear stresses and strains on the brain tissue, causing injury. Secondary, tertiary, and quaternary injuries result from debris, and noxious gases.

With the implementation of better body armor for soldiers, more soldiers are surviving secondary, tertiary, and quaternary blast-related injuries. However, wearing a helmet cannot protect a soldier from blast waves for two primary reasons: blast waves can injure the soldier by entering the head through the body, and blast waves can impact the head by entering the gap between the head and the helmet [6]. Thus, soldiers who are otherwise protected remain susceptible to primary blast injuries.

Many experiments use blast tubes rather than explosive devices in the laboratory because blasts experienced on the battlefield contain large amounts of energy and produce inconsistent wave forms [10]. Blast tubes generate more consistent and controlled waves. Blast waves can be scaled down to fit the laboratory setting because the scaling of the wave does not have an effect on the properties of the wave other than magnitude and duration [10]. Scaling allows for the creation of smaller, reproducible waves with a blast tube, thus allowing researchers to observe wave propagation in a laboratory setting [10].

B. Traumatic Brain Injury

Blast waves generated by IED explosions cause both linear and rotational acceleration on the head, each having different effects on intracranial pressure and strain, and as a result, brain injury. These accelerations are very high; they are significantly higher than that of an impact, leading to greater risk of injury [11]. According to [12], translational head acceleration has a more profound effect on intracranial pressure, whereas rotational acceleration causes more shear stress in the central part of the brain. These internal conditions produce TBI, such as diffuse axonal injury, which can result in mental illness.

After being exposed to blast waves from IED explosions, many soldiers return home with depression and personality changes, and often have trouble readjusting to society [13]. One of the most prominent mental illnesses is Post-Traumatic Stress Disorder (PTSD). PTSD is defined as a mental disability that affects individuals who have undergone an extremely horrifying or stressful event. There is a high correlation between head injury and PTSD; one study surveyed 2,525 American soldiers deployed to Iraq. 43.9 percent of these soldiers had symptoms of PTSD [14].

Diffuse axonal injury is caused by the stretching and tearing of axons**.** This damage, which is quantitatively measured as strain, results from pressure waves passing through portions of the brain that are of different densities, such as the interface of white and gray matter [6].

Shear waves influence brain tissue by causing transverse (shear) strains, resulting in permanent deformation of axons. Strain rate levels in the brain ranging from 15 Hz to 21 Hz are strongly associated with axonal injury. When subjected to a blast, different areas of the brain experience different shear stresses, and there is more damage at interfaces where materials with different densities meet because high-frequency stress waves and low-frequency shear waves interact with these regions differently. These pressure differences cause damage to axons, creating symptoms such as loss of memory or loss of consciousness. When neurons are structurally compromised and the connections between neurons are damaged, normal brain functions become slower.

C. Headforms

There are many considerations when creating or selecting a headform to use when modeling the impact of blast waves on the head. The four major parts to be considered when creating a model of the human head are the scalp, skull, brain, and cerebrospinal fluid (CSF) [15].

The scalp is the outer layer of the human head, consisting of five layers. The scalp ranges from 5 to 7 mm thick over the surface the skull [15]. The importance of including the scalp in a headform that examines blast loading is still a subject of debate. Some studies have incorporated skin simulating materials, such as the two-piece polydimethysiloxane (PDMS) skin used in the RED Head model. In this case, a silicon-based polymer was used to cover the skull in a coating between five and seven mm thick [15]. However, other studies have compared the resulting loading in models with and without scalps, suggesting that the scalp is not necessary in headforms designed for studying primary blast loading [16].

The skull is the primary barrier that blast pressure waves pass through to reach the brain, making it an extremely important component of blast modeling [15]. Important material properties of the skull are the density, 1.4 g/cm^3; the tensile strength, 57.0 MPa; the modulus of elasticity, 9.6 GPa; and Young's modulus 5.3 GPa. The average thickness of the skull varies from 5 mm to 8 mm [16]. Some materials with properties similar to these include DuraForm GF and TC 854 Polyurethane [16]. One model in particular found success with using polyurethane to make a one-piece skull, with a steel base plate bolted into the bottom. The creators of this model stressed the importance of the one-piece skull to minimize any affects the method of joining the two pieces together might have on the wave propagation over and through the skull [15].

The brain's structures are extremely complex, but can be simplified, based on their material properties, to simulate the head's response to blast loading with sufficient accuracy. The brain is primarily composed of two types of cells: neurons and glial cells. The white matter of the brain is mostly mylenated axons and glial cells, while the grey matter of the brain is mostly glial cells and the cell bodies of neurons. The average brain is approximately 1.3 kg and 1.5 L, and has a density of about 1.04 g/cm^3 [15].

While there are many more parts of the brain, it has been established that its is acceptable to assume a homogeneous brain material, providing an average response to blast loading conditions [16]. The cortex, which consists of grey and white matter, takes up the most of the brain volume, and is often chosen to be representative of the entire brain. Grey and white matter have similar material properties, so this is a valid working model [15]. The most important consideration for the brain material is that the material be easy to mold, not liquid or brittle. It should also behave in a viscoelastic manner. The term viscoelastic means that when brain tissue is being deformed, it does not exhibit the characteristics of a simple spring, which is bound by

Hooke’s Law and exhibits linear relationship between stress and strain. Based on these criteria, the most commonly used material to simulate brains in headforms is a silicone gel [15]. One specific type of silicone gel that has been shown to work well is Sylgard® 527 A&B [16].

The function of CSF in the head is to dampen the motion of the brain, providing a cushioning effect. It has a specific gravity of about 1.008 kg/m^3, a volume of about 140 mL (this is about 10 percent of total intracranial volume), and is 99 percent water. Because of this, water is often used to model CSF [15].

C. Blast Wave Pressure Detection

As pressure from a shock wave can induce brain injury, detection of the pressure waves propagating around the head is critical. One way to measure the pressure waves passing over the head is by using pressure sensors. Pressure sensors can be used to measure the air pressure at the sensor and translate that pressure into an electric signal. There are several different types of pressure sensors, each with various advantages and disadvantages. Most pressure sensors have a diaphragm that deflects with respect to the change in pressure [17]. The main difference in types of sensors is the shape of the diaphragm and how the motion of the diaphragm is detected.

Capacitive pressure sensors output a change in voltage, which reflects a change in capacitance, to determine the change in pressure. When the diaphragm of the sensor deflects under the applied pressure, the distance between the plates of the capacitor will change, changing the output voltage of the sensor. The disadvantage of capacitive sensors is their sensitivity to electrical interference. They require a charge to be built up along the metal plates in the capacitor, which can change due to interference of electrical devices [17]. The advantage of the capacitive pressure sensors is that they have more pressure sensitivity and less temperature sensitivity [17].

Piezoresistive pressure sensors use a material such as silicone or a thin film that changes electrical resistance when deformed. The change in ambient pressure is translated to motion of the diaphragm, which alters the voltage across the resistor and, ultimately, the output voltage of the sensor. One problem with the piezoresistive pressure sensors is that the user must compensate for the ambient temperature effect since varying temperature can change the resistance of the resistive material. An advantage of piezoresistive pressure sensors is that they can have simpler circuit design than that of capacitive sensors [17].

Piezoelectric pressure sensors use a material that produces a charge when pressure is applied. These pressure sensors cannot be used to measure absolute pressure, but only the change in pressure. Piezoelectric pressure sensors are similar to piezoresistive sensors in their advantages and disadvantages, except for the fact that the piezoelectric sensors can have a higher bandwidth than piezoresistive sensors [18]. As piezoelectric pressure sensors' high sample rate best suits the purpose of measuring pressure from blast waves, we look to use this type of pressure sensor in our research.

In a study involving the correlation of pressure inside a rat's skull and its environment, two piezoelectric sensors were placed inside the experimenters' blast tube in order to determine the environmental pressure. The sensors had a sampling rate of 500 kHz, and were used to determine the static, dynamic, and reflected pressures. Additionally, the researchers placed miniature fiber optic pressure sensors inside the blast tube in order to compare their readings with the readings from the piezoelectric sensors. The fiber optic sensors had a sampling rate of 40 kHz, and thus were expected to produce less accurate readings. The piezoelectric sensors proved to be more accurate in determining the reflected and dynamic pressures, although the pressure spikes between the two sensors were comparable. In terms of static pressure, the piezoelectric and fiber optic sensors performed similarly [19].

D. Localization of a Blast Wave: Triangulation

The orientation of the skull in relation to the blast is important with regards to the traumatic effects on the brain, so the method by which location of the blast is determined is extremely important [20]. The process of triangulation establishes the delay between the passage of an object's front and back through a particular point. These time delays are used to approximate the speed of the object as well as its direction through the use of multivariate calculus [21]. In this case, the wave peaks of the shock wave provide many "edges" to measure, allowing for prediction of the waves location and intensity as well as the wave intensity's attenuation. This particular method, which is used for both sonic and supersonic waves, is known as acoustic location and is currently employed for such purposes as locating the point of origin of gunfire and ordinance blasts.

The complexity of the triangulation process grows with the number of sensors in use, as well as with the existence of any obstacles that would affect the wave characteristics of the incoming wave. Despite these issues, effective acoustic location paradigms have been constructed which greatly simplify the wave interactions of the blast to be measured, especially in controlled laboratory settings [21].

E. Modeling of Traumatic Brain Injury

By examining the relationships between the properties of a blast wave and the resulting effects on the brain, researchers seek to better understand blast-related TBI. Numerous studies have been conducted over the past 15 years that have explored various aspects of brain tissue damage [22]. Some of these studies have developed analytical models, capable of quantifying the material responses of brain tissue through one or more mathematical equations. Other studies have created virtual models, which are more complex, computer-based simulations of blast-induced injury.

Analytical models, such as the one created by Miller and Chinzei [23], have been created using experimental data to develop relationships between blast pressure loading and stresses experienced by brain tissue. In-vitro studies have shown that brain tissue is viscoelastic [23]; this property of brain tissue is modeled with mathematical equations that govern the behavior of brain tissue under stress [23].

Virtual models consist of digital reconstructions of the skull and brain. The difference between these virtual models and the simpler analytical models is that analytical models are typically represented by one or more equations, capable of yielding a finite mathematical result. In contrast, virtual models digitally construct two- or three-dimensional graphical representations of the human head [22]. Analytical models govern the interactions between very small pieces of virtual brain tissue (finite elements), resulting in a complex distribution of strain rate, pressure, and acceleration values. When blasts are simulated in virtual models, intracranial pressure and shear stress in the brain tissue can be represented graphically with color-gradient maps (see Appendix C) [24], [25], allowing the large quantities of generated data to be easily interpreted. In order for these models to be accurate, the material and geometrical properties of the skull and brain tissues must be accounted for due to their influence on how energy is distributed throughout the head [24].

One of the virtual models we will use in this project was created by Valdez and Balachandran, researchers at the University of Maryland [22]. This model attempts to simulate the mechanisms of brain injury, as previous models have, but also incorporates the complex analytical viscoelastic and fluid models that have been associated experimentally with brain tissue deformation [22]. The advantage of this extended model is that the stresses and strain rates developed in the head can be modeled with a greater degree of accuracy, and the mechanisms of tissue damage can be explored in greater detail. This two dimensional model is capable of simulating and graphically displaying the strain rates, pressures, and acceleration developed inside the brain during a blast event for a given magnitude and orientation of a blast wave [11].

The second, and primary, virtual model we will use was developed by Dr. Raul Radovitzky, an associate professor at Massachusetts Institute of Technology. The model is a three dimensional, full head, finite element model designed to accurately represent the various components of the human head. In order to account for the variation of wave propagation through the disparate components of the head, eleven distinct materials with different mechanical properties are incorporated into the model. Magnetic resonance images and computed tomography were used while generating the mesh to ensure accurate replication. For simplicity purposes, the model simulates a point source blast in an open field and neglects any nonlinear viscoelastic effects. The model was developed to further the understanding of TBI resulting from blast waves, and uses its complex structures to study wave propagation through various materials of the head. This virtual model is also capable of outputting strain rate, pressure, and acceleration readings within brain tissue [26].

F. *Statistical Analysis*

Our statistical analysis will be based off of the cross-correlation methods of German scientists Hans-Peter Kreplin and Helmut Eckelmann, as mentioned in their essay “Propagation of perturbations in the viscous sublayer and adjacent wall region.” Kreplin and Eckelmann measured the varying velocity components and their gradients at the wall in a turbulent channel flow. For each measurement, only one coordinate was varied [27].

First Kreplin and Eckelmann determined the average time shift, using the normalized correlation function. Afterwards, the span-wise space time correlations of the fluctuations of the velocity gradient at the wall were calculated with the same x values but different z values [27]. Team Blast will also perform three space-time correlations, but we will vary multiple coordinates, changing one point at a time. The specifics of our statistical analysis are explained under the heading “Methodology”.

G. Culmination of Literature Review

We have established that blast waves cause extreme changes in air pressure for short periods of time. These pressure waves can transfer energy to vulnerable organs within the body, particularly the brain. The accelerations induced in brain tissue cause stress (force) and strain (stretching), which are two major causes of brain injury. Pressure sensors can be used experimentally to monitor static pressure around the surface of the skull, and they can also be used to triangulate the location and magnitude of a blast event using multivariate calculus. Researchers Balachandran and Valdez as well as Moore have created virtual models that can predict the internal values of acceleration, stress, and strain in brain tissue for a given cross section of the head. Using the external pressure readings at each pressure sensor around the surface of the skull in conjunction with the data obtained from the computerized models of the brain, we seek to establish a correlation between the external pressures on the skull and internal material responses of the human brain. We will use cross-correlation, which is the strongest method available, to determine the significance of these correlations.

IV. METHODOLOGY

A. Team BLAST Methodology and Research Design

This section explains the four phases of our research methodology. In phase 0, we will conduct preliminary research and testing to validate our testing instrumentation, procedures, and methods. We will examine the extent to which we can customize our computerized finite element model, what kind of data we can produce, and the statistical testing necessary to determine relationships between variables. We will also run tests to validate our use of the materials chosen for our headform. We will then conduct preliminary blast-wave simulations to compare the performance of our high-speed piezoelectric pressure sensors to the output of low-quality microphones. In phase I, we will construct and calibrate a sensor array, implemented within a helmet, to record local static pressure (pressure at each pressure sensor) and triangulate a pressure wave's origin and initial magnitude. We will produce pressure waves using a pressure chamber to simulate an explosion. In phase II, we will conduct preliminary blast simulations based on the FE model. We will use these simulations to help us determine how to orient the headform during the physical experiments in order to obtain the widest range of pressure values possible. Using these orientations, we will expose a physical headform to a scaled pressure wave from the blast tube to gather static pressure readings as well as record the blast origin and magnitude data. In phase III, we will input the magnitude and location data into the computer-based FE model. By doing so, we will determine what relationship, if any, exists between the pressure, internal strain rate, and acceleration in the brain tissue as predicted by our model and the external pressure readings around the surface of the headform. In this section, we describe what procedures will be performed in each experiment and why each procedure is necessary for measuring these variables accurately. Additionally, this section addresses confounding variables to be controlled for, as well as the limitations of our methodology.

B. Materials

We will select sensors based upon their sampling rate and cost. Then, we will place these sensors inside of a Modular Integrated Communications Helmet (MICH), which is used by the US armed forces. The helmet will be fitted on a headform constructed via the rapid prototyping machine at the University of Maryland's Autonomous Vehicles Laboratory. The headform's geometry will match that of our FE model head, which represents the anatomical features of the head of a 50th percentile male [28]. Based upon conclusions drawn from Hossain's experiments the skull will be composed of a 7mm-thick polyurethane shell [29]. The soft tissue of the head will be modeled by silicon-based gel. The base of the skull will be sealed water-tight by a stainless steel bottom plate with the ability to securely mount to our testing rig. We will test our configuration with pressure waves produced by a pressure chamber from the University of Maryland's Sensors and Actuators Laboratory.

Based upon the current preliminary testing results, a modified photography tripod will support the headform during testing at pressures less than 25 psi. A screw will fasten the headform to the tripod and prevent the rotation during setup and testing. Based upon the current progress of preliminary testing, this setup should prevent any movement of the headform during testing at pressures less than 25 psi.

For additional information on materials, please see Appendix D.

C. Model

We will use the ANSYS finite element modeler with a combination of meshes developed by Dr. Radovitzky and Dr. Balachandran. Dr. Radovitzky's mesh is three-dimensional and Dr. Balachandran's is two-dimensional. ANSYS allows us to customize the structures affected by the blast as well as the material properties and shape of the brain and skull. We will simulate point source blasts, outputting values of strain rate, internal pressure, and acceleration in the brain tissue at discrete points of time. By implementing this model, we can run simulations with and without a helmet protecting the skull.

D. Phase 0: Preliminary Research

We have begun preliminary research to test the necessity of high-frequency pressure sensors. Using low-cost microphones, we are recording the shape of the waveform and compare this to the shape recorded by a high-frequency pressure sensor. We constructed a circuit (see Appendix D) to condition the signal of the low cost microphone so that the signal can then be directed into a data acquisition card and recorded in the LabVIEW software. We will then place the sensor in front of the pressure chamber and expose it to a series of blast waves while recording the data. Once we have acquired the proper amplifier for our high frequency piezoelectric sensor from PCB, we will build a similar circuit and expose it to the same series of tests. We will compare this curve to the one made from the acoustic pressure sensor's data, which only takes measurements in the millisecond range, and see how much of the wave the acoustic pressure sensor lost in sampling. Based on these results we will then be able to conclude whether we need the pressure sensors to take measurements in the microsecond range or millisecond range. We will then proceed to purchase four sensors from PCB that sample at an appropriate rate. This preliminary test will ensure that we use sensors that are both accurate and cost effective.

Preliminary Research for Computerized Models

The goal for this phase is to successfully run 2D simulations using our FE model. We will analyze our preliminary computer simulation results to determine the points with the largest magnitude of pressure changes and place our sensors accordingly in the physical model. Additionally, we hope to run simulations and see that our output is similar to the data obtained by the physical simulations in the lab.

The reason that we will be using the 2D model in the preliminary research rather than the more anatomically accurate 3D model is that the 3D model is both computationally and time intensive. The results that we obtain from these preliminary experiments will not be subject to rigorous quantitative analysis. As such, the inaccuracies that come with simplifications in the 2D model will be acceptable for preliminary simulations.

D. Phase I: Sensor Array Calibration

In Phase I of our methodology we will design an integrated helmet system using a helmet and pressure sensors. Each sensor will be connected to an amplifying circuit and a data acquisition card, and finally into a computer running LabVIEW for data recording. We will calibrate the sensors integrated within the helmet to triangulate a pressure wave generated by a scaled-down point-source blast, produced by a 25 psi pressure chamber. We will calculate the location of the blast using cross-correlation, in which we compare the two waveforms from different sensors and calculate the time delay between them, or Time Difference of Arrival.

Statistics will be discussed more intensively in the *Statistical Analysis* section of the Methodology.

For the purpose of data collection and analysis, triangulating the origin of a point-source blast is not essential. However, this additional step demonstrates how a single, closed sensor system can be used to monitor blast exposure.

Integration of Helmet and Sensor Array

We will fix four sensors in the helmet so that they form a tetrahedral shape within the helmet. The wires connecting the sensors to their respective amplifying circuits will exit through the back of the helmet.

Testing Procedures

The goal of the following procedures for phase I is to ensure that the integrated helmet system is capable of triangulating blast waves from multiple orientations. We will orient our helmet relative to the pressure chamber so that the front of the helmet is aligned with the front of the pressure chamber at a distance of 0.5 m. We will trigger the pressure chamber and record its initial blast overpressure with an additional sensor placed at the opening of the chamber. We will collect data at our helmet-bound pressure sensors using LabVIEW. A MATLAB subroutine will be used to triangulate the point source of the blast and determine the pressure wave's magnitude. We will replicate this exact procedure from distances of 1.0 m and 1.5 m and at angles of 90, 180, and 270 degrees about the z-axis (the axis normal to the top of the helmet). The results of these triangulation tests will be compared to the known values of the blast's magnitude and orientation, and changes will be made to the triangulation algorithm as necessary to increase accuracy.

Integration of Helmet and Headform

We will strap our integrated helmet system onto our headform, simulating a soldier wearing our helmet being exposed to a blast. We will repeat our testing procedures with our helmet attached to our headform in order to ensure that the triangulation algorithm already used for the integrated helmet system will still function accurately when the headform is introduced. Once we can accurately triangulate point-source blasts from the listed orientations, we will proceed to phase II of our methodology, Testing and Data Collection.

E. Phase II: Testing and Data Collection

The purpose of phase II of our methodology is to test the integrated helmet and headform by exposing it to blasts at the orientations and distances listed in phase I of the methodology. We will record the local static pressures at each sensor at each orientation using LabVIEW. We will then enter the blast origin and magnitude data into our FE model which will output the predicted acceleration, pressure, and the strain in the brain tissue when the pressure propagates through the skull.

F. *Phase III: Statistical Testing*

The purpose of phase III is to analyze the data gathered from phase II of our experiment and determine what correlations can be drawn between data sets. Specifically, we will be examining changing pressure distributions at the surface of the skull, as measured by our helmet-mounted sensors, and the pressure, strain, and acceleration within the brain obtained from the computerized FE model.

G. Statistical Analysis Techniques for Phases I, II, and III

The procedure used for the majority of our data analysis is known as space-time correlation. Two functions, f(t1) and g(t2) are correlated using a range of time differences, Δt. The correlation coefficient for each f(t1) and g(t1+Δt) is examined for a range of values of Δt. The Δt with the highest associated correlation coefficient, R, indicates the time delay of a wave between two locations [27].

$$R_{f,g} = \frac{\overline{\overline{f(t,\vec{x})g(t+\Delta t,\vec{x}+\Delta\vec{x})}}}{\sqrt{\bar{f}^2}\sqrt{\bar{g}^2}} \text{ (Equation 1)}$$

Our analysis will be composed of three sections. The first stage will compare the physical experiment and the simulation, verifying the comparison between the two. The second stage will correlate the experimental data from the different sensors, showing the propagation of the pressure wave, and obtaining the time delays necessary for triangulation. The third, and final, stage of analysis will attempt to link each external pressure reading with internal predictors of injury [27].

The first data set to be correlated is the static pressure measurements from each sensor on the physical model to the corresponding static pressure measurements on the computer simulation. These correlations will not calculate a time delay, but instead establish a high degree of similarity between the experiment and the model, validating our procedure. This leaves Equation 2, shown below, for each of the four sensors used in the experiment, where f(t) is the sensor reading and g(t) is the simulation value [27].

$$R_{f,g} = \frac{\overline{\overline{f(t)g(t)}}}{\sqrt{\bar{f}^2}\sqrt{\bar{g}^2}} \text{ (Equation 2)}$$

The second data set to be correlated is the different static pressure measurements from the physical experiment. Each sensor will be correlated to the 3 others. The established time delays will be used to triangulate the location of the blast with respect to the head, using the speed of the wave propagation, and the known physical separation of the sensors [27]. Each sensor will be compared to another with a range of values for Δt, seeking to maximize the value of R. Equation 3, shown below, will be run iteratively for each combination of sensor readings f and g, for a total of six correlations and established time delays [27].

$$R_{f,g} = \frac{\overline{\overline{\overline{f(t)g(t+\Delta t)}}}}{\sqrt{\bar{f}^2}\sqrt{\bar{g}^2}} \text{ (Equation 3)}$$

Finally, each static pressure reading from a sensor will be correlated with individual points inside the head. Stronger correlations will indicate possible predictive algorithms for internal injury [27]. Equation 4, shown below, will be run iteratively to find the Δt which maximizes R for each combination of external pressure reading f and internal injury predictor g. Each internal point will be correlated with the four sensors for each of the three internal injury predictors, for a total of twelve correlations for each internal point. Based on the computational intensity, some of the subsequent correlations for a given pair of external and internal points may be eliminated after an initial low correlation [27].

$$R_{f,g} = \frac{\overline{\overline{\overline{f(t,)g(t+\Delta t)}}}}{\sqrt{\bar{f}^2}\sqrt{\bar{g}^2}} \text{ (Equation 4)}$$

H. Confounding Variables

The research study will be a high constraint experiment, controlling for many variables. We will be working in a laboratory setting, meaning the reverberation of an acoustic wave may interfere with the localization of a blast. To avoid illegitimate variations in data, we will create a standardized procedure, eliminating any potential procedural variations between team members. Blast waves that soldiers face are too powerful and unpredictable to recreate in a laboratory setting. To account for this source of uncertainty, we will use a pressure chamber, capable of a pressure output of 25 psi, to produce more consistent blasts. Another possible confounding variable is movement of the headform when subjected to a pressure wave, as the model does not take head motion into consideration. To control for these changes we will stabilize the headform on our testing rig by using an isolated head, as opposed to a headform with a free-moving neck.

Another important confounding variable is the number anatomical simplifications made in the 3D computer model. While the model differentiates between the skull, skin and fat, brain tissue, and CSF, it may not account for the true anatomical complexity of the human head. However, due to the limited resources that have been made available, and due to the limited amount of computational capacity that we have available, we must accept the small inaccuracies that come with this model. Finally, since the computerized model only represents the top portion of the human head, we must acknowledge the error that is incurred by not accounting for the blast waves' interaction with the rest of the human body.

VI. CONCLUSION

As the use of IEDs in the battlefield becomes more common in modern warfare, the number of soldiers who suffer from TBI greatly increases. Due to better protection from more technologically advanced body armor, fewer soldiers are dying from other types of injuries caused by blast waves [9]. As a result, primary blast injuries are a significant threats to soldiers, yet very little is known about them.

Currently, the medical community is attempting to understand the relationship between blast waves and brain injuries in order to better the prevention, diagnosis, and treatment of these injuries. There are several models currently in existence that attempt to correlate blast waves and internal effects on the brain, but no model exists that can correlate the pressure on the surface of the skull with pressure, strain rate, and acceleration of the brain. Our research purpose is to identify this connection between external pressure and internal brain condition.

Pressure, strain rate, and acceleration have all been related to brain injury. We will be correlating these measures with pressure on the outside of the skull. If we find such a correlation, it could lead to new ways of preventing and diagnosing TBI caused by blasts. Helmets could be made with the ability to read the skull surface pressure and use that reading to predict the likelihood of brain injury. A similar technique could be conducted to test the effectiveness of helmets. Our study may lead to more experiments with longer time frames and higher budgets. These experiments could provide more detailed observations that further enhance the understanding of TBI.

APPENDIXES

Appendix A: Timeline

Fall 2011 (September 2011 - December 2011)

Team Blast completed and submitted their Draft Thesis Proposal on December 1st. After receiving feedback from Dr. Wallace and Heather Creek, Team Blast made corrections to their Thesis Proposal, as well as submit their Future Directions assignment by the end of the semester (mid-December).

Winter 2012 (Mid-December to January)

Team Blast expanded their literature review and began the process of researching grants at the end of December and the beginning of January. In mid- January, team members met with Dr. Yu to begin familiarizing themselves with laboratory equipment and planning for preliminary testing.

Spring 2012 (End of January 2012 – May 2012)

Team Blast has begun phase 0 of the methodology, and has begun ordering the materials necessary for experimentation. In April, Team Blast will complete Phase 0 of testing, and will place orders on all remaining materials.

Fall 2012(August 2012 – December 2012)

Team Blast will begin phases I and II of testing and will conclude by the end of November, in time to present at Junior Colloquium. In November and the first half of December, Team Blast will begin phase III.

Winter 2013 (November 2012 – January 2013)

Team Blast will complete all applications to present at conferences.

Spring 2013 (February 2013 – May 2013)

Team Blast will complete Phase III and begin drafting a final literature review and a final thesis.

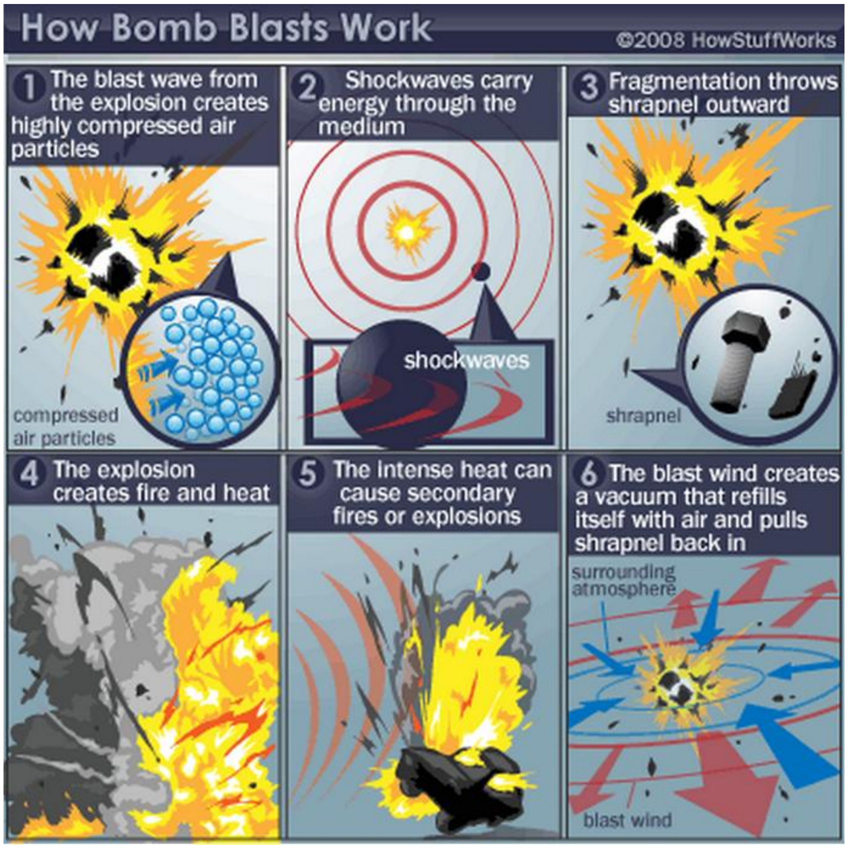
Fall 2013 (August 2013 – December 2013)

Team Blast will continue writing their final literature review and the final thesis draft, as well as attend at least one conference. They will send invitations for professionals and University of Maryland professors to attend the thesis conference in December.

Spring 2014 (January 2014 – February 2014)

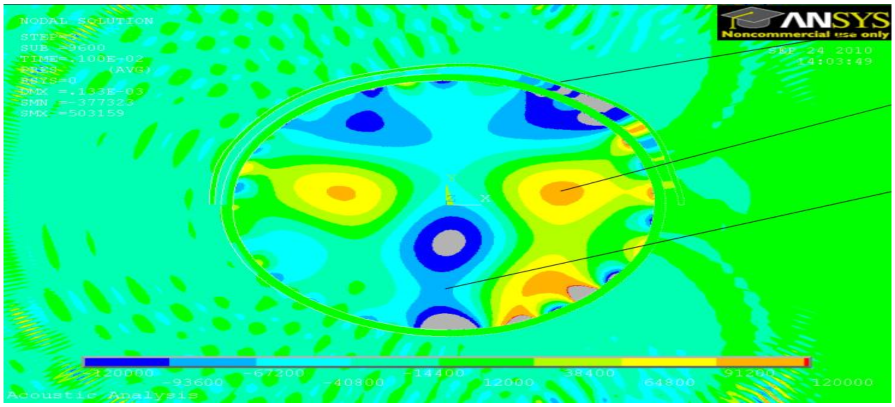
Team Blast will finish writing the thesis by mid- February and will have a one-month editing process. They will present their findings at the Thesis Conference in March.

Appendix B: How Bomb Blasts Work



How a Bomb Blast Works

Appendix C



Distribution of pressure values in Dr. Balachandran’s FE Model

Appendix D: Materials

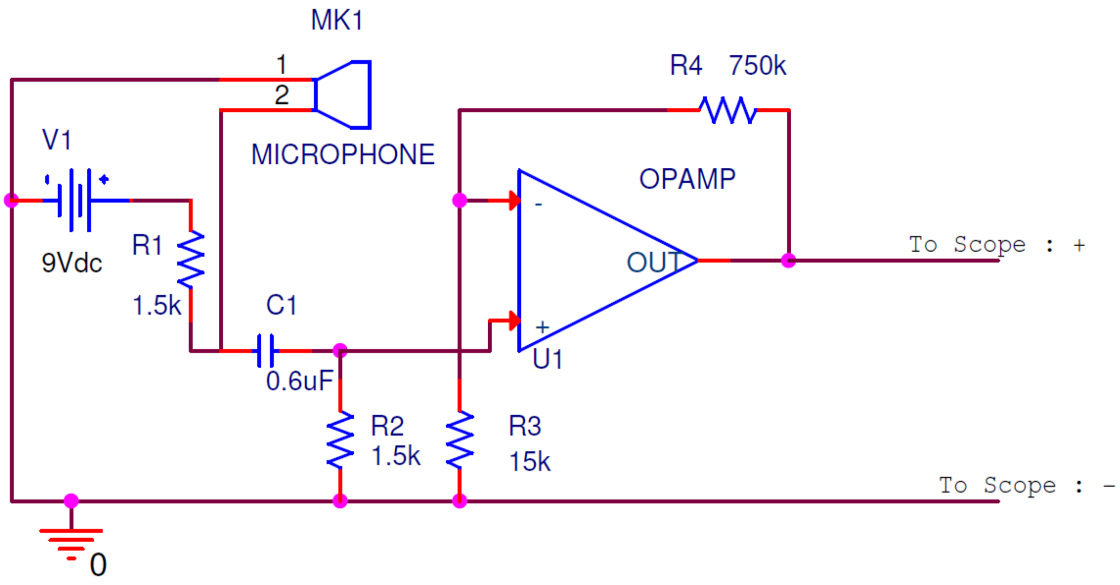
Headform Material Specifications

Based upon conclusions drawn from Hossain’s experiments, the skull’s thickness will be 7 mm, and be will be composed of VeroGray Full Cure 850 polyurethane with a density of 1.17-1.18 g/cm^3 [29]. The soft tissue of the head will be modeled by Siligard® 527 A&B, silicon-based gel because of its ability to accurately simulate brain matter [15].

Materials and Diagram for Acoustic Pressure Sensor Circuit

To construct a conditioning circuit for the acoustic pressure sensors, we will utilize the following materials:

2x 0.33 µF Capacitor
1x Operational Amplifier
1x Acoustic Pressure Sensor
2x 1.5 kΩ Resistors
1x 750 kΩ Resistor
1x 15 kΩ Resistor
1x 9 Volt Battery
1x Data Acquisition Card



Acoustic Pressure Sensor Circuit Diagram

Materials for ICP Pressure Sensor Circuit

The materials required to construct the conditioning circuit for the ICP pressure sensors are as follows:

1x Micro ICP pressure sensor

1x Scope input adaptor (10-32 jack to BNC plug)

1x 4-channel, line-powered Data Acquisition Card (DAQ)

1x ICP sensor signal conditioner

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