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TITLE: Evaluation of the Effects of High Level Overpressure (8+ psi) on Cognitive Performance, Brain Blood Biomarkers and Symptom Reporting

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**RECIPIENT: The Geneva Foundation
Tacoma, WA 98402**

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14. ABSTRACT This is a multi-site observational study of military and law enforcement personnel who are exposed to overpressure (OP) where data is collected in conjunction with occupational training exercises. The study's primary purpose is to characterize a variety of weapon systems/environments (OP, impulse, acoustics) and measure effects (neurocognitive, biomarkers, symptom reporting, etc.) immediately after OP exposure (< 5 min) and/or at end of training day (i.e., acute effects). 5 data collections took place ($n_1 = 31$, $n_2 = 6$, $n_3 = 24$, $n_4 = 31$, $n_5 = 14$) at 4 different sites. Individual overpressure exposures recorded during training frequently exceeded the 4 psi incident safe threshold prescribed by US Army doctrine. Neurocognitive deficits, immediately after blast and at the end of the day, were observed at each test site, but only appeared to affect a small segment of each sample, ranging from 5-30% of subjects. Increases in select protein biomarkers were associated with increased symptom reporting and slower reaction time at the end of the exposure day. The magnitude of gene expression changes following blast exposure was greater in operators that self-reported having a history of TBI. Surrogate head and brain models were customized by the Naval Research Laboratory (NRL) to collect data during wall breaching events at two training sites. Six datasets, two to eight blast events each, of head/brain acceleration and pressure data were collected. In addition, neuronal cell cultures were exposed to wall breaching events during training exercises in two sets. New heads were developed to measure pressures at the eardrum during blast events. Surrogate head and cell culture data are under analysis.					
15. SUBJECT TERMS mTBI, neurotrauma, blast, blast exposure, immediate effects, military, breacher, explosive entry, blast injury, brain injury, blood based biomarker, injury threshold					
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- 1. INTRODUCTION:** Narrative that briefly (one paragraph) describes the subject, purpose and scope of the research.

Military and law enforcement personnel are repeatedly exposed to overpressure (OP) during training and operations. This multi-site observational study will collect individual OP exposure data (including impulse and acoustics data when possible) and measure neurocognitive and physiological (blood based biomarkers, genetic markers, eye-tracking, tactile sensory perception, balance, symptom reporting) effects immediately after OP exposure and/or at end of day. The study will occur in conjunction with training exercises from a variety of weapon systems/environments where operators are exposed to OP ranging from safe (< 4 psi) to high exposure (> 8 psi) levels at local and national military and law enforcement training facilities. A parallel effort will collect biomechanical data using surrogate head forms that are embedded with sensors for obtaining pressures and accelerations. The surrogate head forms will be developed and customized for this project as a collaborative effort by the Naval Research Laboratory (NRL). Data collection efforts from this study will be used to quantify blast and its effects (neurocognitive and physiological) on the operator and identify variable(s) and/or test(s) which will serve to inform medical research with regards to increased risk and/or the effects of OP exposure. In addition, data derived from this study will be available for pertinent medical research in terms of OP exposure and neurotrauma modeling efforts. The Initiating Principal Investigator (PI) for the overall award and effort is Dr. Gary Kamimori at the Walter Reed Army Institute of Research (WRIAR); the Collaborating/Partnering PI for the sub-award to develop surrogate head models is Dr. Amit Bagchi at the Naval Research Laboratory (NRL).

- 2. KEYWORDS:** Provide a brief list of keywords (limit to 20 words).

mTBI, neurotrauma, blast, blast exposure, immediate effects, military, breacher, explosive entry, blast injury, brain injury, blood based biomarker, injury threshold

- 3. ACCOMPLISHMENTS:** The PI is reminded that the recipient organization is required to obtain prior written approval from the awarding agency Grants Officer whenever there are significant changes in the project or its direction.

What were the major goals of the project?

List the major goals of the project as stated in the approved SOW. If the application listed milestones/target dates for important activities or phases of the project, identify these dates and show actual completion dates or the percentage of completion.

Goal 1) Collect high overpressure exposure (8-12 psi) data on human operators during operational training and secondly to collect possible injury data using extensively instrumented human surrogates.

Goal 2) Identify and quantify acute, transient decrements in cognitive performance resulting from overpressure exposure within a variety of environments. This portion of the project will encompass as many different exposure environments as possible in order to characterize overpressure within these specific environments as well as individual operator exposure.

What was accomplished under these goals?

For this reporting period describe: 1) major activities; 2) specific objectives; 3) significant results or key outcomes, including major findings, developments, or conclusions (both positive and negative); and/or 4) other achievements. Include a discussion of stated goals not met. Description shall include pertinent data and graphs in sufficient detail to explain any significant results achieved. A succinct description of the methodology used shall be provided. As the project progresses to completion, the emphasis in reporting in this section should shift from reporting activities to reporting accomplishments.

1) Major Activities

- a. (WRAIR) Human use protocols to collect data at 4 additional sites were approved by WRAIR IRB and HRPO.
- b. (WRAIR) Seven additional associate/collaborating investigators were added to the human use protocol.
- c. (WRAIR) Five human subjects data collections took place at 4 different sites, site #2 (Ft Leonard Wood, MO, April 2018, July/Aug 2018); site #6 (Ft Benning, GA, June 2018); site #1 (Washington County Sheriff's Office, July 2018); site #7 (Camp Hansen, Okinawan, Japan, Nov/Dec 2018).
- d. (WRAIR) Three environmental characterization data collections took place 2x at site #7 (Camp Hansen, Okinawan, Japan and Camp Pendleton, CA) and once at site #8 (Department of Energy).
- e. (WRAIR) Blood based biomarker analyses were initiated and biological specimens were transferred to collaborating investigator for genetic analyses.
- f. (WRAIR) Two 50 cal rifle environmental characterization manuscripts were accepted and will be published; three additional publications are either under review or in preparation.
- g. (WRAIR) Symptom and neurocognitive data from 4 data collections were submitted to the Federal Interagency Traumatic Brain Injury Research (FITBIR) Informatics System during.
- h. (NRL) Two publications to be submitted for peer review are in preparation.
- i. (NRL) Continued tests on the effect of interface conditions between the brain and the skull on transmission of shockwave pressure into the surrogate brain to study repeatability and to expand the tested conditions.
- j. (NRL) Continued testing with neuronal cultures exposed to blast to determine the possible changes to metabolism. More standoff distances were tested to develop a threshold for changes in metabolism.
- k. (NRL) Created new NRL Head-Neck Brain Models (NHBMs) to study the effect of helmet on shockwave transmission. Studied the possible effect of increased under helmet pressure at test sites and in shock tubes.

2) Specific Objectives

- a. (WRAIR) Site #2, CY18 data collection #1, Ft. Leonard Wood, MO, 35th Engineers
 - i. Date(s): April 2018
 - ii. Environment: Heavy wall breaching
 - iii. Data measures: overpressure exposure, acoustics, neurocognitive performance, symptoms, demographics/occupational history, cheek swab, blood sampling
 - iv. Number of subjects (complete data collection): 31

- b. (WRAIR) Site #6, CY18 data collection #2, Ft. Benning, GA, Maneuver Center of Excellence
 - i. Date(s): June 2018
 - ii. Environment: Hand grenades
 - iii. Data measures: overpressure exposure, acoustics, neurocognitive performance, symptoms, stress, demographics/occupational history, cheek swab, blood sampling
 - iv. Number of subjects (complete data collection): 6
- c. (WRAIR) Site #1, CY18 data collection #3, Washington County Sheriff's Office
 - i. Date(s): July 2018
 - ii. Environment: Shotgun breaching
 - iii. Data measures: overpressure exposure, acoustics, neurocognitive performance, symptoms, demographics/occupational history, cheek swab, blood sampling
 - iv. Number of subjects (complete data collection): 24
- d. (WRAIR) Site #2, CY18 data collection #4, Ft. Leonard Wood, MO, 35th Engineers
 - i. Date(s): July/August 2018
 - ii. Environment: Heavy wall breaching
 - iii. Data measures: overpressure exposure, acoustics, neurocognitive performance, symptoms, demographics/occupational history, cheek swab, blood sampling
 - iv. Number of subjects (complete data collection): 31
- e. (WRAIR) Site #7, CY18 data collection #5, Camp Hansen, Okinawa Japan, Marine Expeditionary Force
 - i. Date(s): Nov/Dec 2018
 - ii. Environment: Close quarters training
 - iii. Data measures: overpressure exposure, acoustics, neurocognitive performance, symptoms, stress, demographics/occupational history, cheek swab, blood sampling
 - iv. Number of subjects (complete data collection): 14
- f. (WRAIR) Environmental characterization data collection (overpressure, impulse, and acoustics) occurred at
 - i. Site #7 Camp Hansen, Okinawa, Japan, May 2018
 - ii. Site #7 Camp Pendleton, CA, June 2018
 - iii. Site #8 Department of Energy, July 2018
- g. (WRAIR) Data analysis in progress.
 - i. Analyses of cognitive performance, symptoms, exposure, demographics continues.
 - ii. Analyses of blood samples continues.
 - a. Continued quantitation of a seven biomarker panel (GFAP, UCH-L1, NF-L, Tau, A β -40 and A β -42) in association with symptomology before and after exposure to blast overpressure.
 - b. Developed extensive protocol and SOP to perform proteomics analysis using serum samples and completed a pilot test of our workflow.
 - c. Initiated development of a control dataset (non-overpressure exposed persons) repository for biomarker comparisons.
 - d. Continued measurement and genome location analysis of methylated DNA sequences and transcribed RNA genes in blood samples.

- e. Initiated total RNA isolation on subset of data (blood samples from site #2, CY17 collection #4).
- f. Performed whole genome gene expression transcriptome analysis via RNA-seq for site #2, CY17 collection #4 blood samples.
- g. Performed bioinformatics analyses comparing gene transcript expression profile pre vs post and pre vs follow up exposure to blast representing both acute and sub-acute time point comparisons, respectively or site #2, CY17 collection #4 blood samples.
- h. (NRL) Created new NHBMs to study specific questions regarding shockwave pressure transmission into the brain.
 - i. NHBM was created specifically to study the effect of possible pressure build up under an Enhanced Combat Helmet (ECH). This NHBM has two pressure sensors flush mounted to the top of the skull and one at the left eye socket.
 - ii. Two new modular brains and an instrumented skull were made for site #2 (Ft Leonard Wood, MO) tests at the end of July 2018. These configurations replicated the modular heads used in the past and they allow NRL to test multiple conditions on the same surrogate head form.
 - iii. Conducted field tests at site #2 in April 2018 to further study how standoff distance might affect pressure transmission into the brain with different interface conditions. Two more field data collections were conducted at Quantico in June 2018 and September 2018 (Appendix A).
 - iv. Conducted field tests at site #2 in July 2018 to study the effect of under-helmet pressure. Further tests were conducted at Quantico in August and September 2018. Multiple test were conducted to look at reproducibility and to expand the data set.
 - v. Cell packs were tested with the modular NHBM at various standoffs at Quantico in May, June 2018.

3) Key outcomes

- a. (WRAIR) Environmental characterizations of multiple weapon systems were conducted and provide estimates of operator exposure.
- b. (WRAIR) Measureable neurocognitive impairments (mean response time greater than 30% or 100 ms) immediately after blast exposure were observed in 5-30% of volunteers.
- c. (WRAIR) Measureable neurocognitive impairments (mean response time greater than 30% or 100 ms) were observed in 5-30% of volunteers at the end of the training day.
- d. (WRAIR) Neurocognitive impairments seem to be more prevalent in higher memory demand tasks (procedural reaction time, response inhibition [go no go]).
- e. (WRAIR) A select group of proteins, typically associated with brain trauma or neurological disease, may be acute responders of exposure associated with increased symptom reporting and slower reaction time from neurocognitive performance.
- f. (WRAIR) Gene transcript responsivity varied by self-reported history of TBI, with individuals having prior history of TBI exhibiting greater magnitude of gene expression changes following exposure to blast (Appendix B).
- g. (NRL) Interface conditions play a role in the level of shockwave pressures that are transmitted into the brain. A liquid layer simulating the cerebral spinal fluid (CSF)

increases the peak pressures measured in the brain. The difference in peak pressures between NHBMs with and without the CSF layer increases as the equivalent trinitrotoluene (TNT) standoff distance is decreased. At the farthest equivalent standoff distance tested, an increase of 50% peak pressure was seen. At the closest equivalent standoff distance, the peak pressures were almost double in the CSF surrogate head versus the other conditions tested. If there is tight coupling between the surrogate brain and skull, a high frequency component in the pressure profiles are seen. The pressure-impulse for all the interface conditions tested were not significantly different.

- h. (NRL) Field and shock tube tests show that there is an enhancement of pressures under the Enhanced Combat Helmet (ECH) near the top, rear of the skull. This increase in pressures outside the skull (under the helmet) does correlate to an increase in pressure inside the surrogate brain.

4) None to report.

What opportunities for training and professional development has the project provided?

If the project was not intended to provide training and professional development opportunities or there is nothing significant to report during this reporting period, state "Nothing to Report."

Describe opportunities for training and professional development provided to anyone who worked on the project or anyone who was involved in the activities supported by the project. "Training" activities are those in which individuals with advanced professional skills and experience assist others in attaining greater proficiency. Training activities may include, for example, courses or one-on-one work with a mentor. "Professional development" activities result in increased knowledge or skill in one's area of expertise and may include workshops, conferences, seminars, study groups, and individual study. Include participation in conferences, workshops, and seminars not listed under major activities.

Nothing to Report

How were the results disseminated to communities of interest?

If there is nothing significant to report during this reporting period, state "Nothing to Report."

Describe how the results were disseminated to communities of interest. Include any outreach activities that were undertaken to reach members of communities who are not usually aware of these project activities, for the purpose of enhancing public understanding and increasing interest in learning and careers in science, technology, and the humanities.

(WRAIR) Dr. Kamimori (WRAIR PI) discussed/presented study progress and/or results at the following meetings and conferences,

- International State-of-the-Science Meeting on The Neurological Effects of Repeated Exposure to Military Occupational Blast Implications for Preventions and Health, 12 March 2018, Pentagon City, VA
- 7th Annual Breaching Circle, 26-30 March 2018, Dallas, TX
- National Neuroscience Society Symposium, 11-16 August 2018, Toronto, Canada
- Military Health Systems Research Symposium 20-23 August 2018, Kissimmee, FL

-Military Aspects of Blast and Shock (MABS), 23-28 September 2018, The Hague, Netherlands
 -18th International Breachers Symposium, 21-25 October 2018, Southaven, MS

(WRAIR) Preliminary brief back on site-specific data were presented to the following sites,

-Ft Leonard Wood, MO

-Ft Benning, GA

-Camp Hansen & Command, Okinawa, Japan

-Washington County Sheriff's Office, Beaverton, OR

-Military breaching group meeting (I & III MEF, 35th Engineers FLW @ International Breachers Symposium), Southaven, MS

(WRAIR) Study information and preliminary results were passed to US military and law enforcement agencies (30+ agencies); subsequently, information was provided to select NATO allies (including Netherlands, Belgium, Finland, Canada, Australia, New Zealand, Singapore).

(WRAIR) Study collaborators Dr. Angela Boutte (WRAIR, Brain Trauma, Neuroprotection, and Neurorestoration Branch Collaborating Investigator) and Dr. Haghighi (James J Peters VA Medical Center Collaborating Investigator) each discussed/presented study findings and/or preliminary results at Department of Defense State of the Science Meeting for Blood-Based Traumatic Brain Injury (TBI) Biomarkers, 26-27 November 2018 (Frederick, Maryland). Dr. Boutte also presented findings at National Neuroscience Society Symposium, 11-16 August 2018, Toronto, Canada; Military Health Systems Research Symposium 20-23 August 2018, Kissimmee, FL; and Temple University in Oct 2018.

(WRAIR & NRL) A meeting between collaborators was held on 15 March 2018 to present and discuss current progress, future direction, and review timeline for deliverables.

(NRL) Regular meetings occurred between the NRL and the WRAIR research teams.

(NRL) Presentation given at

-Japan US Forum on Blast and Blunt Injury, 9-11 May 2018, Tokyo, Japan

-Military Aspects of Blast and Shock (MABS), 23-28 September 2018, The Hague, Netherlands

-Personal Armour Systems Symposia (PASS), 1-5 October 2018, Washington, DC

-Military Health Systems Research Symposium 20-23 August 2018, Kissimmee, FL

What do you plan to do during the next reporting period to accomplish the goals?

If this is the final report, state "Nothing to Report."

Describe briefly what you plan to do during the next reporting period to accomplish the goals and objectives.

(WRAIR) Site recruitment will continue.

(WRAIR) SSA documentation will be prepared for new sites and data collection will continue; identified sites include,

-Ft Leonard Wood, MO

- Washington County
- Tacflow Academy
- Camp Pendleton, CA, I EOTG (I MEF)
- Camp Hansen, Okinawa, Japan III EOTG (III MEF)
- Ft Benning, GA

(WRAIR) Data analysis will continue. Statistical analyses using individual exposure data (e.g., additional cumulative overpressure exposure variables, etc.) with data collected pre/post overpressure exposure will continue. This includes correlating various demographic, behavioral, cognitive, and physical outcome metrics.

(WRAIR) For blood samples, testing and comparison of the seven-biomarker panel in serum samples from multiple sites will continue. Development and testing of the blood proteome, genome, and transcriptome will continue and bioinformatics analysis will be initiated. Biomarker level quantitation and analysis in the context of medical history, inclusive of prior brain injury or concussion status defined in subject reporting will be investigated. Genome scale DNA methylation profiling on blood samples for site #2, CY17 data collection #4 will be performed and gene expression transcriptome analysis will be replicated using samples from other site/s.

(WRAIR) Data from sites #2, #6, #7, and others collected in 2019 will be submitted to FITBIR on an annual basis (submission deadline as discussed with Science Officer is 30 September). In addition, exposure data from all data collections sites will be formatted according to the FITBIR data from structure and submitted.

(WRAIR) Submit abstracts to and present at the following conferences,

- 8th Annual Breaching Circle, Phoenix, AZ, 23-27 April 2019
- National Neurotrauma Symposium (Pittsburgh, PA) abstracts due 1 April 2019, conference 30 June – 3 July 2019.
- Military Health Systems Research Symposium (location & dates: TBD)
- 19th International Breachers Symposium, (location & dates: TBD)

(NRL) Complete field testing of instrumented NHBMs and NHBMs containing NRL cell packs.

(NRL) Analyze data from all NHBMs. Organize into papers and submit papers to respective journals.

4. **IMPACT:** Describe distinctive contributions, major accomplishments, innovations, successes, or any change in practice or behavior that has come about as a result of the project relative to:

What was the impact on the development of the principal discipline(s) of the project?

If there is nothing significant to report during this reporting period, state “Nothing to Report.”

Describe how findings, results, techniques that were developed or extended, or other products from the project made an impact or are likely to make an impact on the base of knowledge, theory, and research in the principal disciplinary field(s) of the project. Summarize using language that an intelligent lay audience can understand (Scientific American style).

(WRAIR) Characterizing environmental exposure, identifying inadequacies with current stand-off equations, expanding the variety of training environments, and including acoustic data to further environmental characterization will inform safety and occupational health groups on possible occupational training hazards.

(WRAIR) Data on the immediate neurocognitive decrements associated with high blast exposure will be used by the operational community in their risk/benefit assessment.

(WRAIR) These studies have begun to provide evidence that proteins, peptides, and genes are biomarkers are “responders” of mild-moderate blast overpressure exposure in a variety of paradigms. Results from the past year indicate that a select group of proteins, which are typically associated with brain trauma or disease, may be acute responders of exposure associated with operational decrement. Further, these biomarker changes are detectable within one hour through one day after exposure which makes biomarker blood testing a feasible strategy for early, quantitative, assessment of an event that affects health or resilience. Establishment of blood proteomics and genomics strategies coupled to data science and informatics are laying the groundwork for discovery of novel biomarkers associated with exposure.

(NRL) The development of the various instrumented heads may help answer key questions that have plagued the scientific community. There has been a lot of debate on whether helmets like the ECH help or hinder. Our data suggests that the ECH helmet, in some cases, may result in higher in brain pressures than in the absence of a helmet, and that these elevated pressures correlate to elevated pressure under the helmet (Appendix C). However, there are also situations in which the helmet may result in diminished in brain pressures.

(NRL) Another key finding is that the CSF layer may affect pressure transmission into the brain. While impulse does not seem affected, peak pressures may be dramatically increased. This may have an effect on how data is interpreted in the future involving surrogates (Appendices A and D).

What was the impact on other disciplines?

If there is nothing significant to report during this reporting period, state “Nothing to Report.”

Describe how the findings, results, or techniques that were developed or improved, or other products from the project made an impact or are likely to make an impact on other disciplines.

(WRAIR) Data generated from blood samples during this reporting period indicate that TBI-associated proteins are applicable to detection of overpressure effects without a head wound. Therefore, biomarkers have utility across paradigms and may be capable of very subtle nervous system injury that would not otherwise be detectable.

(NRL) These results could potentially lead to improved helmet designs, providing information on how pressure propagation into the brain is altered by a helmet, as well as providing a surrogate system capable of quantifying these effects. The NHBM developed to study the underwash pressure could also be used to study various helmet designs. Another potential impact

could be on the development of future human head surrogates for blast testing. Findings from instrumented NHBMs can reveal how interface conditions between the brain and the skull affect transmission of shockwave into the surrogate head. This information can be used to develop a more accurate surrogate head/brain models.

What was the impact on technology transfer?

If there is nothing significant to report during this reporting period, state “Nothing to Report.”

Describe ways in which the project made an impact, or is likely to make an impact, on commercial technology or public use, including:

- *transfer of results to entities in government or industry;*
- *instances where the research has led to the initiation of a start-up company; or*
- *adoption of new practices.*

Nothing to Report

What was the impact on society beyond science and technology?

If there is nothing significant to report during this reporting period, state “Nothing to Report.”

Describe how results from the project made an impact, or are likely to make an impact, beyond the bounds of science, engineering, and the academic world on areas such as:

- *improving public knowledge, attitudes, skills, and abilities;*
- *changing behavior, practices, decision making, policies (including regulatory policies), or social actions; or*
- *improving social, economic, civic, or environmental conditions.*

(WRAIR) Results from environmental characterization continues to impact military and law enforcement operators by increasing knowledge of blast pressure, modifying training practices, aiding in mission planning, and improving safety (see Appendix E).

(NRL) Nothing to Report

- 5. CHANGES/PROBLEMS:** The Project Director/Principal Investigator (PD/PI) is reminded that the recipient organization is required to obtain prior written approval from the awarding agency Grants Officer whenever there are significant changes in the project or its direction. If not previously reported in writing, provide the following additional information or state, “Nothing to Report,” if applicable:

Changes in approach and reasons for change

Describe any changes in approach during the reporting period and reasons for these changes.

Remember that significant changes in objectives and scope require prior approval of the agency.

Nothing to Report

Actual or anticipated problems or delays and actions or plans to resolve them

Describe problems or delays encountered during the reporting period and actions or plans to resolve them.

Nothing to Report

Changes that had a significant impact on expenditures

Describe changes during the reporting period that may have had a significant impact on expenditures, for example, delays in hiring staff or favorable developments that enable meeting objectives at less cost than anticipated.

Nothing to Report

Significant changes in use or care of human subjects, vertebrate animals, biohazards, and/or select agents

Describe significant deviations, unexpected outcomes, or changes in approved protocols for the use or care of human subjects, vertebrate animals, biohazards, and/or select agents during the reporting period. If required, were these changes approved by the applicable institution committee (or equivalent) and reported to the agency? Also specify the applicable Institutional Review Board/Institutional Animal Care and Use Committee approval dates.

Significant changes in use or care of human subjects

(WRAIR) A deviation was reported on 26 April 2018 to the WRAIR IRB that informed consent forms with expired WRAIR IRB stamps were distributed and signed by participants; the current stamped copy of the ICF were also distributed to subjects, all of whom signed the form and backdated them to 26 June 2017. Hard copies of the expired stamped ICFs signed by subjects and the current stamped ICFs signed and backdated by subjects were shredded. Electronic copies of the ICF with the current stamp that were signed and backdated by subjects were placed in the study files. The WRAIR IRB Chair determined that the event does not qualify as a major deviation. The fully convened WRAIR IRB determined the event to constitute serious non-compliance as a failure to act in accordance with the protocol, regulations and policies, and good documentation practices governing human subjects research, and will be reported as outlined in WRAIR Standard Operating Procedures (SOP) UWZ-C 606.02. Reporting requirements include: MRMC Office of Research Protections and Army Human Research Protection Office/Office of The Surgeon General. The WRAIR IRB Chair requested the completion of the Research Integrity CITI training by all research team members to be submitted within 45 days from 1 May 2018 in addition to a team discussion about the deviation. Completion of the directive was acknowledged by the WRAIR IRB Chair on 28 June 2018.

Additionally, the following deviations were identified while preparing for a WRAIR post approval compliant monitoring audit and submitted to the WRAIR IRB in the annual continuing review report (submitted 7 May 2018).

From Site #2 (Addendum B)

-The WRAIR IRB stamp on the last page of the ICFs (#2304B v1.4, dated 25 July 2016) was dated "8 June 2014" per WRAIR IRB stamp on all forms. This version if the ICF is no longer in use. This issue was recorded in the deviation log and will be mitigated by closely reviewing the

accuracy upon receipt of approval documents and promptly reporting any inaccuracy to WRAIR HSPB.

- One subject filled their birth year as 2016 on the ICF. The date of birth was verified by the completed demographics form; the correct birthday was documented on the ICF in addition to documentation noting that the issue was recorded in the deviation log.
- One subject wrote text over text in the "Date" field of the ICF; the incorrect dated of consent was circled on the ICF and documentation noting the issue was recorded in the deviation log was written on the ICF.
- Three subjects did not initial and date strike through text on the ICF; documentation noting the issue was recorded in the deviation log was written on the ICF.
- One subject wrote an email address in the "Participant Mailing Address" field in ICF; documentation noting the issue was recorded in the deviation log was written on the ICF.
- One subject scribbled out text in the "Participant Date of Birth" field on the ICF; documentation noting the issue was recorded in the deviation log was written on the ICF.

From Site #4 (Addendum D)

- Two subjects wrote the incorrect date when dating the ICF; the incorrect dated of consent was circled on the ICF and documentation noting the issue was recorded in the deviation log was written on the ICF.
- One subject scribbled out text in the "Print Name of Person Obtaining Consent" field of the ICF; documentation noting the issue was recorded in the deviation log was written on the ICF.

From Site #5 (Addendum F)

- The WRAIR IRB stamp on the first page of the ICFs (#2304F v3.2, dated 5 June 2017) was labeled "Version 3.1" per WRAIR IRB stamp on all forms. This version if the ICF is no longer in use. This issue was recorded in the deviation log and will be mitigated by closely reviewing the accuracy upon receipt of approval documents and promptly reporting any inaccuracy to WRAIR HSPB.
- One subject completed the ICF using pencil; documentation noting the issue was recorded in the deviation log was written on the ICF.
- Two subjects wrote the incorrect date when dating the ICF; the incorrect dated of consent was circled on the ICF and documentation noting the issue was recorded in the deviation log was written on the ICF.

(WRAIR) Core protocol Amendment #5 was submitted to WRAIR HSPB/IRB on 5 February 2018; WRAIR IRB limited approval occurred on 21 February 2018; approved by HRPO on 28 September 2018; WRAIR Commander limited approval occurred on 6 March 2018, updated limited approval on 30 March 2018, and full approval on 8 November 2018. The amendment added one collaborator (Dr. Bilal Khokhar, DVBIC) to the core protocol, two new sites (addendums G and H), and acoustic sensors to collect blast characterization data; adding acoustics sensor required changes to addendums A, B, C, D, F.

(WRAIR) Core protocol Amendment #6 was submitted to WRAIR HSPB/IRB on 20 February 2018; approved by WRAIR IRB on 26 March 2018; approved by HRPO on 27 April 2018; WRAIR Commander approval occurred on 5 December 2018. The amendment added one new collaborator (Dr. Jason Bailie, DVBIC), three new data collection measures, and changed the number of blood draws in addendum B (from 4 to 6).

(WRAIR) Core protocol Update #1 to Amendment #6 was submitted to WRAIR HSPB/IRB on 8 August 2018; approved by WRAIR IRB on 16 October 2018; WRAIR Commander limited approval occurred on 5 December 2018. The update to the amendment added a new site (addendum E), use of digital media, administrative changes resulting from the post approval compliance monitoring audit, and revised details for addendum H. Full approval is pending a letter of support for addendum E.

(WRAIR) Core protocol Amendment #7 was submitted to WRAIR HSPB/IRB on 19 October 2018; approved by WRAIR IRB on 12 November 2018; HRPO approval pending; WRAIR Commander limited approval occurred on 21 November 2018. The amendment added associate and collaborating investigators, DoD policies for pregnant females, and modified blood draw details for addendums D and H. Full approval is pending HRPO approval for adding external collaborators and a letter of support for addendum E.

(WRAIR) Core protocol Amendment #8 was submitted to WRAIR HSPB/IRB on 11 December 2018 and is awaiting approval. The amendment added one new data collection site (addendum I).

(NRL) Nothing to Report, not applicable

Significant changes in use or care of vertebrate animals.

Nothing to Report, not applicable

Significant changes in use of biohazards and/or select agents

Nothing to Report, not applicable

6. PRODUCTS: List any products resulting from the project during the reporting period. If there is nothing to report under a particular item, state “Nothing to Report.”

- Publications, conference papers, and presentations**

Report only the major publication(s) resulting from the work under this award.

Journal publications. *List peer-reviewed articles or papers appearing in scientific, technical, or professional journals. Identify for each publication: Author(s); title; journal; volume: year; page numbers; status of publication (published; accepted, awaiting publication; submitted, under review; other); acknowledgement of federal support (yes/no).*

(WRAIR) Lang M., Kamimori GH, Misistia A, LaValle CR, Ghebremedhin MY, Ramos AN, & Egnoto MJ; Shooter experienced blast overpressure in 50 caliber weapon systems; Journal of Special Operations Medicine; 18(4): 2018; 87-91; published; yes.

Lang M., Kamimori GH, Braun J, & Egnoto MJ; Minimizing 50 Caliber Rifle Blast to Police Snipers: suggestions for Training and Deployment; Journal of the National Tactical Officers Association; Fall 2018; 64-70; published; yes.

Boutte AM, Thangavelu B, LaValle CR, Nemes J, Gilsdorf J, Shear DA, & Kamimori GH; Association of Brain Trauma Serum Biomarkers with Overpressure Exposure and Concussion-like Symptomology: A Preliminary Investigation; JAMA Network Open; under review; yes.

Chatterton Z, Mendelev N, Chen S, Raj T, Walker R, Carr W, Kamimori GH, Beeri M, Ge Y, Dwork A, & Haghighi F; Brain-Derived Circulating Cell-Free DNA defines the brain region and cell specific origins associated with neuronal atrophy; manuscript in preparation for Nature Communications; yes.

Khokhar B, LaValle CR, Bailie J, Carr W, Malik S, Martin EM, & Kamimori GH; Health Symptomology following environmental blast exposure during heavy wall breaching in a military cohort; manuscript in preparation for Journal of Neurotrauma; yes.

(NRL) O'Shaughnessy TJ, McCulloch RS, Chen Y, Soto CM, Christopher JJ, Bagchi A; Effect of simulated and real blast overpressures on in vitro 3D neuronal cell cultures; manuscript in preparation for Journal of Neurotrauma; yes.

Chen Y, O'Shaughnessy TJ, Kamimori GH, Egnoto MJ, Horner D, and Bagchi A; Investigation of overpressure and intracranial pressure across interface conditions towards a more accurate surrogate head model; manuscript in preparation for Annals of Biomedical Engineering; yes.

Books or other non-periodical, one-time publications. *Report any book, monograph, dissertation, abstract, or the like published as or in a separate publication, rather than a periodical or series. Include any significant publication in the proceedings of a one-time conference or in the report of a one-time study, commission, or the like. Identify for each one-time publication: Author(s); title; editor; title of collection, if applicable; bibliographic information; year; type of publication (e.g., book, thesis or dissertation); status of publication (published; accepted, awaiting publication; submitted, under review; other); acknowledgement of federal support (yes/no).*

Kamimori GH, Boutte AM, O'Shaughnessy TJ, LaValle CR, Egnoto MJ, Chen Y, & Bagchi A; A multi-faceted approach to characterizing the effects of repeated low-level blast exposure in operators; National Neuroscience Society Symposium; Toronto, Canada; 2018; abstract & poster; published; yes.

Boutte AM, Thangavelu B, LaValle CR, Egnoto MJ, Gilsdorf J, Shear DA, & Kamimori GH; Targeted Quantitation of Serum Protein Biomarkers in Response to Blast Overpressure Exposure among Military Breachers; National Neuroscience Society Symposium; Toronto, Canada; 2018; abstract & poster; published; yes.

Boutte AM, Thangavelu B, LaValle CR, Egnoto MJ, Gilsdorf J, Shear DA, & Kamimori GH; Targeted Quantitation of Serum Protein Biomarkers in Response to

Blast Overpressure Exposure among Military Breachers; Military Health System Research Symposium; Kissimmee, FL; 2018; abstract & poster; published; yes.

Misistia AC, LaValle CR, Skotak M, & Kamimori GH; Reporting Occupational Blast Wave Exposure During Multiday 50 caliber rifle Course; Military Health System Research Symposium; Kissimmee, FL; 2018; abstract & poster; published; yes.

Sajja VS, LaValle CR, Salib JE, Misistia AC, Ghebremedhin M, Egnoto MJ, Long JB, & Kamimori GH; Integrating Acoustic Levels into a Comprehensive Assessment of Cumulative Low Level Blast Overpressure Effects on Warfighters; Military Health System Research Symposium; Kissimmee, FL; 2018; abstract & poster; published; yes.

Ramos AN, Misistia AC, LaValle CR, & Kamimori GH; Characterization of Overpressure Exposure of Shoulder Mounted Assault Weapon (SMAW) During Training To Personnel and the Immediate Area; Military Health System Research Symposium; Kissimmee, FL; 2018; abstract & poster; published; yes.

Salib JE, Misistia AC, & Kamimori GH; Characterizing Internal and External Overpressure Exposure for Various Ballistic Helmets; Military Health System Research Symposium; Kissimmee, FL; 2018; abstract & poster; published; yes.

O'Shaughnessy TJ, Chen Y, Kamimori GH, Horner DM, Doherty MJ, & Bagchi A; Development of NRL Head-Brain Models & Their Application for Assessing Effects in Breacher Training Exercises; Military Health System Research Symposium; Kissimmee, FL; 2018; abstract & poster; published; yes.

Chen Y, Bagchi A, Kamimori GH, O'Shaughnessy TJ; Shockwave pressure transmission through the ear canal with hearing protection; Personal Armour Systems Symposium, Washington, DC; 2018. poster; published.

O'Shaughnessy TJ, Chen Y, Horner DM, Doherty MJ, Kamimori GH, Bagchi A; Influence of helmet system on blast overpressure transmission into the brain; Personal Armour Systems Symposium 2018 Proceedings. Washington, DC: International Personal Armour Committee, 2018, pp. 659-667.

Chen Y, Bagchi A, Kamimori GH, O'Shaughnessy TJ; Shockwave pressure transmission through the ear canal with hearing protection; Personal Armour Systems Symposium 2018 Proceedings. Washington, DC: International Personal Armour Committee, 2018, pp. 551-560.

Other publications, conference papers, and presentations. *Identify any other publications, conference papers and/or presentations not reported above. Specify the status of the publication as noted above. List presentations made during the last year (international, national, local societies, military meetings, etc.). Use an asterisk (*) if presentation produced a manuscript.*

Kamimori GH, Misistia AC, Sajja VS, Ramos AN, Ghebremedhin M, LaValle CR; Occupational blast exposure during military and law enforcement training; 25th International Symposium on Military Aspects of Blast and Shock; The Hague, Netherlands; 2018; conference presentation & paper; yes.

Boutte AM; Systemic Biomarkers of Acute Overpressure Exposure among Military Personnel; Blood Based Biomarkers for Traumatic Brain Injury State of the Science Meeting; Fort Detrick, MD; 2018; conference presentation; yes.

Boutte AM; Biomarkers of Traumatic Brain Injury and Occupational Exposure: Translational and Applied Research for the Military; Traumatic Brain Injury & Protection Research Symposium; Temple University, Philadelphia, PA; 2018; conference presentation; yes.

Kamimori GH & Boutte AM; Quantifying Occupational Blast Exposure during Military and Law Enforcement Training; International State-of-the-Science Meeting on The Neurological Effects of Repeated Exposure to Military Occupational Blast Implications for Preventions and Health; Pentagon City, VA; 2018; conference presentation; yes.

Kamimori GH, Boutte AM, O'Shaughnessy TJ, LaValle CR, Bagchi A; Immediate and acute effects of heavy wall breaching on cognitive performance and blood biomarkers; 25th International Symposium on Military Aspects of Blast and Shock; The Hague, Netherlands; 2018; conference presentation & paper; yes.

O'Shaughnessy, TJ, Chen, YC, Horner, DM, Kamimori, GH, Bagchi, A; Head surrogates for assessing repeated blast overpressure exposures to breachers; 25th International Symposium on Military Aspects of Blast and Shock; The Hague, Netherlands; 2018; conference presentation & paper; yes.

O'Shaughnessy TJ, Chen Y, Horner DM, Doherty MJ, Kamimori GH, Bagchi A; Influence of helmet system on blast overpressure transmission into the brain; Personal Armour Systems Symposium, Washington, DC; 2018; conference presentation.

O'Shaughnessy, TJ, Chen, YC, Kamimori, GH, Horner, DM, Doherty MJ, Bagchi, A; Assessing Effects of Repeated Blast Overpressure Effects in Breaching Training Exercises Utilizing NRL Head-Brain Models, at the 2018 Japan US Forum on Blast and Blunt Injury, Tokyo, Japan, 2018; abstract and conference presentation; published; yes.

- **Website(s) or other Internet site(s)**

List the URL for any Internet site(s) that disseminates the results of the research activities. A short description of each site should be provided. It is not necessary to include the publications already specified above in this section.

Nothing to Report

- **Technologies or techniques**

Identify technologies or techniques that resulted from the research activities. In addition to a description of the technologies or techniques, describe how they will be shared.

(WRAIR) Nothing to Report

(NRL) The results from the NHBMs (with sensors and with cell packs) will be shared with other DOD agencies. The protocol for making the instrumented NRL head brain model will be shared with other agencies should they want to make a similar surrogate head. The analyzed data and the conclusions drawn from the tests with the NHBMs will also be shared with other DOD agencies.
--

- **Inventions, patent applications, and/or licenses**

Identify inventions, patent applications with date, and/or licenses that have resulted from the research. State whether an application is provisional or non-provisional and indicate the application number. Submission of this information as part of an interim research performance progress report is not a substitute for any other invention reporting required under the terms and conditions of an award.

Nothing to Report

- **Other Products**

Identify any other reportable outcomes that were developed under this project. Reportable outcomes are defined as a research result that is or relates to a product, scientific advance, or research tool that makes a meaningful contribution toward the understanding, prevention, diagnosis, prognosis, treatment, and/or rehabilitation of a disease, injury or condition, or to improve the quality of life. Examples include:

- data or databases;
- biospecimen collections;
- audio or video products;
- software;
- models;
- educational aids or curricula;
- instruments or equipment;
- research material (e.g., Germplasm; cell lines, DNA probes, animal models);
- clinical interventions;
- new business creation; and
- other.

- | |
|--|
| <ul style="list-style-type: none"> • (WRAIR) Data: Overpressure, neurocognitive, symptom, demographic/occupational history data were collected at sites #1, #2, #6, and #7; in addition, stress inventory data were collected at sites #6 and #7. |
|--|

- (WRAIR) Biospecimen collections: cheek swab and blood samples were collected at sites #1, #2 (2 times), #6, and #7.
- (WRAIR) Symptom and neurocognitive (DANA subtasks: SRT, PRT, GNG) data from sites #1, #2, and #4 (some data were collected in 2017 and submitted in 2018) were submitted to FITBIR Informatics System on 28 March and 28 September 2018.
- (WRAIR) Biospecimens were transferred to James J. Peters VA Medical Center, Icahn School of Medicine at Mount Sinai (New York, NY) for additional biomarker (genetic) analyses.
- (NRL) Nothing to Report

7. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

What individuals have worked on the project?

Provide the following information for: (1) PDs/PIs; and (2) each person who has worked at least one person month per year on the project during the reporting period, regardless of the source of compensation (a person month equals approximately 160 hours of effort). If information is unchanged from a previous submission, provide the name only and indicate "no change."

Example:

Name: Mary Smith
 Project Role: Graduate Student
 Research Identifier (e.g. ORCID ID): 1234567
 Nearest person month worked: 5

Contribution to Project: Ms. Smith has performed work in the area of combined error-control and constrained coding.
 Funding Support: The Ford Foundation (Complete only if the funding support is provided from other than this award).

Name: Gary Kamimori
 Project Role: WRAIR PI
 Research Identifier (ORCID ID): 0000-0001-7899-9553
 Nearest person month worked: 9
 Contribution to project: no change.

Name: Angela Bouttè
 Project Role: WRAIR Laboratory Investigator
 Research Identifier (ORCID ID): 0000-0003-3542-8122
 Nearest person month worked: 6
 Contribution to project: no change.
 Funding Support: The Combat Casualty Care Research Program

Name: Fatemeh Haghighi
 Project Role: WRAIR Collaborating Laboratory Investigator

Research Identifier (ORCID ID): 0000-0003-0920-6956

Nearest person month worked: 1

Contribution to project: no change.

Funding Support: VA Merits RX001705, CX001395, BX003794, and CX001728

Name: Amit Bagchi

Project Role: NRL PI

Nearest person month worked: 2

Contribution to project: no change.

Name: Thomas O'Shaughnessy

Project Role: NRL PI

Nearest person month worked: 4

Contribution to project: no change.

Name: YungChia Chen

Project Role: NRL Biomedical/Biomechanical Engineer

Nearest person month worked: 6

Contribution to project: no change.

Name: David M Horner

Project Role: NRL Test Engineer

Nearest person month worked: 2

Contribution to project: no change.

Name: Christina LaValle

Project Role: WRAIR Data Manager/Statistician, Study Coordinator

Research Identifier (ORCID ID): 0000-0003-1529-4761

Nearest person month worked: 12

Contribution to project: no change

Name: Mike Egnoto

Project Role: WRAIR Clinical Informaticist

Nearest person month worked: 10

Contribution to project: no change

Has there been a change in the active other support of the PD/PI(s) or senior/key personnel since the last reporting period?

If there is nothing significant to report during this reporting period, state "Nothing to Report."

If the active support has changed for the PD/PI(s) or senior/key personnel, then describe what the change has been. Changes may occur, for example, if a previously active grant has closed and/or if a previously pending grant is now active. Annotate this information so it is clear what has changed from the previous submission. Submission of other support information is not necessary for pending changes or for changes in the level of effort for active support reported

previously. The awarding agency may require prior written approval if a change in active other support significantly impacts the effort on the project that is the subject of the project report.

Nothing to Report

What other organizations were involved as partners?

If there is nothing significant to report during this reporting period, state “Nothing to Report.”

Describe partner organizations – academic institutions, other nonprofits, industrial or commercial firms, state or local governments, schools or school systems, or other organizations (foreign or domestic) – that were involved with the project. Partner organizations may have provided financial or in-kind support, supplied facilities or equipment, collaborated in the research, exchanged personnel, or otherwise contributed.

Provide the following information for each partnership:

Organization Name:

Location of Organization: (if foreign location list country)

Partner’s contribution to the project (identify one or more)

- Financial support;
- In-kind support (e.g., partner makes software, computers, equipment, etc., available to project staff);
- Facilities (e.g., project staff use the partner’s facilities for project activities);
- Collaboration (e.g., partner’s staff work with project staff on the project);
- Personnel exchanges (e.g., project staff and/or partner’s staff use each other’s facilities, work at each other’s site); and
- Other.

Military

Organization Name: U.S. Army 35th Engineers of Ft Leonard Wood

Location of Organization: Ft Leonard Wood, MO

Partner’s contribution to the project

- Facilities – project staff used partner’s facilities for project activities
- Collaboration – technical discussions between partner and project staff
- Other – partner organization permitted subject recruitment to enroll study volunteers

Organization Name: U.S. Marine Corps Methods of Entry School

Location of Organization: Quantico, VA

Partner’s contribution to the project

- Facilities – project staff used partner’s facilities for project activities
- Collaboration – technical discussions between partner and project staff

Organization Name: 194th Armor & 198th Infantry

Location of Organization: Ft Benning, GA

Partner’s contribution to the project

- Facilities – project staff used partner’s facilities for project activities
- Collaboration – technical discussions between partner and project staff

- Other – partner organization permitted subject recruitment to enroll study volunteers

Organization Name: I & III Marine Expeditionary Force (MEF)

Location of Organization: Camp Pendleton, CA (I MEF) & Camp Hansen, Okinawa, Japan (III MEF)

Partner's contribution to the project

- Facilities – project staff used partner's facilities for project activities
- Collaboration – technical discussions between partner and project staff
- Other – partner organization permitted subject recruitment to enroll study volunteers

Organization Name: 171st Infantry

Location of Organization: Ft Jackson, SC

Partner's contribution to the project

- Facilities – project staff used partner's facilities for project activities
- Collaboration – technical discussions between partner and project staff

Organization Name: US Army Research, Development Engineering Command (RDECOM)

Location of Organization: Aberdeen Proving Ground, Aberdeen, MD and Picatinny Arsenal, Wharton, NJ

Partner's contribution to the project

- Facilities – project staff used partner's facilities for project activities
- Collaboration – technical discussions between partner and project staff

Organization Name: US Army Research Laboratory (ARL)

Location of Organization: Adelphi, MD

Partner's contribution to the project

- Facilities – project staff used partner's facilities for project activities
- Collaboration – technical discussions between partner and project staff

Organization Name: US Army Asymmetric Warfare Group (AWG)

Location of Organization: Ft A.P. Hill, VA

Partner's contribution to the project

- Facilities – project staff used partner's facilities for project activities
- Collaboration – technical discussions between partner and project staff

Organization Name: Engineer Research and Development Center

Location of Organization: Champaign, IL

Partner's contribution to the project

- Facilities – project staff used partner's facilities for project activities
- Collaboration – technical discussions between partner and project staff

Organization Name: US Army Training and Doctrine Command (TRADOC) Maneuver Center of Excellence (MCoE)

Location of Organization: Ft Benning, GA

Partner's contribution to the project

- Facilities – project staff used partner’s facilities for project activities
- Collaboration – technical discussions between partner and project staff

Organization Name: US Army Aeromedical Research Laboratory (USAARL)

Location of Organization: Ft Rucker, AL

Partner’s contribution to the project

- Facilities – project staff used partner’s facilities for project activities
- Collaboration – technical discussions between partner and project staff

Organization Name: Department of Energy

Location of Organization: Oakridge, TN/Albuquerque, NM

Partner’s contribution to the project

- Facilities – project staff used partner’s facilities for project activities
- Collaboration – technical discussions between partner and project staff
- Other – partner organization permitted subject recruitment to enroll study volunteers

Organization Name: Las Vegas Special Weapons and Tactics (SWAT)

Location of Organization: Las Vegas, NV

Partner’s contribution to the project

- Facilities – project staff used partner’s facilities for project activities
- Collaboration – technical discussions between partner and project staff
- Other – partner organization will permit subject recruitment to enroll study volunteers

Organization Name: Washington County Sheriff’s Office

Location of Organization: Beaverton, OR

Partner’s contribution to the project

- Facilities – project staff used partner’s facilities for project activities
- Collaboration – technical discussions between partner and project staff
- Other – partner organization will permit subject recruitment to enroll study volunteers

Organization Name: Portland Special Emergency Reaction Team (SERT)

Location of Organization: Portland, OR

Partner’s contribution to the project

- Facilities – project staff used partner’s facilities for project activities
- Collaboration – technical discussions between partner and project staff

Organization Name: Dallas Special Weapons and Tactics (SWAT)

Location of Organization: Dallas, TX

Partner’s contribution to the project

- Facilities – project staff used partner’s facilities for project activities
- Collaboration – technical discussions between partner and project staff

Organization Name: Maricopa County Sheriff’s Office

Location of Organization: Maricopa, AZ

Partner’s contribution to the project

- Facilities – project staff used partner’s facilities for project activities
- Collaboration – technical discussions between partner and project staff

Organization Name: National Capital Region Breachers Consortium (28 team)

Location of Organization: Washington, DC

Partner’s contribution to the project

- Facilities – project staff used partner’s facilities for project activities
- Collaboration – technical discussions between partner and project staff

Private Tactical Training Groups

Organization Name: Forced Entry Tactical Training (FETT)/Global Assets Integrated

Location of Organization: multiple sites/locations

Partner’s contribution to the project

- Facilities – project staff use partner’s facilities for project activities
- Collaboration – partner staff work with project staff on project

Organization Name: Tacflow Academy

Location of Organization: multiple sites/locations

Partner’s contribution to the project

- Facilities – project staff used partner’s facilities for project activities
- Collaboration – technical discussions between partner and project staff
- Other – partner organization will permit subject recruitment to enroll study volunteers

Organization Name: Tactical Energetic Entry Systems (TEES)

Location of Organization: Southaven, MS

Partner’s contribution to the project

- Facilities – project staff use partner’s facilities for project activities
- Collaboration – partner staff work with project staff on project

Academic

Organization Name: Defense and Veterans Brain Injury Center

Location of Organization: Silver Spring, MD; Colorado Springs, CO; Camp Pendleton, CA

Partner’s contribution to the project

- Collaboration – technical discussions between partner and project staff

Organization Name: Georgia Tech Research Institute (GTRI)

Location of Organization: Atlanta, GA

Partner’s contribution to the project

- Facilities – project staff use partner’s facilities for project activities
- Collaboration – partner staff work with project staff on project

Organization Name: Johns Hopkins University Applied Physics Laboratory

Location of Organization: Laurel, MD

Partner’s contribution to the project

- Facilities – project staff use partner’s facilities for project activities
- Collaboration – partner staff work with project staff on project

Organization Name: New Jersey Institute of Technology

Location of Organization: Newark, NJ

Partner’s contribution to the project

- Facilities – project staff used partner’s facilities for project activities
- Collaboration – partner staff work with project staff on project

Organization Name: James J. Peters VA Medical Center, Icahn School of Medicine at Mount Sinai

Location of Organization: New York, NY

Partner’s contribution to the project

- Facilities – project staff use partner’s facilities for project activities
- Collaboration – partner staff work with project staff on project

Organization Name: Penn State University

Location of Organization: State College, PA

Partner’s contribution to the project

- Collaboration – technical discussions between partner and project staff

Private Technology

Organization Name: Applied Research Associates

Location of Organization: San Antonio, TX

Partner’s contribution to the project

- Collaboration – partner staff work with project staff on project

Organization Name: CFD Research Corporation

Location of Organization: Huntsville, AL

Partner’s contribution to the project

- Collaboration – technical discussions between partner and project staff

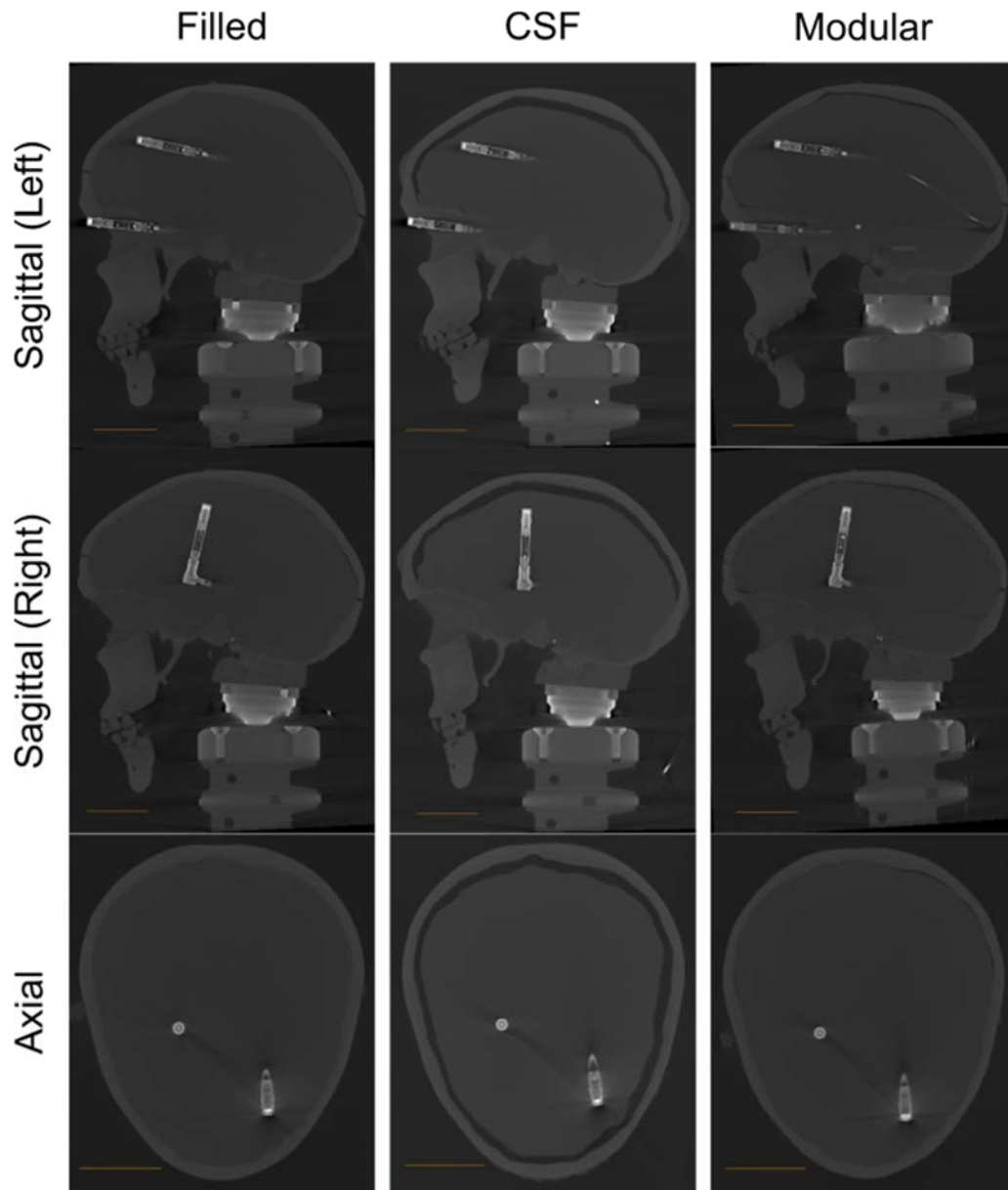
8. SPECIAL REPORTING REQUIREMENTS

COLLABORATIVE AWARDS: For collaborative awards, independent reports are required from BOTH the Initiating PI and the Collaborating/Partnering PI. A duplicative report is acceptable; however, tasks shall be clearly marked with the responsible PI and research site. A report shall be submitted to <https://ers.amedd.army.mil> for each unique award.

QUAD CHARTS: If applicable, the Quad Chart (available on <https://www.usamraa.army.mil>) should be updated and submitted with attachments.

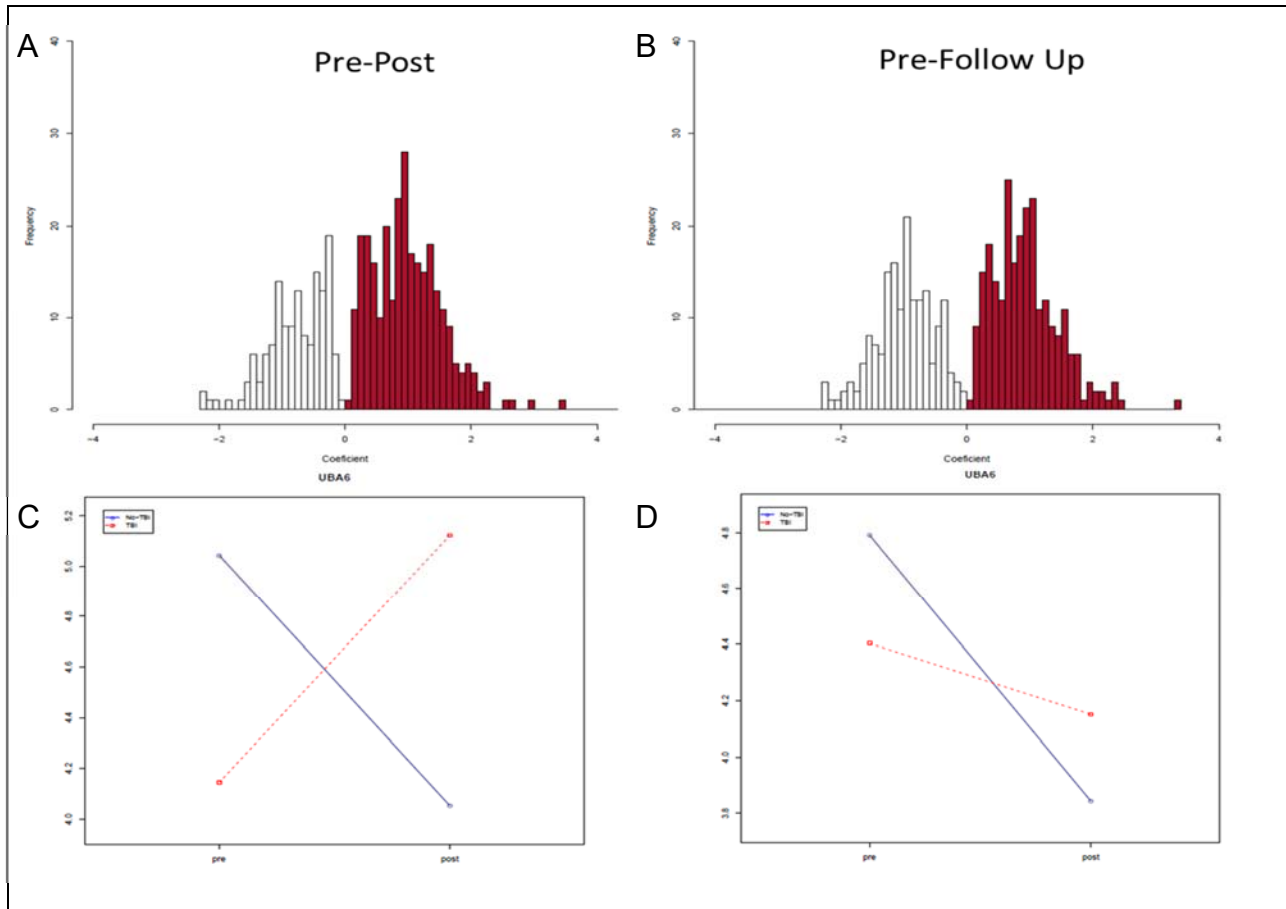
- 9. APPENDICES:** Attach all appendices that contain information that supplements, clarifies or supports the text. Examples include original copies of journal articles, reprints of manuscripts and abstracts, a curriculum vitae, patent applications, study questionnaires, and surveys, etc.
- a. Three NHBMs used in to test the effect of interface conditions between the brain and the skull
 - b. Gene expression responsivity pre vs post blast exposure and pre vs follow up relative to self-reported prior history of concussion/TBI.
 - c. NHBM showing higher intracranial pressure with helmet at two standoff distances
 - d. Effect of overpressure loading (eye pressure) on pressure propagation into the surrogate brain (in-brain pressure) for three brain configurations – filled, CSF, and modular (non-filled)
 - e. Impact of research; operator recognition of research efforts
 - f. Published version of “Shooter experienced blast overpressure in 50 caliber weapon systems,” Journal of Special Operations Medicine
 - g. Published version of “Minimizing 50 Caliber Rifle Blast to Police Snipers: suggestions for Training and Deployment,” Journal of the National Tactical Officers Association (omitted pages are full page advertisements)
 - h. Published version of “Shockwave pressure transmission through the ear canal with hearing protection,” Personal Armour Systems Symposium 2018 Proceedings
 - i. Published version of “Influence of helmet system on blast overpressure transmission into the brain,” Personal Armour Systems Symposium 2018 Proceedings
 - j. Published version of “Head surrogates for assessing repeated blast overpressure exposures to breachers,” 25th International Symposium on Military Aspects of Blast and Shock conference paper
 - k. Published version of “Immediate and acute effects of heavy wall breaching on cognitive performance and blood biomarkers,” 25th International Symposium on Military Aspects of Blast and Shock conference paper
 - l. Published version of “Occupational blast exposure during military and law enforcement training,” 25th International Symposium on Military Aspects of Blast and Shock conference paper

Appendix A: Three NHBMs used in to test the effect of boundary conditions between the brain and the skull

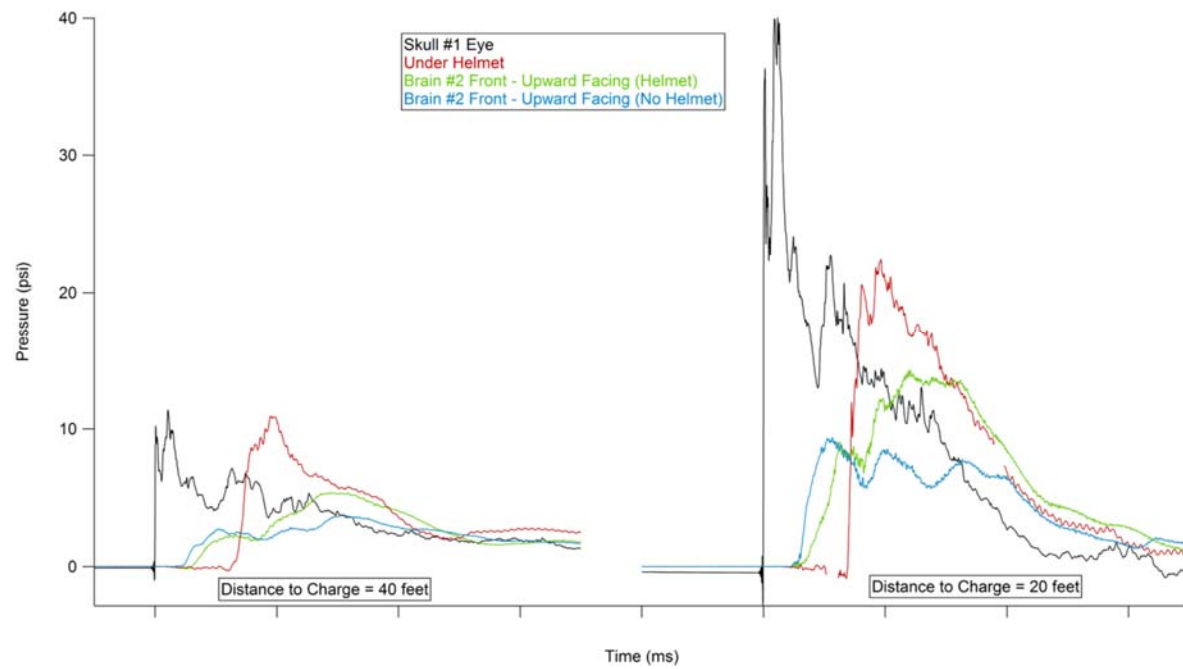


The objects inside the brain are PCB acceleration compensated 50 psi pressure sensors.

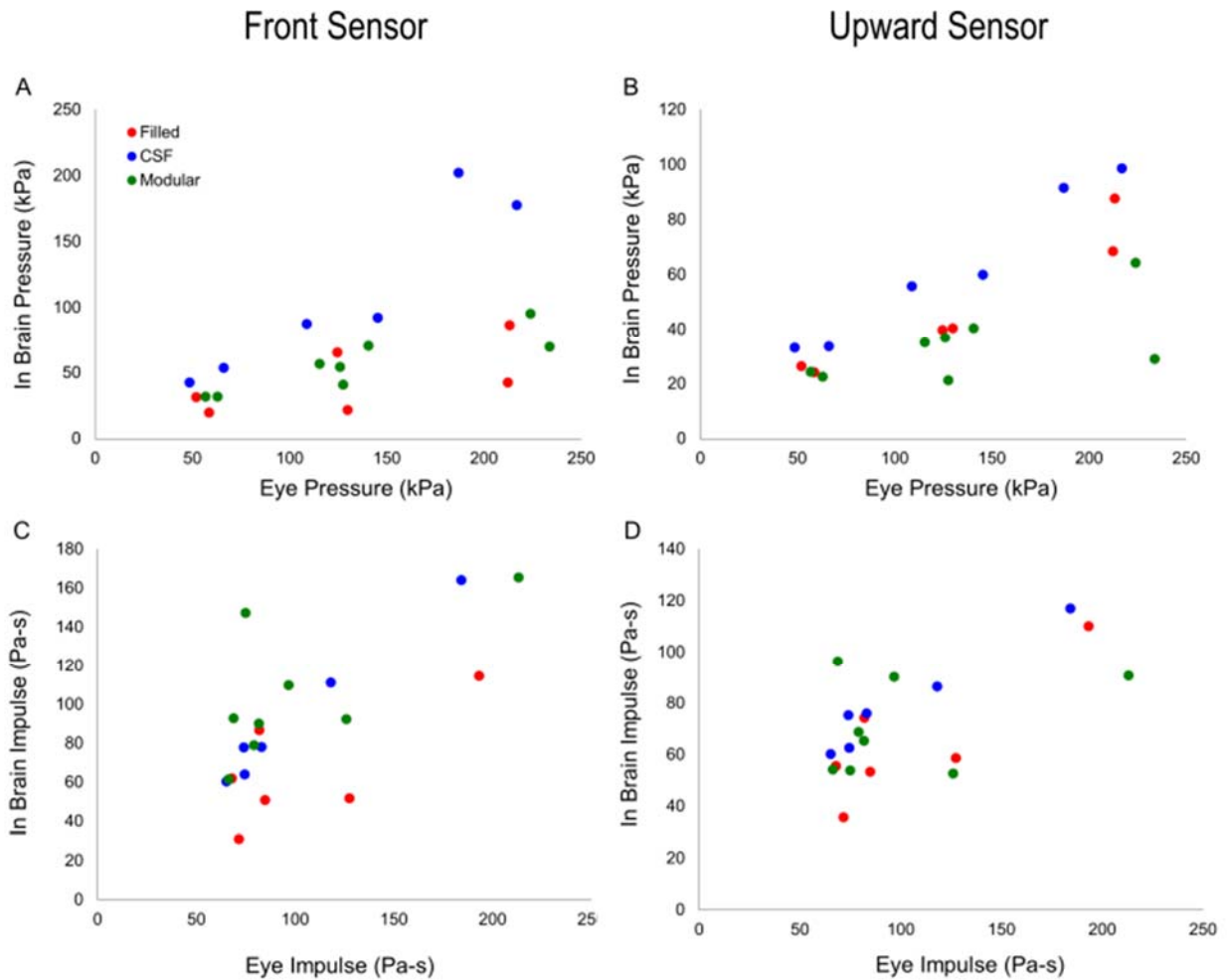
Appendix B: Gene expression responsivity pre vs post blast exposure and pre vs follow up relative to self-reported prior history of concussion/TBI.



Figures (A) and (B) show the differences in change in gene expression following blast exposure in individuals with TBI relative to those without. (A) shows greater difference in gene expression with more positive outliers, i.e. more gene expression responsivity in individuals with history of TBI, denoted by bars in red, where these differences tend to subside at follow up 24 hours following breacher training (B), demonstrating acute responsivity. As an example, (C) and (D) shows a change in expression in a specific gene, ubiquitin like modifier activating enzyme 6, (UBA6). In (C) pre vs post exposure individuals with a history of TBI show an increase in UBA6 expression following blast as compared to a decrease in expression in those with no history of TBI. Comparatively, in (D) for the same gene, gene expression for UBA6 in the TBI individuals almost dissipates 24 following blast.

Appendix C: NHBM showing higher intracranial pressure with helmet at two standoff distances

Appendix D: Effect of overpressure loading (eye pressure) on pressure propagation into the surrogate brain (in-brain pressure) for three brain configurations – filled, CSF, and modular (non-filled)



Front Sensor: Sensor inside the brain and pointing to the front

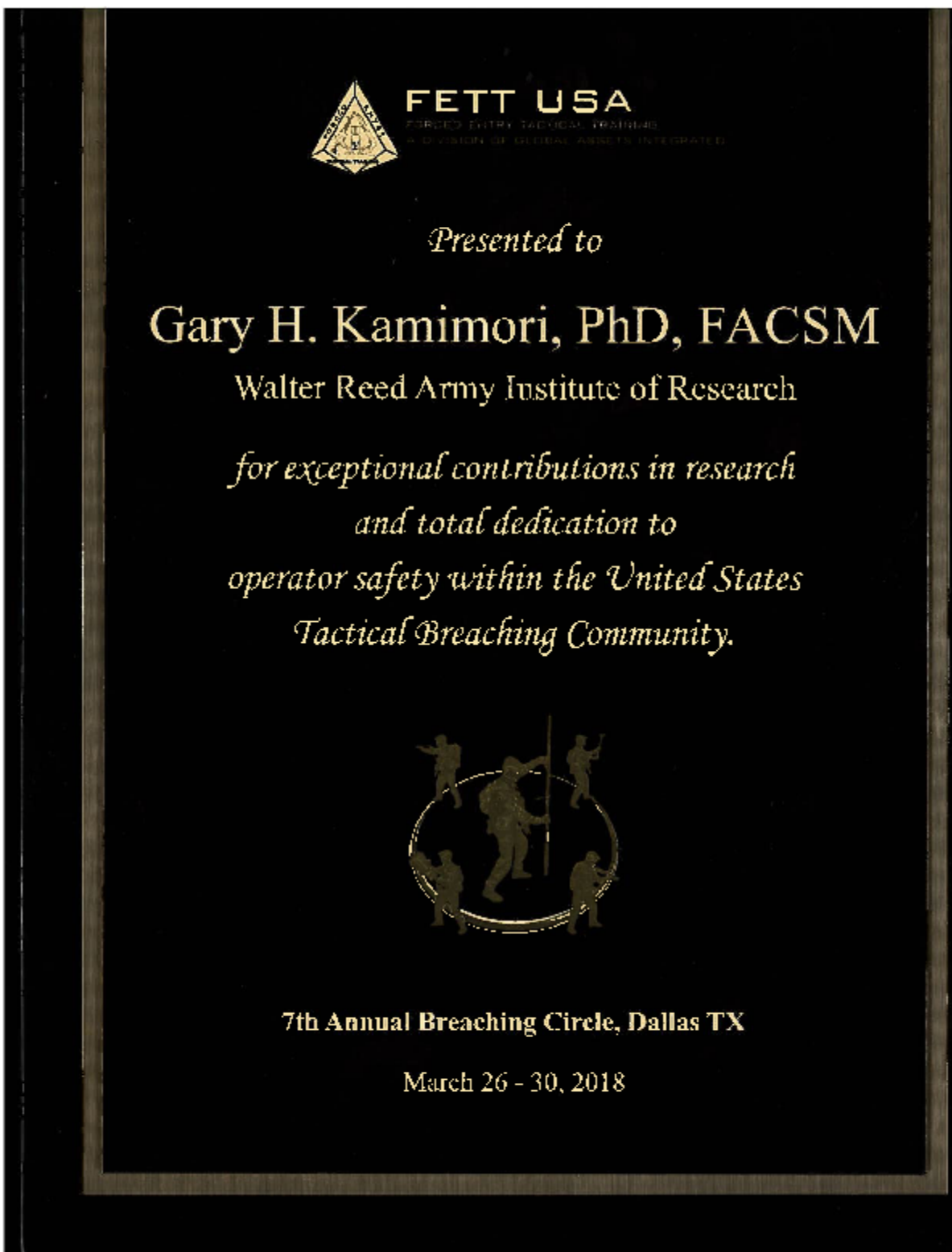
Upward Sensor: Sensor inside the brain and pointing to upward

Note: All sensor locations are shown in Appendix A. The PCB 50 psi pressure sensors were placed in the surrogate brains.

Appendix E: Research impact on operators (impact beyond science and technology)



Appendix E: Research impact on operators (impact beyond science and technology)



Appendix F: Published version of manuscript in JSOM

Shooter-Experienced Blast Overpressure in .50-Caliber Rifles

Mark Lang¹; Gary H. Kamimori, PhD²; Anthony Misistia, MS²; Christina R. LaValle, MS²;
A. N. Ramos²; M. Y. Ghebremedhin, MS²; Michael J. Egnoto, PhD^{2*}

ABSTRACT

Background: Increasingly, military and law enforcement are using .50-caliber rifles for conflict resolution involving barricades, armor, vehicles, and situations that require increased kinetic energy. Consequences to the shooter resulting from the blast produced while firing these rifles remain unknown. We measured blast overpressure (OP) and impulse across various positions, environments, and weapon configurations to evaluate blast exposures to shooters. **Methods:** Two separate, multiday, .50-caliber rifle training courses were evaluated to understand the blast exposure profile received from various tactical training scenarios, such as different firing positions (e.g., standing, prone, seated, kneeling) and locations (e.g., inside and atop vehicles, inside buildings, on hard/soft surfaces) across a variety of .50-caliber rifles with various barrel lengths, muzzle devices, and ammunition. Blackbox Biometrics, Generation 6, gauges were placed on operators to measure incident blast exposure. A total of 444 rounds fired from various .50-caliber rifles were evaluated to determine what OP was received by 32 different shooters. **Results:** Our findings indicate OPs >4 psi are common and that muzzle devices are critical to blast exposure. Shooting positions closer to the ground experienced higher OP and impulse than did other positions. Suppressors mitigated blast effects well. **Conclusion:** When resources and operational parameters allow, suppressors are recommended, as are positions that move the shooter farther from reflective surfaces (standing preferred) to effectively reduce blast exposure. These shooter positions may require the use of supplemental rifle rests/tripods to provide sufficiently stable firing platforms from the standing position.

Keywords: risk evaluation; risk mitigation; work engagement; occupational stress; wearable electronic devices; interdisciplinary research; rifle; overpressure

Introduction

The effects of overpressure (OP) exposure from weapon systems (e.g., .50-caliber rifles, flash bangs) are receiving growing attention from the scientific community. In addition to broad military applications, the US law enforcement community is seeing a significant emergence of "light .50" rifle systems.¹ As more law enforcement agency Special Weapons and Tactics teams, military, and other relevant operators expand their capabilities to include .50-caliber rifles, training doctrines need to evolve to minimize risks to shooters without compromising

capability. The blast, or the forces that result from firing the .50-caliber rifle, strikes the operator with enough energy to warrant implementing strategies that minimize shooter risks that may result from exposure.

The effects of blast on the operator of weapon systems have been the subject of research for over 50 years.² Current research suggests some individuals may experience deleterious effects that may affect readiness after repeated exposure to blast³⁻⁵ and could experience negative consequences to health.^{6,7} This presents a two-fold problem: Improper training not only could jeopardize shooters' ability to perform their duties in critical situations but also pose a risk to their long term health unnecessarily.

The purpose of this research was to characterize OP exposure associated with firing the .50-caliber rifle during training and to understand what components of the weapon have the most impact on operator exposure. The peak blast OP as well as impulse, which is the total force exerted on an object from an OP, were measured in conjunction during two separate .50-caliber rifle training courses. These blast characteristics were measured across different barrel lengths, muzzle devices (including suppressors), shooting positions, and shooting locations. Measurements were made during realistic training environments that mimic the operational environments likely to be encountered by shooters. It was hypothesized that even though many .50-caliber rifles exceed current military doctrine for blast exposure (≥4 psi), reasonable changes in environment, weapon system configuration, or shooting position can help mitigate shooter exposure. The 4-psi threshold for OP originates from a collection of reports supporting atomic weapon development, which noted that an increased probability in the rupture of the tympanic membrane was possible at OPs >4 psi.⁸ Hearing damage has been linked to traumatic brain injury,⁹ and so the 4-psi threshold has carried over as a proxy that indicates, to some extent, that the 4-psi threshold, in accordance with current research and understanding, represents a best known point where the potential for neurocognitive perturbation may occur. Additional information on the 4-psi threshold can be found in SWO 60-AA Vol 1 REV. 9—Demolitions Technical Manual, and FM 3-34.214 (FM 5-250)—US Army Explosives and Demolition.

All OP measurements in this article are in pounds per square inch and represent incident OP. This article is organized as

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follows: The two courses are presented as study 1 and study 2 and are described in detail with accompanying results from both trainings. General conclusions are drawn about operator exposure to OP under various conditions, and the final section describes implications and recommendations resulting from this work.

Study 1

General Description

To begin assessing shooter OP exposure, evaluations of shooting position and barrel length were conducted to compare shooter OP exposures while firing.

In the first course (3 days), OP was characterized on a total of 451 rounds fired by 20 shooters from various .50-caliber rifles with 20- and 29-inch barrels while participating in a .50 Cal/Hard Target Weapons training course taught by Tacflow Academy (www.tacflow.com). These measurements yielded 224 usable data points for analysis. Shooters engaged targets from the seated/kneeling, prone, and standing positions while outside, as well as inside and atop an armored vehicle (Lenco BearCat); from the top of a fire training tower; and through a window in an enclosed room. Ammunition varied between shooters based on target and department supply, with M33 Ball (660 grain) being a commonly fielded ammunition.

Weather was overcast with occasional showers and gusts of wind up to 43 mph. Temperatures ranged from a high of 91°F (33°C) to a low of 54°F (12°C), with most shots being fired at approximately 77°F (25°C). Average humidity throughout the test days was 77%. Shots were taken at approximately 597 ft above sea level.

Students were given five Blackbox Biometrics, Generation 6 (B3 Gen6; www.b3inc.com) blast gauges affixed to the shooter with gauges on the front of their hats or head, on the right and left shoulders, and on both wrists along the distal radioulnar joint (the position at which people generally wear a wrist watch). The B3 Gen6 gauge does not register peak OP <2.5 psi. Visual analysis of shooter positioning allowed us to determine which gauge provided the best incident OP measure. Incident OP was used because all known safety tables are tied to incident OP, because reflective OP can vary wildly from experienced OP based on the orientation of the sensor. Reported values use a left-shoulder gauge, because research experience notes that for a predominately right-handed cohort, this orientation gives the most accurate incident OP measurement (Table 1).

Conclusions: Study 1

Overall, .50-caliber rifles can produce excessive OP, and research has overlooked the roles of rifle configuration, shooting environment, or shooter position on the OP shooters receive when using these rifles. Notably, the most common firing position operators used with the weapon platform was prone, which consistently produced OP in excess of 4 psi. Of note, longer barrels resulted in decreased OP across shooting positions, but the effect was marginal and inconsistent (Table 1). Impulse did not vary meaningfully in aggregate across barrel length, but shooting in confined or rigid spaces did seem to increase experienced impulse to operators. The inconsistent decrease in OP from barrel length is likely due to the muzzle devices.

TABLE 1 Study 1: Overpressure and Impulse by Shooting Position and Barrel Length

Position and Barrel Length (inches)	OP, mean (SD), psi	95% CI	Impulse, mean (SD) (m * psi)	No.
Kneeling				
20	5.04 (—)	—	1.74 (—)	1
29	3.48 (1.10)	1.43, 4.89	1.83 (1.42)	8
Prone				
20	5.81 (0.99)	4.52, 9.22	2.97 (1.18)	34
29	4.69 (1.26)	2.96, 8.02	2.24 (0.91)	113
Standing				
20	8.20 (0.46)*	7.84, 8.55	3.27 (1.94)	2
29	4.07 (1.21)	2.56, 6.14	2.18 (1.09)	31
Prone (BearCat)				
20	3.90 (1.69)	2.65, 5.91	1.31 (0.76)	3
29	3.72 (0.13)	3.55, 3.81	2.69 (2.38)	6
Standing (BearCat)				
20	—	—	—	—
29	4.20 (1.38)	3.00, 5.85	2.18 (1.18)	4
Tower				
20	4.27 (0.34)	4.01, 4.76	3.08 (0.49)	4
29	—	—	—	—
Window				
20	5.15 (0.90)	4.48, 6.58	3.83 (0.91)	7
29	3.97 (1.51)	2.29, 7.76	4.23 (1.26)	11
Total for 20*	5.56 (0.93)	3.11, 9.22	2.60 (1.13)	51
Total for 29*	4.43 (1.22)	1.02, 8.42	2.25 (1.12)	173
TOTAL	4.69 (1.56)	1.02, 9.21	2.33 (1.12)	224

—, not measured; CI, confidence interval; OP, overpressure; SD, standard deviation.

*Suspected complication with shooter ammunition or sensor placement.

Study 2

General Description

Based on information collected during study 1, there was a greater focus on the variation in barrel length in this data collection, and special attention was paid to muzzle devices. Broadly, muzzle devices were broken down into the following categories: (1) no muzzle device (just a target crown on the end of the barrel); (2) a 45° slant muzzle brake, similar to the one fielded by Barrett M82A1 rifles; (3) ported flash suppressors with a series of holes drilled around them in a 270° arc, with the bottom portion remaining undrilled to minimize dust and debris disturbance while firing (similar to an A2-style flash hider but with holes instead of slots); and (4) a suppressor (generally, the AWC Turbodyne or Barrett .50-caliber suppressors).

Measurements were collected from a total of 220 rounds fired by 12 shooters from various .50-caliber rifles with 24-, 26-, 27-, 28-, and 29-inch barrels without a muzzle brake and with a 45° muzzle brake participating in a .50 Cal/Hard Target Weapons course instructed by Tacflow Academy over 4 days.

Usable OP data were identified from a total of 89 rounds fired. Shooters in this course engaged targets from seated/kneeling, standing, and prone positions while outside, atop an armored vehicle (Lenco BearCat), and from inside an armored vehicle (Lenco BearCat). Ammunition varied between shooters based on target and supply, with Hornady 750 grain A-MAX being a

commonly fielded ammunition. Weather was generally partly cloudy with gusts of wind up to 15 mph. Temperatures ranged from a high of 76°F (24°C) with a low 50°F (10°C) throughout measurements, with the majority of shots being taken at approximately 70°F (21°C). Average humidity throughout test days was 37%, with no precipitation. Shots were taken at approximately 1,867 ft above sea level. Students were measured with B3 Gen6 blast gauges identical to those used in study 1.

Notably, firing from inside or atop vehicles was associated with higher OP measurements (Table 2). OP across all shots fired was reported as a mean of 4.51 psi (standard deviation, 0.52; $n = 89$). Removing the rounds fired from the vehicles, the mean OP dropped to 4.39 (0.56) psi ($n = 76$). Looking at the vehicle rounds exclusively, notably higher OP was observed (mean, 5.21 [0.27]; $n = 13$). Where possible, care should be taken to minimize shooting from atop hard, metallic surfaces and from within vehicles. Similar to data in study 1, impulse seemed exacerbated by firing from atop or within rigid structures.

Evaluating the effects of position across all barrel lengths and muzzle devices, the seated position seemed to be the most problematic (Table 3). Likely, this has to do with how the body leans forward while in the seated firing position, which cants the body further toward the muzzle while using the offhand for support. In addition, the seated shooting position creates a somewhat concave form, which potentially may be collecting and focusing blast.

As a general trend, moving the weapons platform closer to the ground or resting it on a rigid structure seemed to increase the OP experienced by the operator. Impulse did not seem to vary greatly between positions.

TABLE 3 Study 2: Effects of Position

Position	OP, mean (SD), psi	95% CI	Impulse, mean (SD) (m × psi)	No.
Kneeling	5.23 (0.84)	3.93, 6.40	2.34 (0.57)	9
Sitting	5.67 (0.48)	5.27, 6.40	2.32 (0.85)	4
Standing	4.51 (0.35)	3.97, 5.05	2.31 (0.82)	9
Prone	5.62 (0.98)	3.03, 6.84	2.27 (0.93)	13
Prone (IT)	6.09 (0.25)	5.94, 6.39	4.16 (0.30)	3
Prone (OT)	6.82 (0.38)	6.59, 7.26	2.95 (1.34)	3

—, not measured; CI, confidence interval; IT, inside BearCat; OP, overpressure; OT, atop BearCat; SD, standard deviation.

To isolate position and its relationship to OP, muzzle device and barrel length were controlled for in the following analyses, and evaluated position was the only variable using the 29-in barrel with the 45° slanting muzzle brake (one of the most common rifle configurations; Table 3). The seated position remains the most problematic, but it became clear from our data that the closer the operator is to a reflective surface (vehicle, hard surface, or on dirt), the OP on the shooter is more likely to exceed the current standard of 4 psi and likely will exceed 5.6 psi. We suspect that the 45° muzzle brake on the 29-in barrel is sufficiently far away from the operator that the shooter is in the cone of redirected blast resulting from the muzzle brake. Impulse was exacerbated by firing from within or atop rigid structures and vehicles.

To further investigate the effects of barrel length, barrel length was isolated and investigated. Data are shown in Table 4. Once variation in muzzle device was controlled for by using only data from .50-caliber rifles with identical muzzle brakes,

TABLE 2 Study 2: Overpressure and Impulse by Shooting Position, Barrel Length, and Muzzle Device

Position	Barrel Length (inches)	Muzzle Device	OP, mean (SD), psi	95% CI	Impulse, mean (SD) (m × psi)	No.
Kneeling	24	None	4.26 (0.34)	4.00, 4.52	1.96 (0.31)	2
	27	None	3.05 (0.15)	2.93, 3.16	4.14 (1.12)	2
	28	45° slant	5.77 (0.15)	5.65, 5.88	2.69 (1.94)	2
	29	None	3.36 (0.11)	3.30, 3.52	3.09 (1.20)	4
		45° slant	5.23 (0.84)	3.93, 6.40	2.34 (0.57)	9
Sitting	24	None	3.59 (0.31)	3.35, 3.83	3.27 (0.30)	2
	29	45° slant	5.67 (0.48)	5.27, 6.40	2.32 (0.85)	4
Prone	24	None	3.59 (0.31)	3.52, 3.83	2.25 (0.10)	2
	26	45° slant	3.99 (0.12)	3.92, 4.14	3.43 (1.76)	3
	26	Ported FH	3.02 (0.29)	2.71, 3.38	1.39 (1.09)	5
	27	None	3.29 (0.14)	3.15, 3.41	1.57 (1.08)	5
	28	45° slant	4.97 (—)	—	1.45 (—)	2
	29	45° slant	5.62 (0.98)	3.03, 6.84	2.27 (0.93)	13
Standing	24	None	3.23 (0.25)	2.93, 3.38	1.60 (0.41)	3
	27	None	4.09 (1.25)	2.90, 5.59	2.94 (0.74)	4
	29	None	3.40 (1.21)	2.61, 5.59	1.71 (0.18)	5
	29	45° slant	4.51 (0.35)	3.94, 5.05	2.31 (0.82)	9
	26	45° slant	3.38 (0.46)	3.02, 3.73	2.91 (0.21)	2
Prone (IT)	27	None	4.31 (0.13)	4.31, 4.54	3.70 (0.28)	3
	29	45° slant	6.09 (0.25)	5.940, 6.390	4.16 (0.30)	3
	27	None	4.64 (0.16)	4.521, 4.759	2.98 (2.16)	2
Prone (OT)	29	45° slant	6.82 (0.38)	6.585, 7.265	2.95 (1.34)	3
TOTAL	—	—	4.51 (0.52)	—	2.61 (1.63)	89

—, not measured; CI, confidence interval; IT, inside BearCat; OP, overpressure; OT, atop BearCat; SD, standard deviation.

barrel length was inconsistent and largely inconsequential to shooter OP. OP increased, then decreased, as longer barrels were tested.

TABLE 4 Study 2: Effects of Barrel Length

Barrel Length (inches)	OP, mean (SD), psi	95% CI	Impulse, mean (SD) (m × psi)	No.
24	3.62 (0.30)	2.93, 4.51	2.16 (0.73)	9
26	3.38 (0.23)	2.71, 4.14	2.19 (1.37)	8
27	3.82 (0.42)	2.93, 5.56	2.53 (1.38)	16
28	5.37 (0.08)	4.98, 5.87	1.69 (1.18)	4
29	4.86 (0.72)	2.64, 7.26	2.63 (1.88)	50

CI, confidence interval; OP, overpressure; SD, standard deviation.

To determine which muzzle devices were best for different operational needs, muzzle devices were isolated and investigated. The data are listed in Table 5. Ported brakes that do not direct the blast to the rear to help mitigate felt recoil are a good option for OP mitigation, followed by not using any type of muzzle device (target crown). Slanted brakes are good at helping reduce the amount of recoil the shooter feels, but they come at the expense of increasing experienced OP on the operator. This does not mean they should not be used, only that this limitation should be understood. Shooter efforts to mitigate OP are better spent on careful selection of a muzzle device rather than increasing barrel length, because no reasonable barrel length can overcome the increase in exposure from redirected blast.

TABLE 5: Study 2: Effects of Muzzle Device

Muzzle Device	OP, mean (SD), psi	95% CI	Impulse, mean (SD) (m × psi)	No.
No brake; OT and IT excluded	3.52 (0.74)	2.64, 5.56	2.41 (1.05)	27
Ported muzzle brake; OT and IT excluded	3.08 (0.30)	2.71, 3.38	1.38 (.98)	6
45° slant brake; OT and IT excluded	5.16 (0.87)	3.04, 6.83	2.26 (0.99)	42
No brake; OT and IT only	4.25 (0.61)	3.03, 4.77	3.46 (1.06)	6
Ported muzzle brake; OT and IT only	—	—	—	—
45° slant brake; OT and IT only	5.69 (1.49)	3.02, 7.28	3.39 (0.97)	8

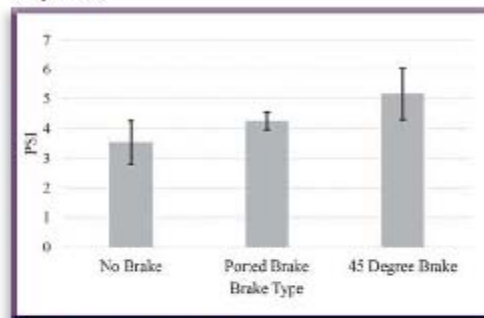
—, not measured; CI, confidence interval; IT, inside BearCat; OP, overpressure; OT, atop BearCat; SD, standard deviation.

Conclusions: Study 2

Within constraints and availability to the operator, as determined by mission parameters, barrel length had an inconsistent and inconsequential impact on shooter OP. Muzzle devices, however, seem to influence OP consistently, with brakes that mitigate recoil increasing shooter OP over all other brakes tested (Figure 1).

Emphasis on OP mitigation should focus on muzzle device, with additional scrutiny applied to the selection of slanted

FIGURE 1 Comparison of muzzle brake type and shooter overpressure.



PSI, pounds per square inch.

muzzle brakes that help control recoil. Attention to selecting firing positions, particularly those that put shooters atop rigid metal surfaces or from within vehicles, should be scrutinized before use to ensure they are necessary for mission parameters. Firing from within vehicles to simulate a vehicle hide and from atop rigid structures should be minimized when reasonably possible within training environments, because they seem to considerably increase OP and impulse exposure. It is reasonable to assume that minimal firing from within vehicles and atop rigid surfaces for verification of shooting platform and concealment is all that is necessary for shooters, because firing from other positions provides sufficiently transferrable skills to not degrade performance. Overwhelmingly, the use of suppressors on .50-caliber rifles in vehicle hides can be an effective means at mitigating OP and still allow for operational readiness and use. Use of slanted muzzle brakes that mitigate recoil by directing blast toward the operator increase OP but greatly improve capacity for firing multiple follow-up shots and may not be readily avoidable if that ability is required (but see the exception discussed later). As such, it is not prudent to eliminate the chevron- or arrowhead-style brakes from consideration; instead, it is advisable that trainings minimize their use where possible.

Evaluation of Suppressor Use

Additional, limited testing was done with suppressors during study 2. Limited data (n = 23 shots with suppressors) from the study found a 92% reduction in OP readings as compared with no muzzle device, a 120% reduction in measured OP as compared to the 4° muzzle brake, and a 49% reduction in measured OP compared with a flash hider. Direct comparisons could not be made to the other data, because the sensors used for the rest of the analysis with the best incident orientation did not trigger for any of the 23 shots. As such, we compared a less desirable sensor (i.e., wrist) with other wrist sensors to determine the cited data. We believe this is not representative of the incident blast received; therefore, we do not report those values. However, we do feel the readings are proportionally equivalent, which is why we report them as a change in percentage.

We evaluated other shoulder sensors across different conditions and found them to respond proportionally to the wrist, further supporting this method. Results show substantial promise for suppressor use as a meaningful way to lower experienced OP

Appendix G: Published version of manuscript in JNTOA

SNIPER



MINIMIZING .50-CALIBER RIFLE BLAST TO POLICE SNIPERS: Suggestions for training and deployment

BY MARK LANG, GARY H KAMIMORI, JUDE BRAUN AND MICHAEL J EGNOTO

The value of .50-caliber rifles in modern policing to resolve conflicts involving barricades, armor, vehicles and similarly difficult situations is immense. Despite an increasing need for .50-caliber capabilities, training doctrines developed to minimize

police sniper risk from their own weapons have lagged. Research on blast from .50-caliber rifles reports consistent pressure readings over 4 psi on the shooter, often exceeding the current safety threshold for blast exposure. Working with pressures

of this magnitude can have negative consequences on short-term performance and may hold long-term health consequences, as well.

At a minimum, police snipers are incurring an avoidable risk by not evolving training methodologies to



Police sniper engaging targets from an improvised shooting position

account for the effects from the tools they use. This work suggests that training doctrines for the .50 need to focus not only on police marksmen performance, but also on developing methods of training that do not compromise reflexes, health or capability. To determine what adaptations were effective, a comprehensive series of experiments was conducted.

These findings result from seven days of data collection with nearly 40 shooters, each wearing five blast sensors across their body providing measurements on over 300 rounds of .50-caliber ammunition expended

from a multitude of .50-caliber rifles during two training courses conducted at Tacflow. The following suggestions to the environment, rifle and shooting position are the findings of a team of blast engineers, LEO trainers and scientists. These strategies do not eliminate the risks of overpressure, but represent the current state of the field in ways to minimize blast, and thereby minimize consequences to performance and potential health effects. Most of these techniques can be implemented at minimal cost or with minimal additional equipment. Taking these basic precautions provide additional assurances that police snipers will not incur unnecessary stressors that can negatively impact performance resulting from training.

CHANGES TO THE ENVIRONMENT

A significant amount of attention during the data collection was focused on the environment police snipers were put into during training. To mimic operational environments, it was common to have police snipers engage targets from inside or on top of vehicles, from on top of rigid structures like towers or rooftops, and from inside windows of rooms — all realistic to the shooting positions faced during day-to-day activities. However, little attention was paid to the benefit of high round counts from these environments.

The capability to send accurate fire from inside or on top of a vehicle is necessary — but how many rounds need to be fired to achieve that goal? After familiarization with the environment, does continued practice produce improved results from that position as opposed to focusing on shooting fundamentals in other environments that may reduce the blast/

concussive forces experienced by the shooter?

Measurements of blast overpressure indicated that firing on top of rigid structures produced nearly 21 percent more blast than firing from the ground (dirt/grass), and firing from within vehicles produced nearly 12 percent more blast overpressure than firing from the ground. (Table 1)

As such, it is best to spend significant attention to selecting firing positions to determine if the risks are worth the training benefits, particularly those that put shooters on top of rigid metal surfaces or within vehicles. These hard environments, be they in or on top of vehicles, on concrete pads, etc., expose police snipers to significantly higher levels of blast, and it is unclear what benefits are gained beyond the rounds necessary for familiarization with that position and to verify capability.

Trainers should scrutinize not only firing locations, but round counts in these locations to ensure they are necessary for mission parameters before use. Firing from within vehicles to simulate a vehicle hide and from on top of rigid structures should be minimized when reasonably possible within training environments, as they seem to have negative consequence in terms of pressure and exposure, and it is reasonable to assume that minimal firing from these positions for verification of shooting platform and concealment is all that is necessary for police snipers. Firing from other positions provides sufficiently transferrable skills to not degrade performance.

CHANGES TO THE RIFLE

Substantive changes to a weapon system as received from the factory can be a controversial topic within

Table 1
Shooting Location Pressure Readings

Shooting Location	Mean Pressure (Stan. Dev.)	Percent Diff. from Baseline
Prone grass (baseline)	5.62 psi (0.98)	—
On top of vehicle (BearCat)	6.09 psi (0.25)	12%
Inside vehicle (BearCat)	6.82 psi (0.38)	21%

Note: Measurements were collected from 29-inch barrel .50-cal with 45-degree muzzle brake

Table 2
Barrel Length Pressure Readings

Barrel Length	Mean Pressure (Stan. Dev.)	Percent Diff. from Baseline
24-inch (baseline)	3.62 psi (0.30)	—
26-inch	3.38 psi (0.23)	-7%
27-inch	3.82 psi (0.42)	6%
28-inch	5.37 psi (0.08)	48%
29-inch	4.86 psi (0.72)	34%

Note: Muzzle devices were held consistent across all barrels tested for this analysis

Table 3
Muzzle Device Pressure Readings

Muzzle Device	Mean Pressure (Stan. Dev.)	Percent Diff. from Baseline
No brake (baseline)	3.52 psi (0.74)	—
Ported muzzle brake	3.08 psi (0.30)	-13%
45-degree slant brake	5.16 psi (0.87)	47%

Table 4
Shooting Position Pressure Readings

Shooting Position	Mean Pressure (Stan. Dev.)	Percent Diff. from Baseline
Standing (baseline)	4.51 psi (0.35)	—
Kneeling	5.23 psi (0.84)	16%
Sitting	5.67 psi (0.48)	26%
Prone	5.62 psi (0.98)	25%

Note: Measurements were collected from 29-inch barrel .50-cal with 45-degree muzzle brake

law enforcement circles. Bearing that in mind, suggestions here make no substantive change to the function of the weapon system in terms of rate, method, accuracy or ability to fire. Changes to .50-caliber rifles investigated barrel length and muzzle accessories only. Findings indicated that between barrel length and muzzle device with attention to blast exposure of the shooter, barrel length is largely irrelevant, with shorter barrels being preferable. (Table 2)

This is fortuitous, as current field conditions often highlight the benefit of a compact weapon system, and selecting a shorter-barreled rifle makes sense for many departments. The results of our experimental testing indicate that compact rifles offer no additional blast risk to longer platforms, and should be adopted without concern and as needs arise.

Emphasis for overpressure mitigation should focus on muzzle device, with additional scrutiny applied to the selection of slanted muzzle brakes. Use of slanted muzzle brakes which mitigate recoil by directing blast toward the operator increase overpressure but greatly improve capacity for firing multiple follow-up shots and may not be readily avoidable if that ability is required (see suppressor discussion below for exception). As such, we do not advocate for the elimination of chevron or arrowhead style brakes from consideration, but suggest that training scenarios minimize their use if possible, especially if deploying in hard environments like inside vehicles or on concrete pads. (Table 3)

Additional, limited testing was done with suppressors. Data from the test found a 92 percent reduction in pressure readings as compared to no muzzle device, a 120 percent reduction in measured pressure as compared to the 45-degree muzzle brake, and a 49 percent reduction as compared to a flash hider. Sample size was limited, but results show substantial promise for suppressor



Police sniper firing from the prone position

usage as a meaningful way to lower experienced pressure to the shooter without decreasing shooter capability, so long as added weapon length is not detrimental to mission outcomes. If resources allow, the integration of a suppressor onto the weapon platform is highly advisable.

CHANGES TO THE SHOOTING POSITION

Often, police snipers have to take the best available position that allows them to interdict a threat when called for. To prepare, police snipers need to train and be ready to deploy in a multitude of improvised shooting positions. However, much .50-caliber training focuses on prone shooting, as seen in above photo.

Though stable and excellent for building marksmanship fundamentals, prone shooting limits the ability of shooters to see over objects and also places them in a position to be exposed to higher blast. The focus on prone shooting while noting this limitation, and the realization that prone shooting is often associated

with higher levels of blast exposure, suggest a benefit to moving shooters to more elevated positions, preferably standing. (Table 4)

To facilitate a stable platform, the use of secondary equipment such as rifle rest/tripods are worth investing for operational deployments. Taken together, a capable .50-caliber program can be developed that minimizes risk to shooter health and effectiveness without compromising field capability and readiness. We also recommend firing from the standing position where possible.

KEY TAKEAWAYS

The goal of any competent training regimen is ensuring economy of resources expended while maximizing benefits gained. Currently, many .50-caliber training courses are inefficient with regard to shooter risks from firing the weapon. Too much expenditure of human performance is being made, endangering critical capability and health without driving real-world skill far enough ahead to justify the risks. We recog-

nize policing comes with peril, and realistic training comes with mindful, minimized dangers, as well — so why are we not spending our limited time, efforts and resources in a way that pushes our performance to the highest level possible with the minimum of risk?

In this article, we covered four basic areas trainers can control that generally have little to no cost (suppressors/silencers excluded) and advance training outcomes. In short, muzzle devices influence blast substantially. Shooting positions closer to the ground (prone or seated) experience higher blast and impulse than other positions. Suppressors mitigate blast effects well. Having shooters fire from rigid surfaces (concrete pads, on top or within vehicles, etc.) increases measurable blast overpressure.

That is not to say we need to avoid all these behaviors, but we as trainers need to make sure that we are spending our limited training resources wisely — and shooting from unbeneficial positions or in some configurations more than is necessary

for familiarization purposes just is not likely to be worth it.

Instead, modify and adopt positions that move police snipers further from the ground (standing preferred). These positions may require the use of supplemental rifle rests/tripods, but they provide more difficult shooting platforms that not only minimize blast exposure, but help develop shooter fundamentals.

RECOMMENDATIONS

Actionable items that can be implemented in terms of equipment changes for current training programs are:

- Use double hearing protection with proper fit. Often, foam/silicon in-ear plugs are ill fitting. Trainers are encouraged to ensure people are using proper fitting plugs, and to be aware that variation in plug size can happen from ear to ear, not just person to person. When using over-the-ear muffs in addition to plugs, electronic muffs with quality compression circuits or technology that allows for amplification of non-damaging sounds (like range commands) while blocking gunfire are advisable. When combining over-the-ear protection with safety glasses, ensure that the wearer still has good fit/seal around the ear or the sound mitigation will be severely compromised. Proper hearing protection does not mitigate the blast received by the shooter, but does help reduce a mechanism through which blast effects can create deleterious effects on shooter performance.

- For stability when shooting from positions other than prone, trainers should consider products that provide greater flexibility in firing positions for their marksmen, and that afford departments more versatility in the field to position

themselves in a greater range of shooting positions. As new products come to market, courses are encouraged to select tools that adapt as well as possible to the goals and needs of their departments.

WE AS TRAINERS NEED TO MAKE SURE THAT WE ARE SPENDING OUR LIMITED TRAINING RESOURCES WISELY – AND SHOOTING FROM UNBENEFICIAL POSITIONS OR IN SOME CONFIGURATIONS MORE THAN IS NECESSARY FOR FAMILIARIZATION PURPOSES JUST IS NOT LIKELY TO BE WORTH IT.

- Regarding muzzle devices, there are benefits to considering platforms that are suppressor-compatible. We do not advocate for the abandonment of the arrowhead muzzle device, but if resources allow, the adoption of platforms with suppressor and muzzle device modification capabilities should be considered strongly.

- Products that can act as a cage over existing muzzle brakes are reasonable tools to keep rifles with high potential for overpressures in excess of 4 psi in service while lowering possibilities of blast effects on the shooter.

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Appendix H: Published PASS paper, Chen et al.

Shockwave pressure transmission through the ear canal with hearing protection

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Abstract. There have been a large number of studies relating blast overpressure exposure to hearing loss and the determination of the effectiveness of various forms of hearing protection to mitigate this loss. However, less effort has been focused on measuring overpressure penetration into the middle ear, particularly outside of standard auditory frequencies. Repeated exposure to low level overpressure events leads to complaints of dizziness and nausea in some people. One hypothesis is that overpressure penetration into the middle ear is directly affecting the vestibular organs. In order to determine overpressure penetration into the ear, we developed a human head surrogate with an anatomically accurate ear and ear canal. Pressure sensors of varying capabilities were placed at the location of the ear drum and the head and eye sockets filled with a tissue simulant gel. The surrogate was placed near various breaching situations to determine the portion of pressure, compared to free field, entering the ear canal and impinging on the eardrum. The surrogate was also used in conjunction with a shock tube to determine the effect of directionality on the pressure transmission to the eardrum. The presence of hearing protection not only decreased the peak amplitude of pressures into the ear but also changed the frequency spectrum from the pressures as measured at the eardrum. External versus internal pressures were compared to determine what portion of external pressure actually transmits into the ear canal and into auditory organs with and without the hearing protection.

1. INTRODUCTION

Auditory damage is a common complaint among the members of the armed forces [1,2] and more so among members exposed to weapons fire which can range from small arms to explosives [2–4]. For both acute and chronic acoustic trauma, the degree of impairment depends on both the duration and loudness of noise exposure. The louder the noise, the shorter the duration necessary to induce hearing loss. While chronic noise induced hearing loss is well documented, exposure to blasts, or impulse noise, can also induce trauma beyond hearing loss and is less understood.

The effect of impulse noise is different from steady noise [5,6]. Impulse noise is defined as air pressure above atmospheric pressure that has a duration of less than a second [7,8]. Impulse noise has been shown to have a greater impact than continuous noise of the same power spectrum [6,9], and blast overpressures are a specific subset of impulse noise. Blast overpressures have high amplitudes of very short duration, but unlike general impulse noise can cause injuries beyond the auditory system [8]. The resulting auditory damage can be permanent or temporary, depending on the severity of exposure.

The blast from explosives detonation have been known to cause any number of hearing difficulties in addition to hearing loss. The overpressures from blast can rupture the tympanic membrane, disrupt the ossicular bones, and damage the cochlea [3,4,10,11]. The outer ear, the pinna can be damaged from shrapnel or explosion. Of the inner ear injury, overpressures can cause structural damage to the hair cells resulting in conductive hearing loss. Warfighters and personnel with blast exposure have reported other conditions such as dizziness, vertigo, hearing loss, and tinnitus, a condition shown to interfere with hearing [11].

However, repeated exposures to low level overpressures have also induced complaints such as dizziness and nausea which do not seem to be directly related to hearing loss or physical damage to the middle and inner ear. Kubli *et al.* [12] looked at the effect of repeated mild exposures to blast during breaching exercises and saw no significant acute or long term effects in hearing thresholds or distortion product otoacoustic emissions (DPOAEs). However, Onge *et al.* [13] saw increases in hearing thresholds at 1kHz, 2kHz, and 3kHz but no changes in vestibular function as measured by balance.

It was been noted experimentally that pressures inside the ear canal and at the eardrum in response to a sound or a blast event is higher than free field measurements taken at the same distance from the source [14,15]. A study conducted with an artificial head on short impulsive sounds saw an increase of pressure in the ear canal and eardrum compared to free field measurements [16]. This has also been shown computationally [17]. The increase in pressure inside the ear according to computational models,

is that a stagnation point occurs at the auricle, amplifying the pressure entering into the ear canal as well as at the eardrum [17].

To gain further understanding of the effect of blast on the ear, a custom acoustic test fixture (ATF) was created. A commercial ATF is available and is produced by the French-German Research Institute de Saint Louis (ISL) and consists of a solid acrylic head. The use of solid acrylic may greatly impede the transmission of shockwaves through the head and impede a portion of pressure load that may act upon the auditory organs. To make the test fixture more biofidelic, anatomically correct ears with ear canals made of polyurethane with a shore hardness that matched the softness of the pinna of an ANSI standard ear. The ears were attached to a plastic human skull, with simulated flesh and brain.

2. METHODS AND MATERIALS

The surrogate ears were created through 3D printing of a urethane-like material (Figure 1A). The hardness of this material was set to an approximate durometer of 55A (Xometry, Bethesda, MD). The outer ear as well as the ear canal was created of the same material as a single piece.

The skull was filled with brain simulant material (Sylgard 3-6636 at a ratio of 1:1.5, part A:part B respectively) and a simulated flesh layer was applied to the skull so as to provide the appropriate weight and attenuation around the ear/ear canal to appropriately shape the sound/pressure waves entering the sensor via the ear canal. Two anatomically correct ears were mounted on the skull. A blast acoustic sensor was placed in the left ear and a pressure sensor was placed in the right other. A pressure sensor was placed in the eye (Figure 1B). The ears were tested with and without foam hearing protection as well as with and without the presence of a helmet.



Figure 1. Acoustic test fixture (ATF). The ATF as pictured from the profile view (A) and from the front (B). In this image, the eye sockets have not been filled with the tissue simulant and the sensor is held in place with glue. A previous version of the sensed ear (C) shows the location of the microphone in the ear canal.

2.1 Acoustic Test Fixture (ATF)

A custom acoustic test fixture was created for this study. A skull (Classic Human Skull #1020159, 3B Scientific, Tucker, GA) was drilled to fit anatomically correct 3D printed ears. The surrogate ears, left and right, were created based on a full sized right ear model (Model 2251, GPI Anatomicals, Lake Bluff, IL). The ears were 3D printed in a urethane-like material to match the softness of ANSI standard pinna.

A blast microphone (Model#: 378A14, PCB, Depew, NY) was secured to the left ear where the ear drum was located, secured with structural plastic adhesive (DP8010 blue, 3M™ Scotch-Weld™, Maplewood, MN; Figure 1C). The image in Figure 1C is of a previous version of the sensed ear. In this previous version the ear was made of clear plastic (Model 2251) which made it easier to photograph the placement of the sensor.

Two 50psi pressure sensors (Model#: 113B28, PCB, Depew, NY) were imbedded in the head. In the right ear, a 50psi (344.7kpa) sensor was secured in a similar manner as the microphone in the left ear. A 50psi sensor was placed in the left eye cavity facing forward. This sensor was held in place briefly with hot glue until the tissue simulant could be added to the eye cavities and hold the pressure sensor more permanently (Figure 1B).

Once each ear was attached to the skull with plastic adhesive, the skull cavities and outside were filled and covered with Sylgard 3-6636 (Dow Corning, Auburn, MI). This was done to simulate flesh and tissue. To accomplish this, a waterproof barrier was created around the skull. Sylgard 3-6636 was poured and allowed to polymerize after which the barrier was removed. Sylgard 3-6636 was poured on the face of the skull and the excess was allowed to drip away to form the outer flesh layer. This also secured the surrogate ears to the skull. The sinus cavities were kept open. This is to prevent the impedance

of pressure waves passing through the throat and mouth region into the microphone located in the ear canal.

2.2 Test Fixture

The skull with sensed ears was attached to a Hybrid III neck (Model#: 78051-336-H, Humanetics, Plymouth, MI) with a custom attachment (Figure 1A). The skull/neck combination was attached to an 80/20 stand with three foam torsos that fit three heads. The stand measured 48in by 57in by 57.5in tall (1.2m x 1.4m x 1.5m tall) (Figure 2). A foam torso was used to simulate any effect the body may have on pressure reflections and changes to the head. Body armor was placed over the foam torsos to protect the torsos and cables from shrapnel.

Two other sensed heads, each attached to Hybrid III necks were also placed on the stand. Heads 1 and 2 each had sensors in the left eye. Head 1 was located between Heads 2 and 3 on the stand (Figure 2A, C). Head 2 was located to the left of Head 1; Head 3 (sensored ears head) was located to the right of Head 1. Head 3 is the ATF previous described (Section 2.1) whereas Heads 1 and 2 are manufactured similarly to Head 3 but lack surrogate ears.

A pencil gage was placed to the left of Head 2 at shoulder height (Figure 2C). This gage measured the incident pressure at the stand. The sensing element for the pencil gage faced away from the stand to minimize any reflections from the three surrogates and the stand.

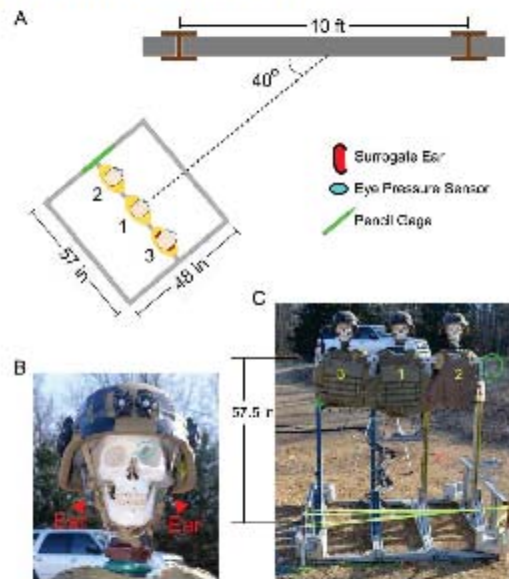


Figure 2. Acoustic test fixture (ATF) and placement in the test field where standoff is measured to the forehead of Head 1 (A). (B) Head 3 has two surrogate ears and has a pressure sensor in the left eye socket (circled in blue). (C) The entire stand is 57.5in from the ground to the top of the stand. Hybrid III necks are mounted to the top of the stand. A pencil gage is attached to the left side of the stand (circled in green)

2.3 Field Tests

Field tests were conducted during the Urban Mobility Breacher Course (UMBC) at Fort Leonard Wood, Mo. The stand was angled 40° from the breaching wall (8 to 10 feet (2.4 to 3.0m) wide, 80in (2.0m) tall, 8in (0.2m) thick) with the 40° measured to Head 1 (Figure 2A). The breaching wall was made of cinder blocks filled with dry mortar. Three different standoffs and one type of ear protection with and without helmet was used for a total combination of six conditions: foam earplugs and helmet at standoffs 40ft (12.2m), 30ft (9.1m) and 20ft (6.1m), and no earplugs or helmet at the same three standoffs. The foam

ear plugs were commercially available (Quiet Contour, Moldex-Metric, Inc, Culver City, CA) with a noise reduction rating of 33 dB. Standoff was measured to the forehead of Head 1. The Heads were tested at each standoff with the earplugs and helmets in place; both the earplugs and helmets were then removed and the three standoffs repeated.

2.4 Data Acquisition System

The data acquisition system consisted of an NI PXIe-8135 embedded controller with two NI PXI-6115 multifunction I/O modules using SignalExpress 2012 data acquisition software (all from National Instruments Corp., Austin, TX). All sensors were connected to the data acquisition system through a signal conditioner (Model#: 480B21, PCB Piezotronics, Depew, NY). Data was acquired at 1 MHz and the system triggered off the Head 3's eye pressure sensor. A 0.1ms pre-trigger buffer was used.

The data was processed with Igor Pro (version 6, WaveMetrics, Inc, Lake Oswego, OR). The pressure signal was filtered with a low pass finite impulse response (FIR) digital filter with a Hanning window and cutoff frequency of 100KHz. Each signal was set to a baseline based on the average of the first hundred data points for each signal.

3. RESULTS

3.1 Pressures at the heads

The pressures at each head are measured by the eye sensors (Figures 1 and 2). A comparison of the eye sensors for each head at the three different standoffs show that the three heads see similar pressure profiles (Figure 1). It is important to note that because the data acquisition system was setup to trigger based on each eye sensor, the arrival time of the blast wave to each head cannot be determined. Arrival times relative to each eye sensor can be determined. While overall pressure profile for each of the three heads at each of the standoffs are similar, the initial peak and maximum peak pressures can vary by up to 2psi (13.8kpa) at the larger standoffs and by 10psi (68.9kpa) at the 20ft (6.1m) standoff (Table 1).

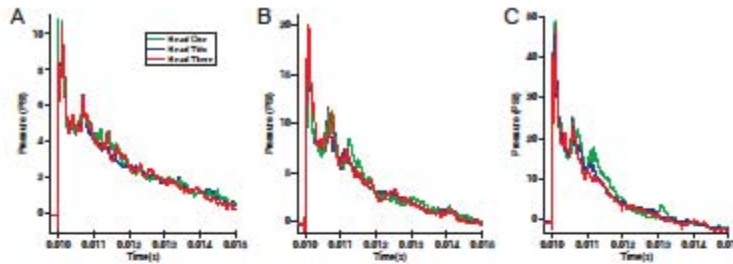


Figure 3. Pressure from the eye sensor for Heads 1 (green), 2 (blue), and 3 (red) at the 40ft standoff (A), 30ft standoff (B), and the 20ft standoff (C).

Table 1. The initial and maximum peak pressures in psi (and kpa) detected by the eye sensors for each of the conditions.

Earplugs	Head	40ft (12.2m) Standoff		30ft (9.1m) Standoff		20ft (6.1m) Standoff	
		Initial	Maximum	Initial	Maximum	Initial	Maximum
Yes	1	11.2(77.2)	11.2(77.2)	13.8(94.9)	19.2(132.6)	39.0(269.2)	48.7(336.1)
Yes	2	9.7(66.9)	10.2(70.3)	14.3(98.8)	17.6(121.5)	33.3(230.2)	45.4(312.8)
Yes	3	--	--	16.6(114.6)	20.0(138.0)	--	--
No	1	10.8(74.5)	12.1(83.4)	16.6(115.1)	16.6(115.1)	36.3(250.4)	42.8(295.4)
No	2	9.5(65.5)	10.9(75.2)	13.0(89.9)	15.7(108.3)	31.9(219.8)	42.2(290.6)
No	3	8.33(57.2)	10.4(71.7)	15.2(104.5)	18.0(124.0)	26.8(185.0)	47.1(324.8)

The pressure profiles for Head 3 at the 40ft (12.2m) and 20ft (6.1m) standoffs with earplugs and helmet did not record properly. Therefore, this data is absent from analysis. Comparisons for Head 3 eye sensor with Heads 1 and 2 for the 40ft (12.2m) and 20ft (6.1m) standoff are from the no helmet, no earplug condition. The presence of both helmet and earplugs do not seem to affect the pressure profile detected with the eye sensors for Heads 1 and 2 (Figure 4).

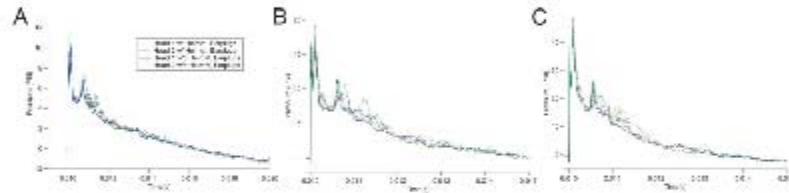


Figure 4. Pressure from the eye sensor for Heads 1 (green) and 2 (blue) at the 40ft (12.2m) standoff (A), 30ft (9.1m) standoff (B), and the 20ft (6.1m) standoff (C) with (dotted line) and without helmets (solid line).

3.2 Pressures at the eardrums

Pressure at the unoccluded eardrum is characterized by two major positive pressure peaks and no significant after affects (Figure 5). The changes in standoffs seem to only change the amplitudes of these two peaks but the overall behavior remains relatively unchanged. The peak pressures are listed in Table 2. It is important to note that the 50.57psi (348.7kpa) peak for the 20ft (6.1m) standoff is not accurate. This is because the peak pressure reading exceeded the capacity of the pressure sensor at the eardrum for this standoff.

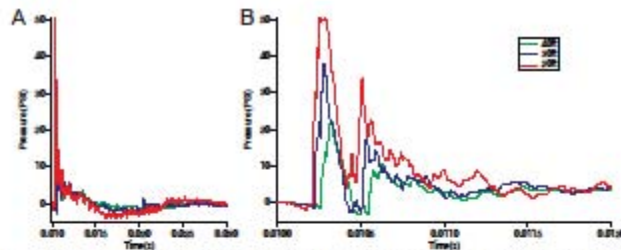


Figure 5. Pressure at the eardrum measured with the pressure sensor for the unoccluded condition at the 40ft (12.2m) (green), 30ft (9.1m) (blue), and 20ft (6.1m) (red) standoffs. A and B are the same data at different time scales.

Table 2. Maximum and secondary peak pressures in psi (kpa) for the unoccluded right ear

Standoff in ft (m)	Maximum Pressure	Second Peak Pressure
40 (12.2)	22.16 (152.8)	10.42 (71.8)
30 (9.1)	37.67 (259.7)	18.24 (125.8)
20 (6.1)	50.57 (348.7)	33.79 (233.0)

A comparison between the peak pressures seen by the Head 3 eye sensor to that of the right ear sensor shows a significant increase of pressure at the eardrum. At the 40ft (12.2m) standoff, peak eye to peak eardrum was 10.41psi (71.8kpa) to 22.16psi (152.8kpa); at 30ft (9.1m) it was 17.99psi (124.0 kpa) to 37.67psi (259.7kpa); at 20ft (6.1m) it was 47.10psi (324.8kpa) to a pressure higher than 50.57psi (348.7kpa). This increase at the eardrum compared to the eye is approximately double (2.1 times for both 40ft (12.2m) and 30ft (9.1m)) and this ratio seems to remain relatively unchanged with regard to standoff.

Based on this general doubling of pressures between eye to eardrum, the true pressures at the 20ft (6.1m) standoff for the ear would likely be close to 95psi (655kpa). For all standoffs without earplugs, the pressures exceeded the maximum limit for the microphone (left ear) (data not presented).

With the ear occluded by foam earplugs, the pressure at the eardrum dropped dramatically (Figure 6), by approximately 93% in the right ear. There is a difference between the pressures measured with the microphone versus the pressure sensor (Figure 6A and 6B). This could be due to a confluence of reasons such as imperfect placement of the hearing protection between the two surrogate ears, slight changes in angle from the wall to the stand which may change the angle of each ear relative to the blast source, and differences in sensors. However, the relative increase of the peak pressure due to a change in standoffs is the same between left and right ear. This suggests that the reason for difference in pressures between the left and right ear is maintained between shots. Despite the difference in amplitude, the overall pressure profiles between the pressure sensor and the microphone are similar.

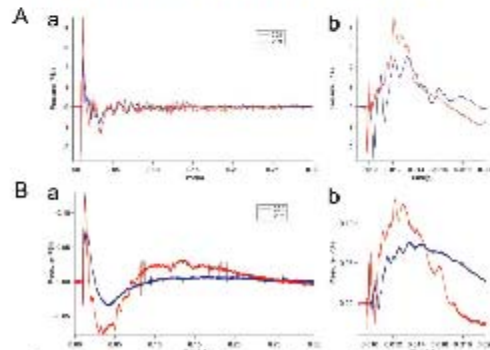


Figure 6. Pressure at the eardrum measured with the right ear with the pressure sensor (Aa and b; same data, different time scales) and for the left ear with the microphone (Ba and b; same data, different time scales) for the 30ft (9.1m) (blue) and 20ft (6.1m) (red) standoffs.

In addition to the change in amplitude, the overall pressure profile with a foam earplug in place is also different. Without the earplug, the pressure in the right ear (pressure sensor) did not see a negative pressure, only two large positive pressure peaks. With the earplug in place, both ears saw the pressure at the sensing surface initially go negative followed by some oscillation. Overall there is a large positive pressure peak followed by a longer duration of negative pressure in both ears. The microphone detected a longer negative pressure duration than the pressure sensor.

Table 3. Maximum and minimum pressures in psi (kpa) for both right and left ears with earplugs

Ear	30ft Standoff		20ft Standoff		20ft/30ft Peak Ratio
	Max Pressure	Min Pressure	Max Pressure	Min Pressure	
Right	2.54 (17.5)	-2.67 (18.4)	4.52 (31.2)	-2.27 (-15.7)	1.8
Left	0.08 (0.55)	-0.04 (0.27)	0.13 (0.90)	-0.08 (-0.55)	1.7

4. DISCUSSION

In the unoccluded ear, the pressure sensors saw two positive pressure peaks where the amplitude of the peaks correlated with standoff. The pressures at the occluded eardrum undergo more significant pressure shifts, alternating between negative and positive pressures. While both the microphone and the pressure sensor detects sound pressure levels, the microphone, being a condenser microphone, produces a voltage out based on the capacitance changes between the diaphragm and the back plate generated in the presence of sound pressures [18]. Any force that causes the diaphragm to move can cause capacitance change. Wind, mechanical forces, and other shock vibrations can all induce movement of the diaphragm which can contribute to noise and false readings.

However, the negative-positive pressure oscillations were measured by both the microphone and the pressure sensor in the occluded ear. While the overall amplitude of the pressures measured in the left

and right ear were different, the behavior was similar across for both sensors. It is possible that the earplugs may shift in the ear canal, potentially causing pressure oscillations at the eardrums. The other possibility is that the pressure oscillations were a result of the shockwave passing through the foam earplugs.

It is important to note that the measured pressures exceeded safe levels, even with the occluded condition, at the farthest standoff. At 40ft (12.2m) with hearing protection, the microphone measured 0.08psi (0.55kpa), which is approximately 150dB. Impulse noise at lower decibels (106 to 117 dB SPL) have been shown to alter hearing performance permanently [19]. The lowest pressures that have been shown to cause the eardrum to burst are around 4psi (27.6kpa) incident for the unprotected ear [15]. At all standoffs in this test series, incident pressures exceeded this level. Future work will entail trying to find the cause for the different pressure magnitudes of the occluded condition between the microphone and the pressure sensor.

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References

- [1] J.S. Yong, D.-Y. Wang, Impact of noise on hearing in the military, *Mil. Med. Res.* 2 (2015). doi:10.1186/s40779-015-0034-5.
- [2] M.J. Ramsey, P.D. Littlefield, Delayed Otological Trauma, in: *Otolaryngol. Neck Surg. Combat Casualty Care Oper. Iraqi Freedom Oper. Endur. Freedom*, Department of Defense, Army Borden Institute, 2015.
- [3] A. Dougherty, A. J Macgregor, P. Han, E. Viirre, K. Heltemes, M. Michael R. Galarneau, Blast-related ear injuries among U.S. military personnel, *J. Rehabil. Res. Dev.* 50 (2013). doi:10.1682/JRRD.2012.02.0024.
- [4] P.D. Littlefield, M.J. Ramsey, Acute Otological Trauma, in: *Otolaryngol. Neck Surg. Combat Casualty Care Oper. Iraqi Freedom Oper. Endur. Freedom*, Department of Defense, Army Borden Institute, 2015.
- [5] S. Mäntysalo, J. Vuori, Effects of Impulse Noise and Continuous Steady State Noise on Hearing, *Br. J. Ind. Med.* 41 (1984) 122–132.
- [6] D.E. Dunn, R.R. Davis, C.J. Merry, J.R. Franks, Hearing loss in the chinchilla from impact and continuous noise exposure, *J. Acoust. Soc. Am.* 90 (1991) 1979–1985. doi:10.1121/1.401677.
- [7] B.E. Amrein, T.R. Letowski, High Level Impulse Sounds and Human Hearing: Standards, Physiology, Quantification, Army Research Laboratory, 2012.
- [8] H.R. Boomer, *Handbook of Human Systems Integration*, John Wiley & Sons, 2003.
- [9] J. Starck, E. Toppila, I. Pyykko, Impulse noise and risk criteria, *Noise Health* 5 (2003) 63.
- [10] C.-H. Choi, Mechanisms and Treatment of Blast Induced Hearing Loss, *Korean J. Audiol.* 16 (2012) 103–107. doi:10.7874/kja.2012.16.3.103.
- [11] M.E. Hoffer, C. Balaban, K. Gottshall, B.J. Balough, M.R. Maddox, J.R. Penta, Blast Exposure: Vestibular Consequences and Associated Characteristics, *Otol. Neurotol.* 31 (2010) 232–236. doi:10.1097/MAO.0b013e3181c993c3.
- [12] L.R. Kubli, R.L. Pinto, H.L. Burrows, P.D. Littlefield, D.S. Brungart, The Effects of Repeated Low-Level Blast Exposure on Hearing in Marines, *Noise Health* 19 (2017) 227–238. doi:10.4103/nah.NAH_58_16.
- [13] P. St. Onge, D.S. McIlwain, M.E. Hill, T.J. Walilko, L.B. Bardolf, Marine Corps Breacher Training Study: Auditory and Vestibular Findings, *US Army Med. Dep. J.* (2011) 97–107.
- [14] F.M. Wiener, D.A. Ross, The Pressure Distribution in the Auditory Canal in a Progressive Sound Field, *J. Acoust. Soc. Am.* 18 (1946) 401–408. doi:10.1121/1.1916378.

- [15] F.G. Hirsch, Effects of Overpressure on the Ear - A Review, Defense Atomic Support Agency, 1966.
- [16] E. Osmundsen, K. Gjaevenes, The diffraction of short duration impulsive sound waves by an artificial head, *J. Sound Vib.* 37 (1974) 39-IN1. doi:10.1016/S0022-460X(74)80056-8.
- [17] M. Fadaei, O. Abouali, H. Emdad, M. Faramarzi, G. Ahmadi, Numerical simulation of wave propagation in a realistic model of the human external ear, *Comput. Methods Biomech. Biomed. Engin.* 18 (2015) 1797–1810. doi:10.1080/10255842.2014.974578.
- [18] M. Vorländer, Acoustic Measurements, in: G. Müller, M. Möser (Eds.), *Handb. Eng. Acoust.*, Springer Science & Business Media, 2012.
- [19] M. Rezaee, M. Mojtahed, M. Ghasemi, B. Saedi, Assessment of Impulse Noise Level and Acoustic Trauma in Military Personnel, *Trauma Mon.* 16 (2012) 182–187. doi:10.5812/kowsar.22517464.2674.

Appendix I: Published PASS paper, O'Shaughnessy et al.

Influence of helmet system on blast overpressure transmission into the brain

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Abstract. Exposure to blast overpressures is a reality of the modern military experience, whether it be on the battlefield or during training. While exposures during training are controlled and maintained within safety standards, there is still concern over the effects of repeated exposure, even to these low level overpressures. While quantifying the overpressure of a blast event in air is relatively straight forward, the challenge is to determine the amount of energy that penetrates into the brain, potentially causing damage. To this end, we have constructed several gel-based brain surrogates with integral pressure sensors and accelerometers and mounted these 'brains' within surrogate heads. During several military training exercises, these surrogate systems were exposed to different levels of blast overpressure from low (considered safe) through high (expected to produce significant injury). Pressures within the brain were measured both with and without helmets present. Initial results suggest that regardless of the size of the overpressure exposure, the peak pressures measured within the brain surrogate were approximately 30% of the incoming peak overpressure (reflected pressure measurement at the eye). At low overpressures, the pressure measured under the helmet was close to the reflected pressure measured at the eye. As the overpressure exposures increased, however, the under helmet pressure relative to the eye measurements decreased. At the highest overpressure exposure tested, the under helmet pressure was only ~60% of that measured at the eye. At low to moderate pressures, the presence of a helmet resulted in a roughly 20-40% increase in measured brain pressures relative to no helmet. Interestingly, at the highest overpressure tested the increase in brain pressure due to a helmet was approximately 60%. It is clear that the interaction of blast overpressure events with the human head, brain, and armor systems is complex and likely varies depending on the blast magnitude.

1. INTRODUCTION

Exposure to blast overpressures is a reality of the modern military experience, whether it be on the battlefield or during training. While exposures during training are controlled and maintained within safety standards, there is still concern over the effects of repeated exposure, even to these low level overpressures. While quantifying the overpressure of a blast event in air is relatively straight forward, the challenge is to determine the amount of energy that penetrates into the brain, potentially causing damage.

Modern military helmets are designed to mitigate the effects of blunt and ballistic impacts [1, 2] and are very effective for this task. However, they are not specifically designed to mitigate blast overpressure effects, largely due to the lack of understanding regarding the interactions of the blast overpressure wave with the human head and brain. In particular, there is no clear pathophysiology between blast overpressure exposure and mild traumatic brain injury [3]. Even less well studied are the possible effects of repeated, low pressure exposures. To begin to design a helmet with blast overpressure mitigation in mind, two things are necessary. First, a better understanding of force transmission into the brain during a blast and how a helmet interacting with blast forces alters this process. The second is an improved understanding of the effects of the blast overpressure wave on the brain from a biological standpoint, including the mechanism(s) of injury. The present effort is focused on the first of these needs.

There have been a number of computational models of the head and brain generated to address the issue of blast overpressure waves interacting with a helmet system and the human head and brain. Two general findings from these efforts have been that there is a pressure build up under the helmet, in the gap between the head and helmet created by the pad system [4-7], and that overall the helmet tends to reduce pressures in the brain versus the case of the head without a helmet [8-9].

While quite a few computational efforts have been reported, there is a lack of testing for these effects experimentally. Two of the above groups validated their models of under the helmet pressures, sometimes referred to as under wash, using head surrogates with surface mounted pressure sensors and

either a shock tube [4] or live blast testing [6]. Additionally, Sharma *et al.* [8] validated their head model against shock tube data obtained for an instrumented cadaver head, however, all helmet vs. no helmet comparisons were done computationally.

The present effort was designed to fill in this gap of experimental data on pressure propagation into the brain during a blast and how a helmet alters this response. To this end, two head and brain surrogates were constructed with pressure sensors at strategic locations within the brains, as well as one under the helmet. These were exposed to live breaching events at the Urban Mobility Breacher Course (UMBC) at Fort Leonard Wood, Mo. generating data at three blast pressure levels, with and without helmets.

2. METHODS

2.1 Surrogate manufacture

The basis for the modular GelMan-Head system is a commercial, anatomically accurate human skull with a removable skull cap (Model #1020159, 3B Scientific, Tucker, GA). A custom mount consisting of two aluminum plates and two epoxy inserts was designed to connect the skull, through the foramen magnum to a Hybrid-III neck (Humanetics, Plymouth, MI). Two 50 psi (345 kPa) pressure sensors (Model#113B28, PCB Inc., Depew, NY) were mounted to the skull, one in the left eye orbit and the second flush mounted with the left temple, though only the eye sensor was used for this project. The holes in the lower portion of the skull were then temporarily sealed and the skull filled with Sylgard 184 (Dow Corning, Auburn, MI) up to 18 mm from the top of, and level with, the lower skull section (Figure 1A). Once cured, the Sylgard 184 provided a flat platform on which to place various brain modules. Additionally, a tri-axis accelerometer (Model #356A01; PCB, Inc.) was secured to the back of the skull with epoxy and the eye sockets were filled with Sylgard 184. Two of these skulls were used for this project.

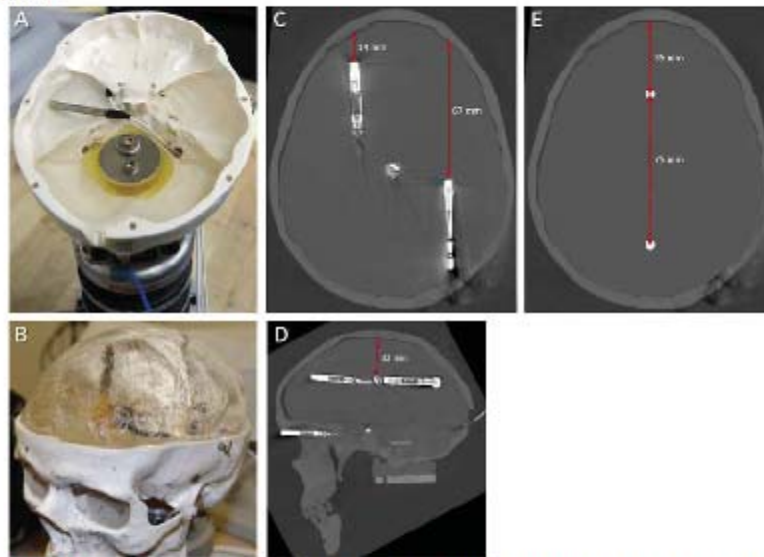


Figure 1. A: The bottom portion of the instrumented skull mounted to a Hybrid III neck. The two pressure sensors are visible as well as the internal portion of the neck mount. All are located under a layer of Sylgard 184 (transparent). B: Brain #2 in the skull. The front, upward facing sensor is visible through the Sylgard 3-6636 gel. C: Top down view of the CT scan of Head #1 show the locations of the two pressure sensors (long and to the sides) and the accelerometer (square at center). D: Side view composite of several layers of the CT scan showing the relative locations of the three in brain sensor. The eye sensor is also visible. E: Schematic drawing overlaid on CT scan showing locations of the upward facing sensors in Head #2.

The surrogate brains for use with the above skulls are space filling, i.e. the gel brain fills the entire upper skull cavity and does not attempt to replicate the surface features of the brain. Brains were manufactured using a mold made from a foam positive of the skull cavity above the Sylgard 184 layer and below the skull cap. The large opening of the mold (equal to the flat surface of the Sylgard 184 platform) allowed for easy positioning of sensors using 3D printed jigs to hold the sensors in place while the gel used for the brain cured around them. The material for the brains was Sylgard 3-6636 (Dow Corning) mixed at a ratio of 1:1.5, parts A:B respectively. Two brains were manufactured for this project, one with two forward facing pressure sensors and an accelerometer (Brain #1) and the second with two upward facing pressure sensors (Brain #2; Figure 1B). The sensors were of the same types as those used for the skulls.

A commercial service was used to obtain a 3D scan of Brain #1 within Skull #1 using x-ray computed tomography (CT; NTS LabInsight, Chesapeake MD). This provided a check on the positioning of the sensors within the GelMan-Head device. The sensing surfaces of the two pressure sensors in Brain #1 were located 14 mm and 67 mm from the front of the skull, while the accelerometer was at the centroid of the skull (Figure 1C). The sensors were located 32 mm from the upper most point of the skull cap (Figure 1D). Brain #2 was not imaged, however the two pressure sensors were located approximately 35 mm and 110 mm from the front of the skull along the mid-line (Figure 1E). The sensing surfaces were pointing upwards and located 10 mm from the surface of the skull at their respective locations.

2.2 Field Layout

Tests were conducted at the Urban Mobility Breacher Course (UMBC) at Fort Leonard Wood, Mo. A total of six identical blast events were recorded using two GelMan-Head systems, as described in the previous section. The heads were mounted 41 cm apart on an aluminum frame with the height of the 'eye' sensors being 1.7 m above the ground. Below each head was a foam torso outfitted with a soft armor tactical vest to account for potential reflections off of the torso (Figure 2A-B). A 500 psi (3450 kPa) pencil gauge (Model #137A22, PCB Inc.) was mounted at the center of the stand, directly below the center GelMan-Head, 0.84 m above the ground.

For each blast event, a breaching charge was placed on the center of a 2.5-3 m long, 2 m high cinder block wall. The stand with the heads was located at one of three distances from the charge (6.6, 9.7, or 12.7m) at a 40° angle from the wall (Figure 2C). The three distances were measured from the site of the charge to the forehead on the center GelMan-Head.



Figure 2. A: Three GelMan-Head surrogates on the aluminum frame with vest and helmets. Heads #1 and #2 are described here-in. Head #3 was a prototype head and not a part of this manuscript. B: Rear view of the heads on the stand. The cinder block walls are visible in the background. The helmet pressure sensor on Head #2 is indicated with a red arrow. C: To scale drawing of the blast arena for the 6.6 m standoff.

2.3 Helmet Preparation

Blast events were recorded with the two heads, both with and without helmets. Due to the lack of a skin layer, the heads were fitted with standard issue, size small, helmets. The pad configuration for the helmets was the standard 7 pad layout with two additional smaller pads on the center left and center right portion of the helmet. The rear, large pad was also replaced with the smaller pad to allow egress of the sensor cables from the skulls.

The helmet on Head #2 was additionally equipped with a 50 psi (345 kPa) sensor identical to the ones used for the skulls and brains. A small hole was drilled through the helmet at approximately 45° to the rear of the apex (Figure 2B) and the sensor epoxied in with the sensor surface flush with the inside of the helmet. Care was taken to ensure that the sensor was not covered by one of the pads.

2.4 Data acquisition and analysis

Data acquisition was via two USB-6356 X Series DAQs (National Instruments Corp., Austin, TX) connected through two sensor signal conditioners (Model #483C05, PCB Piezotronics). Data was acquired via a laptop running SignalExpress 2014 (National Instruments). Data were acquired at 1 MHz and the system triggered off of the Head #1 'eye' pressure sensor. A 10 ms pre-trigger buffer was used. For this project a total of 7 channels of pressure data was processed and analyzed: Skull #1 Eye, Brain #1 Front, Brain #1 Mid, Brain #2 Forward, Brain #2 Rear, Under Helmet #2, and the pencil gauge.

Post processing of the data was performed using Igor Pro v6 (Wavemetrics, Inc., Lake Oswego, OR). Data were scaled based on the calibrated sensitivities of the various sensors, filtered at 100 kHz via a digital low-pass FIR, and peak values extracted.

3. RESULTS

Data was recorded for a total of 6 blast events. Three distances from the breaching charge (12.7, 9.7, and 6.6 m) resulted in peak incident pressures, as measured by the pencil gauge, of approximately 50, 67, and 143 kPa, respectively. This set of three distances was repeated twice, once with helmets on and the second time without helmets. Incident and reflective (Skull #1 Eye sensor) were remarkably consistent at each distance between the two shots, with the largest difference being ~14% at the furthest distance (lowest pressure).

Due to the reproducibility of the blast events, comparisons of the 'in brain' pressure sensors between shots with a helmet and without helmet are possible. Figure 3 summarizes the results of the 'in brain' pressures with and without helmet and relates them to the reflected (eye) pressure and under helmet pressure (for the case with helmet in place). Firstly, if one compares the under helmet pressure to the reflected pressure, at the furthest distance these pressures are essentially the same. However, at the two closer distances, the under helmet pressure is 72% and 56% of the matching reflective pressure, at 9.7 and 6.6 m respectively. The under helmet pressures for the 9.7 and 12.7 m blasts are similar at 88 and 75 kPa, respectively, a roughly 16% difference.

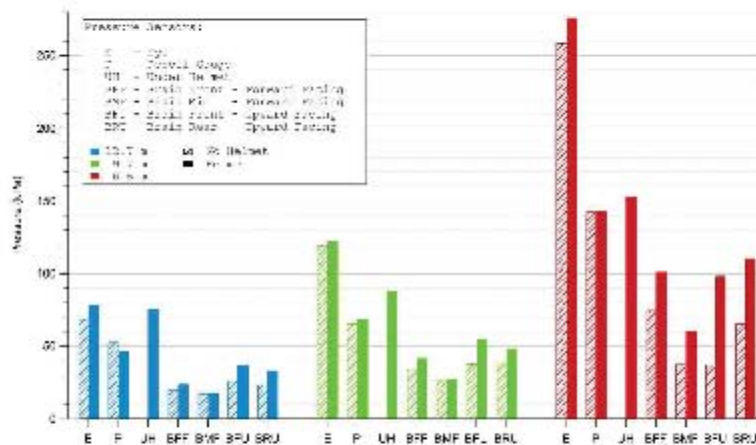


Figure 3. Incident pressures of 50, 67, and 143 kPa resulted in the above peak pressures under the helmet and within the surrogate brains.

In order to better correlate the effect of the helmet on the 'in brain' pressure measurements, the data were normalized to the peak reflective pressure for each blast and the percent difference between helmet and no helmet plotted (Figure 4). The most notable result is that for the two upward facing pressure sensors and the forward facing sensor at the front of the brain, the pressure is elevated within the brain when the helmet is present.

The forward facing pressure sensor at the middle of the brain actually showed slightly lower pressures when the helmet was present at the two further distances (lower pressures). For the forward facing mid-brain sensor and upward facing rear sensor, the closest standoffs yielded a distinctly higher pressure in the brain of the heads with helmets than those without.

The temporal relationship between the pressures at the tested locations can best be elucidated by plotting the pressure traces versus time. Figure 5 does this for select pressure sensors for both the lowest and highest pressure events (12.7 and 6.6 m standoffs, respectively). The reflected pressure recorded by the eye sensor is shown for both the helmet and no helmet cases and demonstrates the reproducibility of the incoming blast pressure wave, as well as the fact that the helmet, as expected, had no influence on the pressure recorded at the eye.

The under helmet pressure sensor is delayed by approximately 600-700 μ s due to its location towards the rear of the head. When the reflected and under helmet pressure traces are aligned (Figure 5; Inset), it becomes apparent that the rise time of the under helmet pressure is slower than that of the incoming reflected pressure, but the decay times of the two are similar. The differences in peak pressures at the two standoffs has already been mentioned.

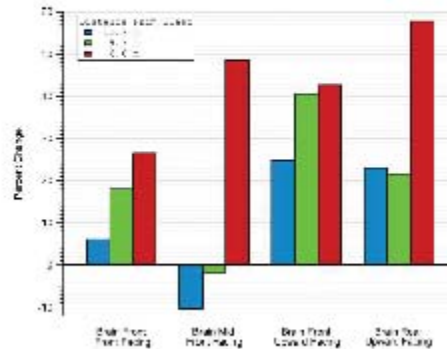


Figure 4. The percent change in pressure between no helmet and helmet for the 4 'in brain' pressure sensors. A positive value indicates an increase in pressure when the helmet was on. Data were normalized to the peak reflective pressure measured at the eye of Head #1 for a given blast event.

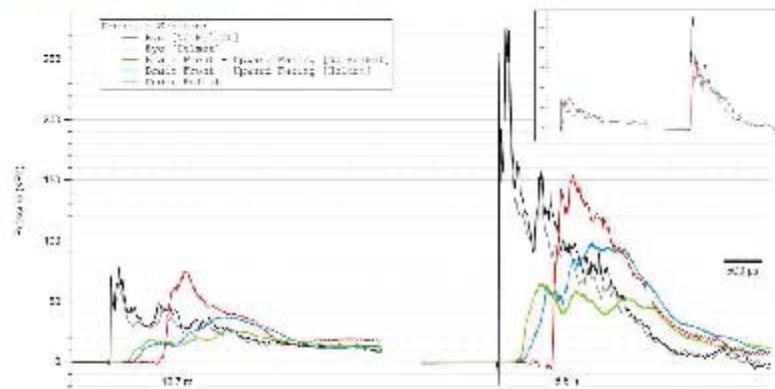


Figure 5. Pressure traces from two standoff distances showing the relationship between 'in brain' and under helmet pressure build up. The inset shows the reflected pressure (eye sensor, with helmet) and under helmet pressure sensor traces aligned to make comparisons between the two waveforms easier to visualize.

The upward facing front brain pressure sensor shows a much slower rise time, beginning approximately 200 μ s after the eye sensor first registers. For both standoffs, the 'in brain' pressure plateaus for several milliseconds before beginning to decay when no helmet is present. However, when a helmet is present, there is a second peak that occurs after the initial peak; the initial peak is not altered by the helmet. The second peak in the 'in brain' pressure occurs after the peak of the under helmet

pressure. 'In brain' and under helmet pressures then decay along a similar time course. The results at the middle standoff distance (9.7 m) and the rear upward facing brain pressure sensor follow the same trends as those shown here.

4. DISCUSSION

The results reported here are one of the first attempts to experimentally determine the effect of a helmet on blast overpressure transmission into the brain. While the findings are interesting, the limitations of the study need to be kept in mind. First, there is only a single set of data at each standoff distance. The data is collected during training exercises to ensure realistic exposure scenarios, but there are a limited number of blast events per training cycle. Replication and extension of this work is planned for future training courses. However, prior testing at the training site, using a similar head/brain surrogate to the one used here, demonstrated high reproducibility between recorded pressure events from identical blast scenarios. In addition, the reflected and incident pressure recordings reported here also show consistency for blasts recorded at the same standoff distances.

The second limitation of this study is the use of synthetic materials to simulate the biological materials of the human head and brain. While efforts are made to match the synthetic materials to their biological counterparts, there will inevitably be differences. As such, one must be cautious of looking at the absolute pressure values recorded, as they will likely be offset from what would occur in biological specimen. However, it is likely that the trends seen in the surrogate system will be replicated to some level within the biologic system being simulated.

Two major trends were observed in the experimental data. The first was in the under helmet pressure recording. At the lowest incident pressure tested (furthest standoff distance), the under helmet pressure was approximately equal to the reflected pressure at the front of the skull (measured by the eye sensor). Not unexpectedly, the under helmet pressure increased as the standoff distance decreased, however, it did not track the reflected pressure at the front of the skull. Instead, it became a smaller and smaller fraction of the reflected pressure at the skull front. It is likely this effect is due to the limited gap space under the helmet formed by the pads separating the helmet and the head. Computational models have shown the pad design and placement can alter the predicted under helmet pressures [8]. It should also be noted that the under helmet pressure sensor was located roughly where the computational models predicted the highest under helmet pressures [5-6].

The second trend is that the presence of the helmet generally resulted in an increase in the pressures recorded by the sensors in the brain. The two upward facing sensors clearly show increased peak pressures when the helmet is in place vs. absent. The biggest increase occurred at the rear sensor with an ~60% increase in recorded pressure. The front facing sensors are less clear. The more forward of these recorded a progressive percent increase (helmet vs. no helmet) as the incoming pressure increased. However, the front facing sensor located mid-brain recorded a lower pressure for the further standoff and no difference for the middle distance. However, at the closest distance to the blast, it recorded the second largest, near 50%, increase between helmet and no helmet.

The question is whether the under helmet pressure is responsible for these increases. Plotting the upward facing pressure sensor traces against the reflected pressure at the front of the skull and the under helmet pressure suggest this might be the case. There is a second peak in the 'in brain' pressure traces that slightly lags the formation of the under helmet pressure. This second peak is absent when the helmet is removed from the head.

These experimental findings do not match with the predictions of several computational models that suggested that the presence of a helmet would lower pressures experienced within the brain [8-9]. The cause of the discrepancy is unclear. The computational models and the physical surrogates are not identical, however, both model the human head and as well as the same helmet geometry. It's unlikely that small differences here would result in this level of discrepancy. Materials properties could potentially cause this effect. For example, it's been suggested that flex in the skull may result in pressure transmission into the brain [5]. If the plastic that the surrogate heads are constructed from over flexes relative to bone, it could lead to increased pressure levels in the brain in response to the increased under helmet pressure. Testing of the plastic's material properties are underway to determine if this is a possibility. Replacement of the plastic with a stiffer material could also be used to rule out this as a possible explanation. A third possibility for the discrepancy lies in the test arena. The computation models are simulating ideal blast events or shock tube overpressures, whereas the physical surrogates were placed in front of live breaching charges and are responding to a much more complicated blast scenario than the computational models. Finally, the disagreement between the experimental measurements and computational results may be due to the differences in the locations where the physical

or virtual pressure measurements were taken. Further work will be required to determine the root causes of the discrepancies.

5. CONCLUSIONS

Blast pressure interactions with the human head and brain are complex and the effect of a helmet on this system is only beginning to be understood. Using physical surrogates of the human head and brain, this study expands the understanding of blast effects on the head/brain/helmet system. At low overpressures, the pressure measured under the helmet was close to the reflected pressure measured at the eye. As the overpressure exposures increased, however, the under helmet pressure relative to the eye measurements decreased. At the highest overpressure exposure tested, the under helmet pressure was only ~60% of that measured at the eye. At low to moderate pressures, the presence of a helmet resulted in a roughly 20-40% increase in measured brain pressures relative to no helmet. At the highest overpressure tested the increase in brain pressure due to a helmet was approximately 60%. It is clear that the interaction of blast overpressure events with the human head, brain, and armor systems is complex and likely varies depending on the blast magnitude.

Acknowledgments

The authors thank Sgt. 1st Class Geoffrey Davis for the opportunity to collect data at the Urban Mobility Breaching Course (UMBC) at Fort Leonard Wood, MO. This work was supported under award #W81XWH-16-2-0001 from the MRMC JPCS program. American Society of Engineering Education and Naval Research Lab are thanked for the post-doctoral fellowship support for YungChia Chen. Robert Saunders is thanked for technical support.

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References

- [1] National Research Council, Review of Department of Defense Test Protocols for Combat Helmets (The National Academies Press, Washington, DC, USA, 2014)
- [2] Wallace D. and Rayner S., J Mil Veterans Health, 2012; 20; 10-17.
- [3] Moore D.F. and Jaffee M.S., Neurorehabilitation, 2010; 26; 179-181.
- [4] Ganpule S., Gu L., Alai A. and Chandra N., Comput Methods Biomech Biomed Eng, 2012; 15; 1233-1244.
- [5] Moss W.C., King M.J. and Blackman E.G., PRL, 2009; 103; 108702-1-108702-4.
- [6] Mott D.R., Schwer D.A., Young T.R., Jr., Levine J., Dionne J.-P., Makris A. and Hubler G., Blast-induced pressure fields beneath military helmet, Proceedings of the 20th International Symposium on Military Aspects of Blast and Shock, Oslo, Norway, September 1-5, 2008.
- [7] Zhang T. and Satapathy S., Effect of helmet pads on the load transfer to head under blast loadings, Proceedings of ASME 2014 International Mechanical Engineering Congress and Exposition, Montreal, Canada, November 14-20, 2014.
- [8] Sharma S., Makwana R. and Zhang L., Evaluation of blast mitigation capability of advanced combat helmet by finite element modeling, 12th International LS-DYNA Users Conference, Detroit, MI, USA, June 3-5 2012.
- [9] Zhang L., Makwana R. and Sharma S., Frontiers in Neurology, 2013; 4; 1-12.

Appendix J: Published MABS paper, O'Shaughnessy et al.**HEAD SURROGATES FOR ASSESSING REPEATED BLAST OVERPRESSURE EXPOSURES TO BREACHERS**

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ABSTRACT

Blast overpressure and its associated effects (e.g., secondary and tertiary effects from a blast incident) are believed to be responsible for a number of instances of traumatic brain injury (TBI). As the US role has reduced in combat theaters, symptoms associated with mild TBI (mTBI) have been reported by instructors in training classes in overpressure environments from repetitive low-level blasts. This paper discusses the techniques developed for quantifying such repeated exposures in breacher training environments using the U.S. Naval Research Laboratory's (NRL) surrogate head/brain systems developed specifically for these applications. The presentation will show the NRL headform, with embedded instrumentation, such as pressure and acceleration sensors, with the added capability to use NRL cell pack with neuronal cell cultures. This work demonstrates a modular, portable device that can be utilized for assessing the external threat and insult to the brain (using surrogate brain materials) for training environments with repeated low-level exposures.

INTRODUCTION

The effect of blast overpressures on the warfighter is an important question. Even when not in a combat zone, the threat of blast overpressures is prevalent. This is especially true during training on various weapons and breaching methods. Research into this area requires several methods, one of which is to create biofidelic surrogate models.

A number of surrogate systems have been created to study the effect of blast on the human body of varying degrees of biofidelity. A common method is to use an ellipsoid or egg shaped plastic shell filled with a silicone gel as brain simulant [1–3]. The BI²PED was developed by the Defence Research and Development Canada (DRDC) Valcartier Research Center to test the effectiveness of the headgear [3]. This headform is able to characterize the external pressure field around the head, give the global head acceleration, and intracranial pressures [4]. Commercial anthropomorphic test dummies (ATD), such as the Hybrid III test dummies, developed for kinematic or impact testing have been used in blast research but lack the ability to determine pressure transmission into the surrogate [5,6]. Furthermore, the materials used in ATDs are less biofidelic when comparing the levels of shockwave transmission and may affect the validity of the results.

The NRL GelMan was originally created to test the threat level from various weapons effects on warfighters [7] and has evolved to testing protective equipment [8] by determining the behind armor blast, blunt and ballistic impact in the surrogate tissues. The GelMan Thoracic surrogate was also used to determine the effect of underwater threats on swimmers [7], with the current GelMan Head being created to test the effect of a helmet on the brain during a blast [8].

This paper documents the evolution of the GelMan Head to the current modular format. The current design of the GelMan Head allows making multiple modular surrogate brains with different sensor configurations to meet the requirements of the tests. Other modifications can be made to the head to meet other test-specific requirements for assessing blast effects on the head such as pressure transmission through the ear canal.

METHODOLOGY

The Modular GelMan Head employs a commercial, anatomically accurate human skull with a removable skullcap (Model #1020159, 3B Scientific, Tucker, GA). The use of commercially available products facilitates the quick manufacturing of surrogate skulls and brains. Hybrid III necks (Model#: 78051-336-H, Humanetics, Plymouth, MI) and foam torsos were used in conjunction with GelMan Heads to better mimic the actual response of the blast on the warfighter.

GelMan Skull Manufacturing

To attach the GelMan Head onto the Hybrid III neck, a custom mounting plate system was needed to connect the skull to the neck through the foramen magnum. A flat metal plate was needed on the bottom side of the foramen magnum for attaching the Hybrid III neck mounting plate. To accomplish this without the need for drilling into the skull, an interfacing system between the foramen magnum and the flat metal plate was created.

To make the interface, or mounting inserts, modeling wax was used to make impressions of the inside and outside of the foramen magnum. From this, two molds were created from Dragon Skin (Dragon Skin® 10 Medium, Smooth-on, Inc, Macungie, PA); the use of the molds allows for consistency when replicating new mounting inserts for subsequent skulls. Mixed epoxy (Devcon 5 Minute Epoxy, ITW Polymers Adhesives, Danvers, MA) was poured directly into the molds and allowed to cure. Once cured, the flat sides of the inserts were lightly sanded and cleaned (Figure 1A). The epoxy inserts were then placed on either side of the foramen magnum providing flat surfaces upon which aluminum plates rested. Two screws secured the aluminum plates together, sandwiching the epoxy inserts in place tightly in conjunction with the skull (Figure 1B). A modified Hybrid III neck mounting plate was then secured to the bottom aluminum plate (Figure 1C).

Prior to completion of the skulls, a 50 psi (345 kPa) pressure sensor (Model#113B28, PCB Inc., Depew, NY) was mounted in the left eye cavity (Figure 1D). In some versions of the GelMan Head, a second flush mounted sensor was placed at the left temple. A tri-axis accelerometer (Model #356A01; PCB, Depew, NY) was also secured to the back of the skull with epoxy (Figure 1C).

To simplify the placement of the modular brain in the skull as well as to cover the neck mounting system and skull pressure sensor wires, a platform was added (Figure 2D, E). This was made from pouring Sylgard 184 (Dow Corning, Auburn, MI) into the skull, embedding the epoxy insert, aluminum plate, and pressure sensors in place (Figure 1E). To accomplish this, all the holes in the lower portion of the skull were temporarily sealed prior to adding the Sylgard. The height of the platform came to 18 mm from the top of the skull line. Once cured, the temporary sealant was removed and the eye sockets filled with Sylgard 184.

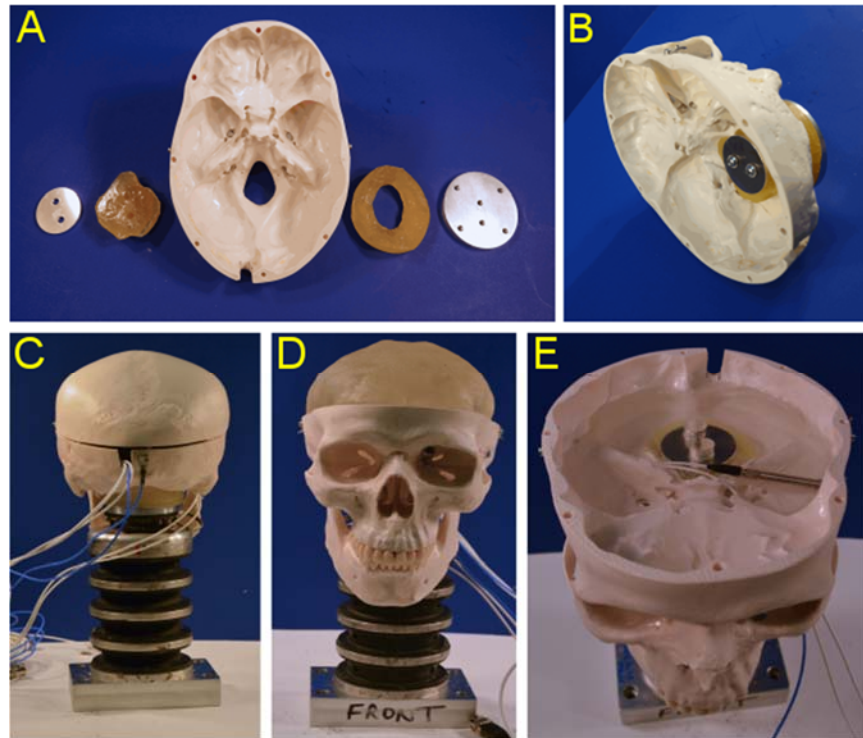


Figure 1. Attachment of the GelMan Head onto the Hybrid III neck was accomplished by using two custom epoxy pieces and two aluminum plates (A). The top plate and insert are pictured to the left of the bottom half of the skull; the bottom plate and insert are to the right of the bottom half of the skull. The two epoxy pieces were sandwiched between the aluminum plates with screws through the foramen magnum (B). The Hybrid III neck plate was screwed to the bottom aluminum plate (C) allowing the skull to be placed on the neck (D). The epoxy pieces and aluminum plates were positioned prior to pouring the Sylgard 184 platform (E).

GelMan Modular Brain

Ensuring manufacturing repeatability of the modular brain required the use of a mold. To make the mold, the skull with the Sylgard 184 platform was filled with melted Sim-Test (Corbin Manufacturing and Supply, Inc, White City, OR). Once cooled, the Sim-Test formed the positive shape of the skull cavity. A negative mold was created from the positive form using Dragon Skin (Figure 2A).

Sensors were positioned in the modular brain using a 3D printed holder (Figure 2B, C). 3D printing the sensor holders facilitated fast manufacturing of the modular brain. The same holder was used to replicate sensor positions in different modular brains. New holders were easily created to produce modular brains with different sensor placements. Hot glue was used to attach the sensors to the holder (Figure 2B). The use of hot glue also allowed for easy detachment of sensors from the holder.

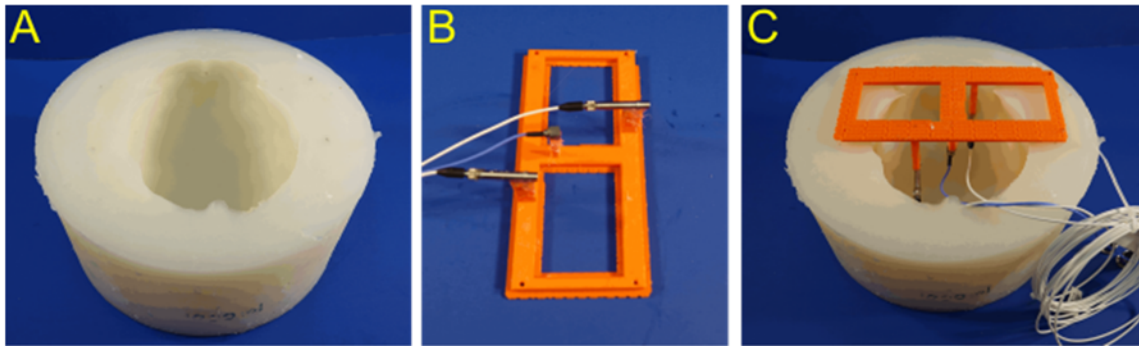


Figure 2. The mold for the modular brain was made from Dragon Skin (A). Holders for positioning the sensors were 3D printed (B) and placed on the mold upside down (C).

With sensors in position, enough brain simulant, Sylgard 3-6636 (mix ratio 1:1.5; Dow Corning, Auburn, MI), was poured into the brain mold such that the sensors were halfway embedded and the Sylgard allowed to cure. Afterwards, the sensors were detached from the holder and more Sylgard added to complete the brain. Multiple pours helped to ensure proper sensor placement and clean removal of the sensor holder. The different layers were not visible suggesting complete polymerization between the second layer and the first. It is important to note that the mold was coated in a thin layer of petroleum jelly prior to pouring the Sylgard. Without this layer, the Sylgard will cure to the silicone mold, making removal of the surrogate brain from the mold impossible.

After full curing, the surrogate brain was removed from the mold. The modular brain was submerged in isopropanol to remove the petroleum jelly. Once cleaned, brain was then wrapped in cellophane to protect it from dirt and debris.

GelMan Stand

The GelMan Head was mounted to a custom designed aluminum frame made from 80/20 framing (Figure 3). Foam torsos were attached to the frame so that each head tested also had a torso with armor to emulate the aerodynamics of a warfighter in a blast environment. The height of the stand was 1.4m (not including the height of the neck and head). The width and height of the stand can easily be altered, increasing the adaptability of the GelMan system.

Data Acquisition System

Two USB-6356 X Series DAQs (National Instruments Corp., Austin, TX) connected through two signal conditioners (Model #483C05, PCB Piezotronics) operated via a laptop running SignalExpress 2014 (National Instruments) were used to acquire data. The sample rate was 1 MHz and the system triggered off the ‘eye’ pressure sensor. A 10ms pre-trigger buffer was used. Post processing of the data was performed using Igor Pro v6 (Wavemetrics, Inc., Lake Oswego, OR). The data were scaled using the sensitivities of the various sensors and filtered at 100 kHz via a digital low-pass FIR.

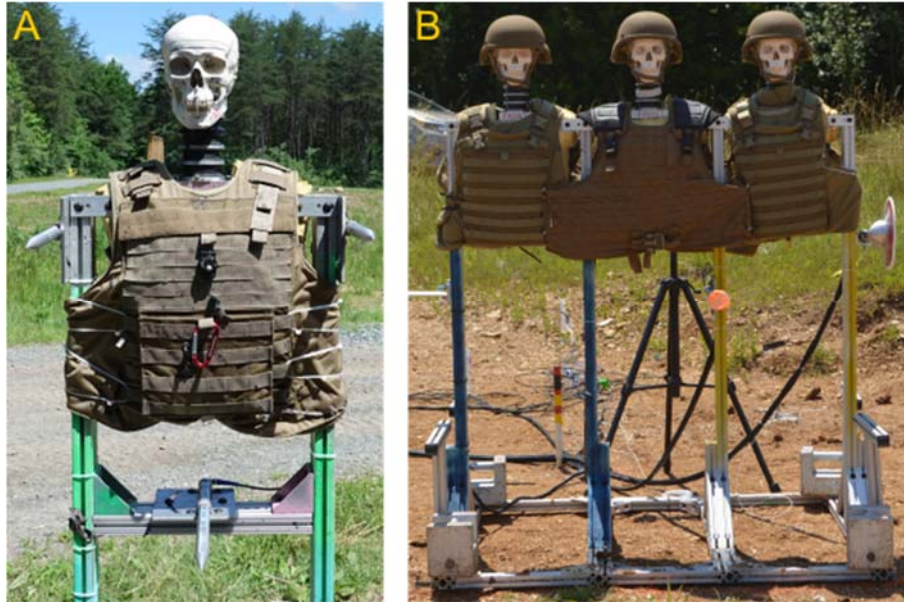


Figure 3. The stand can be easily configured to have a single (A) or a triple head and torso configuration (B).

RESULTS

In blast events where the GelMan Heads were placed 12.7 m from breaching walls constructed from cinderblocks filled with concrete, both the pressure sensors in the left eye orbital (Figure 4A) and the temple (Figure 4B) display classical Friedlander pressure waves; they are also similar to the incident pressure waves measured with the pencil gauge located on the stand (Figure 4C). The peak pressure measured with the eye sensor is approximately double the incident pressure as measured with the pencil gauge, 78.4 kPa versus 46.7 kPa respectively. This suggests that the eye sensor measures the approximate reflected pressures at the head. The temple sensor saw peak pressures halfway between the eye sensor and the pencil gauge at 62.7 kPa.

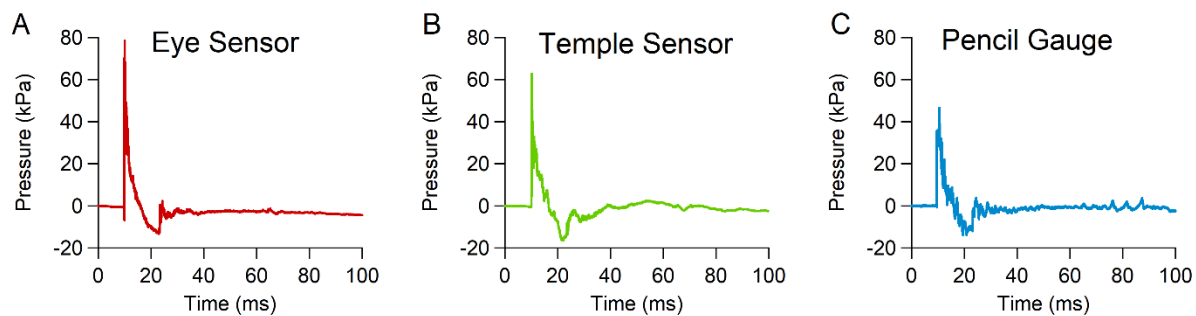


Figure 4. Pressure profiles measured from pressure sensors at the left eye orbital (A), the temple (B), and from the pencil gauge (C) which measured incident pressure.

The pressures in the brain show similar pressure profiles and duration of the positive phase to the eye and temple sensors but with much lower peak pressures (Figure 5). The peak pressure measured with the in brain front sensor was 23.9 kPa and 18.2 kPa with the middle pressure sensor.

For a forward facing blast event, most of the acceleration is in the vertical (Z axis) and horizontal (X axis) directions. There is little lateral acceleration (Y axis). The largest absolute acceleration occurred in the vertical direction, as a downward acceleration of 167.5 g. Accelerations in the horizontal (X) and lateral (Y) directions did not exceed an absolute magnitude of 50 g and 5 g, respectively.

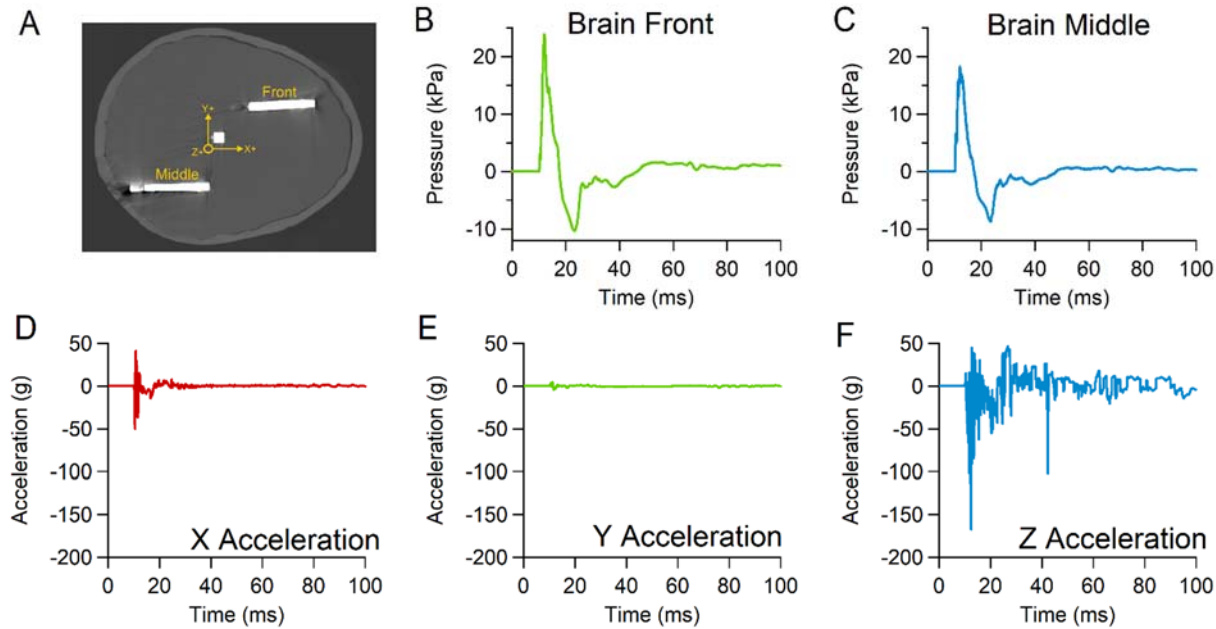


Figure 5. The orientation and location of the front and middle in brain pressure sensors and tri-axial accelerometer are shown in the X-ray image of the GelMan Head with modular brain (A). Pressure profiles in the surrogate brain as detected by the front pressure sensor (B) and the middle pressure sensor (C). (D-F) Accelerations in the X, Y, and Z directions.

Figure 6 shows data recorded with a single GelMan Head from three identical wall breach events. The pressures recorded at the eye sensor demonstrate the similarity of the three overpressure events, as they impact the outer shell of the GelMan Head (Figure 6A). The pressures recorded from the forward facing, front pressure sensor within the surrogate brain (Figure 5A) also exhibited a remarkable similarity (Figure 6B), demonstrating the ability of a GelMan Head to reproducibly record overpressure events within the surrogate brain.

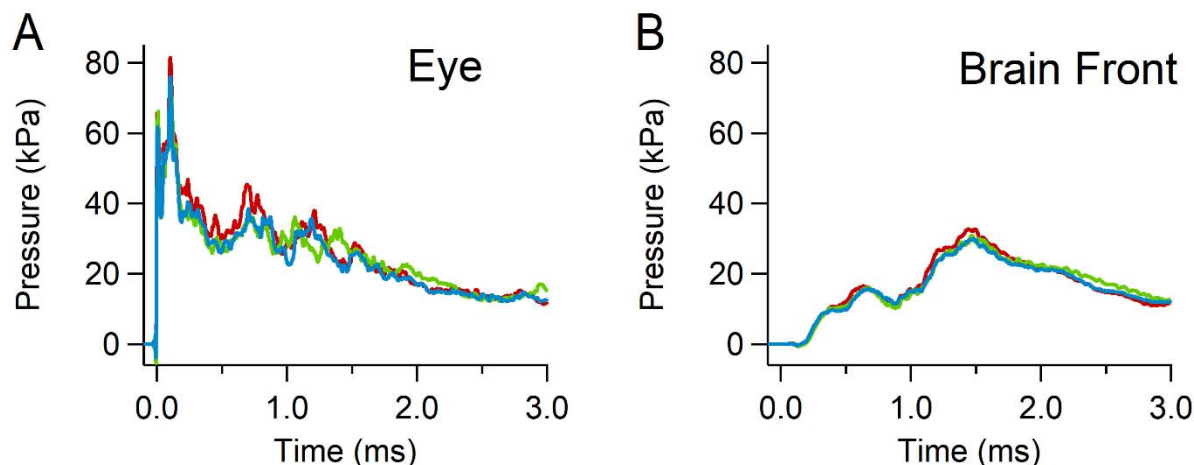


Figure 6. Three identical breaching events were recorded with a single helmeted GelMan Head. Each color trace represents one of the events and results are shown for both the eye sensor (A) and the front, forward facing brain sensor (B).

In order to demonstrate reproducibility between identically manufactured GelMan Heads, two were placed side by side without helmets on a multi-head stand (Figure 3B) and subjected to a blast overpressure event. For this test, there were two pressure sensors located within the brain; a forward facing sensor located near the front of the brain (same location as the front sensor in Figure 4A) and an upward facing pressure sensor (located roughly where the front of the midline sensor is in Figure 4A). Figure 7 shows the similarity in response of the brain sensors between the two heads.

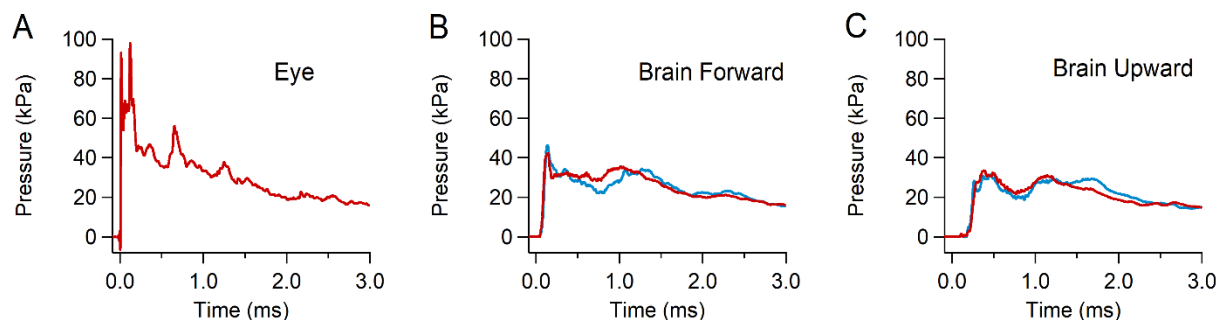


Figure 7. Results from two identical GelMan Heads in response to a blast overpressure event. (A) Reflected pressure recorded by the eye sensor of head 1. No data was recorded for head 2's eye sensor due to a cable failure. (B) Comparison of head 1's forward facing pressure sensor (red) to head 2's (blue). (C) Comparison of pressures recorded by the two heads upward facing sensors.

DISCUSSION

In the past, the NRL GelMan Head was limited in sensor placement in the brain and cable routing of cables out of the cranium. In these head surrogates the brain was first molded, and then sensors were surgically placed in the brain material and the incision sections were filled with the tissue simulant material. This technique allowed the brain to be made in a single pour with a single of

polymerization phase, but left the possibility of a less than perfect interface between the sensor faces and the brain material. Experimental results showed that this technique was better suited to acceleration measurements, and became a limitation in pressure measurement due to any separation between sensor face and surrogate brain tissue simulant. In the present design, the brain is built up in stages, using a special fixture designed to locate the sensor precisely at a particular location in the mold for the brain, thus ensuring that the sensors are within less than 2 mm from the desired location in the finished brain. The tissue simulant polymer is poured and after the sensor is securely located in the brain, the special fixture is removed and the molding process is continued. Using this technique, multiple sensors can be located in different locations and orientations, and the placement of these sensors can be easily repeated from one brain to another.

Another feature of this approach to the GelMan Head fabrication has been to introduce design modularity for such surrogate systems. The modularity of the GelMan Head permits testing of multiple sensor locations in the surrogate brain with a single GelMan Skull from one test to another by simply replacing the brain in minutes, thus simplifying brain fabrication to address specific questions for those tests. Using commercially available components allows for short fabrication and brain changeover time when adapting GelMan Head to various test conditions, including a version which can accommodate the NRL cell pack with live neuronal cell cultures. Changing the material for the brain and/or including a fluid in the cranium cavity to emulate the cerebrospinal fluids also can be easily accomplished. The details of the tissue surrogate material variants and their effects on GelMan Head performance as a system are being addressed in a future paper.

A key question in the design and use of instrumented brain surrogates is their repeatability. Figure 6 shows the representative repeatability between successive identical tests using the same surrogate head. The peak overpressure compare well and the overall pressure profiles very similar and tend to overlap each other. Considering the variability in the explosive preparation and packaging, and other factors such as terrain, ambient temperature and relative humidity, and inherent variability from one test to another, repeatability of these tests is acceptable and usable for other tests.

A second assessment criterion for design and fabrication is the reproducibility of data in one test by multiple surrogate heads in the same test conditions and subjected to the same overpressure effects. Figure 6 shows a comparison of head on overpressures measured from one breaching test by two identical surrogate heads, mounted as part of a triple stand as shown in Figure 3B. The pressure profiles from both a forward facing (Figure 7A) and upward facing (Figure 7B) overlay each other well, and the peak pressures are very close to each other.

Comparing the eye sensor data with the pressure sensors inside the brain can provide a measure of the attenuation of the pressure by the skull surrogate and by the tissue in the brain. In the data shown in Figure 7, the decrease in peak pressure is about 55% and 67% from the eye sensor to the forward facing and upward facing sensors, respectively. The consistency in these pressures and rate of decrease of the pressures can be considered good measures of reproducibility of the surrogate instrumented head-brain systems.

Likewise, the linear accelerations measured in the GelMan Head saw a peak of 167.5g in the downward direction. Studies in the traditional civilian impact head injuries suggest a linear acceleration threshold for mild traumatic brain injury to be in the region of 67g to over 100g with a typical impact duration lasting on the average 10-16 ms [9,10]. Further analysis of accelerations due to blast over pressure and comparison with accepted thresholds of injury for blunt impacts

need to be made to provide a comprehensive assessment of the impact of these measurements inside the brain and on the skull.

The NRL surrogate headform provides a platform for comparing the performance of helmet systems in breaching and other combat scenarios with blast overpressure, and ballistic and blunt impact threats. In addition, work is going on to compare these human subjects data being collected by collaborators in US Army, and determine if there is a way to establish a better understanding of mild traumatic brain injuries in similar circumstances.

CONCLUSIONS AND FUTURE WORK

This paper discussed the approach taken by NRL to design and fabricate modular GelMan heads that can be used for collecting blast effects data in the field. Data collected from breaching experiments using these heads show that the repeatability from test to test for the same head as well as the data collected by different identical heads is acceptable. The small differences in the datasets are attributed to inherent variations in blast tests. All the details shown here are for an instrumented surrogate head. The same approach can be also utilized for a surrogate headform with the NRL cell pack containing neuronal cell cultures, or modified to explore other pathways of energy propagation into the brain, such as the ear canal.

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REFERENCES

- [1] Zhu, F., Wagner, C., Leonardi, A.D.C., Jin, X., VandeVord, P., Chou, C. et al. (2012) Using a gel/plastic surrogate to study the biomechanical response of the head under air shock loading: a combined experimental and numerical investigation. *Biomechanics and Modeling in Mechanobiology*, **11**, 341–53. <https://doi.org/10.1007/s10237-011-0314-2>
- [2] Goeller, J., Wardlaw, A., Treichler, D., O'Bruba, J. and Weiss, G. (2012) Investigation of Cavitation as a Possible Damage Mechanism in Blast-Induced Traumatic Brain Injury. *Journal of Neurotrauma*, **29**, 1970–81. <https://doi.org/10.1089/neu.2011.2224>
- [3] Bouamoul, D.A. and Ouellet, M.S. (2012) A Blast Headform Surrogate for the Assessment of Blast-Induced Traumatic Brain Injury. Florida.
- [4] Ouellet, S., Bir, C. and Bouamoul, A. (2014 Feb) Direct Comparison of the Primary Blast Response of a Physical Head Model with Post-mortem Human Subjects [Internet]. Defence Research and Development Canada-Valcartier Research Center Quebec, QC Canada, Defence Research and Development Canada-Valcartier Research Center Quebec, QC Canada.
- [5] Makris, A., Nerenberg, J., Dionne, J.P., Bass, C.R. and Chichester, C. (2006 Jan) Reduction of Blast Induced Head Acceleration in the Field of Anti-Personnel Mine Clearance: [Internet]. Defense Technical Information Center, Fort Belvoir, VA. <https://doi.org/10.21236/ADA458451>
- [6] Sogbesan, E.A. (2011) Design and Analysis of Blast Induced Traumatic Brain Injury Mechanism Using a Surrogate Headform: Instrumentation and Outcomes. University of Nebraska - Lincoln.

- [7] Matic, P., Simmonds, K. and Pogue, W. (2007 Sep) GelMan Thoracic Surrogate for Underwater Threat Neutralization. Naval Research Laboratory, Washington (DC). p. 8.
- [8] Simmonds, K.E., Bagchi, A., Leung, A.C., III, W.R.P., Matic, P., Byers, J.M. et al. (2009) Sensor Systems for Measuring Helmet-Head-Brain Response to Blast. p. 76–86.
- [9] Zhang, L., Yang, K.H. and King, A.I. (2004) A Proposed Injury Threshold for Mild Traumatic Brain Injury. *Journal of Biomechanical Engineering*, **126**, 226. <https://doi.org/10.1115/1.1691446>
- [10] Greenwald, R.M., Gwin, J.T., Chu, J.J. and Crisco, J.J. (2008) Head Impact Severity Measures for Evaluating Mild Traumatic Brain Injury Risk Exposure. *Neurosurgery*, **62**, 789–98. <https://doi.org/10.1227/01.neu.0000318162.67472.ad>

Appendix K: Published MABS paper, Kamimori et al.

IMMEDIATE AND ACUTE EFFECTS OF HEAVY WALL BREACHING ON COGNITIVE PERFORMANCE AND BLOOD BIOMARKERS

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ABSTRACT

Key words: overpressure, occupational exposure, blast, breacher

There are military occupational specialties that involve routine and repetitive exposure to blast overpressure during training and operations. This presentation will examine data collected in conjunction with heavy wall breaching during an Urban Mobility Breaching Course (UMBC) taught by the 35th Engineers (Ft. Leonard Wood, MO, USA). Data were collected five times over a 16 month period and involved 157 volunteers. UMBC includes breaching large charges designed to create passable entry ways in concrete walls and chain-linked fences. Blast gauges (Black Box Biometrics, Rochester, NY, USA) were attached to operators to estimate individual operator overpressure exposure. Neurocognitive performance was determined using the Defense Automated Neurobehavioral Assessment (DANA) Rapid test battery before exposure (baseline), immediately after detonating the back-to-back charges, and at the end of the training day (acute). Symptom reporting and blood samples were collected at the beginning and at the end of the training day in accordance with baseline and acute timepoints.

Neurocognitive deficits (i.e., increased response time) identified immediately after blast exposure were associated with higher peak overpressures and seem to be more prevalent in higher memory demand tasks. Acute neurocognitive effects show association in line with the sum of (e.g. cumulative) peak overpressure and cumulative impulse. Acute effects related to peak overpressure were consistent with existing literature. Preliminary results for blood-based biomarker analyses are ongoing. Tau, GFAP, and NFL were evaluated, for which results will be presented in future work.

During a number of the same breaching events, head/brain surrogates (NRL GelMan Head) containing pressure sensors under the helmet, on the head, and within the simulated brain were positioned at several standoff distances from the charge, the farthest standoff being equivalent to that used for training. These surrogates were designed to determine how the pressures experienced at these positions interact with the head and helmet and then penetrate into the brain. These studies advance the understanding of occupational blast exposure and associated neurocognitive and physiological effects. Results assist risk/benefit assessment and aid in developing appropriate response strategies for military personnel exposed to blast overpressure.

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INTRODUCTION

Chronic exposure to operational overpressure among military and law enforcement personnel is a growing area of interest for health research. [1], [2], [3], [4] The current corpus of blast effects literature is divided. Transient, but measurable, effects are regularly identifiable in a proportion of the population. [1, 2] However, assessment of symptomologies and duration thereof is inconsistent.

To investigate the potential negative consequences of blast, a variety of assessments are used. Neurocognitive performance is often assessed with the Defense Automated Neurobehavioral Assessment (DANA). [5] The Naval Research Lab Head Brain Model (NHBM), is a surrogate, modular design that allows for the evaluation of blast in environments where human and animal models are not appropriate while providing an accurate proxy model for human head exposures to blast. [14] Therefore, neurological proxy measurements are made via GelMan Heads to evaluate the extent to which blast exposure may create consequences that are generally hidden to regular observation without significant tissue harvest. Finally, the blast overpressure levels to which personnel are exposed as a function of breaching in training environments are measured with BlackBox Biometrics (B3, Rochester, NY, USA) blast gauges. More recently, blood-based biomarkers which typically consist of pro-inflammatory cytokines or proteins that are enriched in the central nervous system are assessed throughout timepoints from study participants to establish patterns due to blast overpressure incidence or amplitude [2,15] [9] Neurofilament Light chain (NFL) levels have shown promise as an indicator of neurocognitive trauma. [10] [11] Similarly, previous research has warranted the further investigation of GFAP [12] and Tau [12, 13] in subjects exposed to blast overpressure.

This work evaluates immediate and acute effects across two years of data collection to evaluate what, if any, consequences of blast exist in military training environments for heavy breaching. This work first describes the sample of participants and characterizes their exposures. Next, the individual measurements are described and a schedule of interactions is provided. Finally, results and implications of findings are discussed, concluding with future directions.

STUDY DESIGN/PARADIGM

The current study represents a multi-year data collection inclusive of five different breaching sessions during multiple Urban Mobility Breaching Course (UMBC) with the 35th Engineers (Ft. Leonard Wood, MO) from Summer 2016 through Winter 2017. Breaches were conducted as a regular part of the single-day training, with participants conducting breaches on both fence and concrete obstacles. Typical fence charges had Net Explosive Weights (NEW) of approximately 3.5 lbs, while concrete charges typically had NEWs of 10 lbs. Minor variation in data collection methodologies were unavoidable (constraints due to changes in course structure, weather, etc.) but were generally minimal in their deviation.

METHODS

Defense Automated Neurobehavioral Assessment (DANA) The DANA is a neurocognitive assessment tool that uses a standardized library of cognitive and psychological assessments [5]. The brief assessment takes approximately five minutes to complete, and is comprised of three components: The Simple Reaction Time (SRT), Procedural Reaction Time (PRO) and Go/No-Go (GNG) assessments. DANA measurements were collected at the beginning of each UMBC prior to blast exposure at the beginning of the course, at the beginning of each day, immediately following blast exposure (within 5 minutes of blast) and at the end of the day (several hours after blast).

Biomarker Evaluation

Blood was drawn for biomarker assessment the day before training, beginning and end the training day with blast, and the morning after blast training day. Note, blood was not drawn in one course over the Summer of 2016. Detailed results of blood-based biomarkers will be reported in forthcoming manuscript.

Proxy-Head Evaluation

Previous studies have shown that the NHBM models provide quality data. [15] [16] Therefore, the NHBM was used for this investigation into breacher effects as previously reported [cite]. NHBM's are mounted 20-40 ft. away from the breaching charges and are deployed during cinderblock wall blasts only.

Blast Assessment

Blast gauges were affixed to personnel on their shoulders and their helmets to ensure measurements of incident pressure (as determined through visual analysis of each detonation and the relationship of that blast to the personnel being exposed) was obtained. Gauges were on all personnel evaluated and measured all overpressure exposures experienced by those personnel throughout their participation in the course.

DATA MANAGEMENT AND STATISTICS

To prepare the data for analysis, several preliminary steps were taken. First, standard outlier analyses were performed to ensure sensor integrity and accuracy of DANA. No concerning data points or patterns emerged, so the analyses proceeded as planned. Incident measurements, obtained from pressure readings on the left or right shoulder sensors, were used for all blast data presented below. If sensor values were unobtainable, linear interpolation confirmed by off-side comparison was used to estimate missing data. This was identified in less than 10% of all cases reported. DANA evaluations used 30% change in SRT and 100 ms change in PRT to define impairment. These standards were used to be consistent with previous evaluations conducted by this research team. Otherwise, all statistical tests used are as reported (T-test, etc.).

RESULTS

Overall Effects of Blast Overpressure

Of the five UMBC courses evaluated, average overpressures experienced by subjects ranged from 3.93 psi (SD = 0.82) to 5.18 psi (SD = 1.15), with average impulse ranging from 8.02 psi*ms (SD = 1.74) to 13.06 psi*ms (SD = 1.37). For the purposes of this investigation, DANA impairments are defined as a 30% degradation in SRT, or a 100 ms detriment in PRT. SRT impairments appeared on average in 6% of subjects immediately, and 8% of subjects acutely. PRT experienced higher levels of degradation with 14% and 13% of subjects expressing immediate and acute effects respectively. The effect upon GNG is under evaluation. Data is shown in Table 1.

Table 1 – Overall Effects of Blast Overpressure

Collection	M OP	Max OP	Impulse	SRT IM	SRT AC	PRT IM	PRT AC
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<i>Aug 2016</i>	5.18 (1.54)	7.36	10.47 (1.58)	2/22 [9.1%]	3/24 [12.5%]	10/22 [45.6%]	11/24 [45.8%]
<i>Mar 2017</i>	4.57 (1.06)	6.6	9.89 (1.89)	1/27 [3.7%]	4/27 [14.8%]	1/26 [3.8%]	3/26 [7.7%]
<i>Apr 2017</i>	3.93 (0.82)	6.49	8.02 (1.74)	1/27 [3.7%]	0/27 [0%]	2/27 [7.4%]	0/27 [0%]
<i>Jun 2017</i>	4.58 (0.70)	6.82	12.08 (1.35)	2/27 [7.4%]	3/27 [11.1%]	3/26 [11.5%]	1/26 [3.8%]
<i>Dec 2017</i>	4.61 (0.62)	6.49	13.06 (1.37)	2/26 [7.7%]	1/26 [3.8%]	2/27 [7.4%]	2/27 [7.4%]

Table 1. M OP = mean overpressure, Max OP = maximum overpressure, Impulse is average impulse for the course, SRT IM = SRT proportion of compromised scores in the immediate effects score for the course, SRT AC = proportion of compromised scores in the SRT acute effects scores, PRT IM = proportion of compromised PRT immediate effects scores, and PRT AC = proportion of compromised PRT acute scores. SRT and PRT proportions include student and instructors. Standard deviations are shown in parentheses where appropriate. Percentages in brackets. The highest and lowest average OP blast days are highlighted in the table.

Tentatively, differences between mean overpressure, max overpressure, impulse, and neurocognitive decline are apparent. Notably, the highest course average, impulse, and max overpressure did correspond to the highest level of deficit, and the lowest average overpressure, impulse, and max overpressure (tied), had the lowest amount of overall neurocognitive decline. However, the three other courses were insufficiently dissimilar to identify a more robust finding. To ensure sensor error (in terms of sensor placement or incident assessment was not driving the perceived relationship between maximum and minimum exposures and the respective maximum and minimum proportions of decline), a series of mixed models were conducted with variable sensor positions across data collections. Results indicated that there was not an interaction between study and sensor position for overpressure ($DF(8, 422) = .87, p = .55$) and impulse ($DF(8, 398) = 1.11, p = .36$). There were significant differences in overpressure and impulse between studies ($DF(4,430) = 27.64, p < .01$; $DF(4,406) = 114.99, p < .01$, respectively) and between sensor positions ($DF(2,430), p < .01$; $DF(2,406) = 4.31, p = .01$, respectively)., It is not yet clear what proportion of deficit is being contributed by mean overpressure, max overpressure, and impulse respectively to any detriments that may exist.

Relation of Blast to Neurocognitive Impairment

To further investigate the possibility of neurocognitive detriment for immediate and acute measurements and blast exposure, a series of pre-determined t-tests were conducted using student data (instructor data were excluded because they received a different exposure profile). Instead of the previously conducted analyses by course and pressure (group level assessments of detriment and pressure) individual levels of detriment were assessed by dividing the cohort of all UMBC participants from all 5 data collections into deficient and non-deficient groups based on the aforementioned thresholds for DANA scores. Results are reported in terms of immediate and acute effects with the relevant pressures being reported. Overpressure varied significantly such that subjects with immediate deficits in DANA scores were exposed to higher average overpressures ($M = 5.06$ psi) than those without deficient scores ($M = 4.52$ psi, $t(143)=2.07, p = .04$). Similarly, acute effects were apparent for that those with higher cumulative overpressure ($M = 15.02$ psi compared to $M = 11.61$ psi, $t(131)=3.39, p < .01$) and cumulative impulse ($M = 33.88$ psi*ms) than the unaffected ($M = 29.59$ psi*ms , $t(131)=2.16, p = .03$). The total number of blast events varied slightly across classes. To address this potential confound and to act as a robustness of

effects check, the total cumulative peak overpressure for subjects was calculated (i.e. if one had 3 blasts, the 3 peaks would be added together and reported), and a t-test was calculated evaluating those with neurocognitive decline vs those without. Results were consistent with previously reported findings herein, noting that individuals with higher cumulative overpressure (15.2psi) experienced more neurocognitive decline for acute affects than those without decline (11.6psi).

The Effect of Blast Overpressure upon NHBM

Time constraints prevented complete analysis of GelHeads. However, results from the June 2017 collection (line 4 of table 1; M OP = 4.58 psi (SD = 0.70), max op = 6.82 psi, impulse = 12.08 psi*ms (SD = 1.35)). Pencil probe data at 40 ft (same distance as personnel) indicated good reliability in readings with the B3 blast gauges worn by breachers. Findings indicated that head orientation could amplify or suppress pressures on the brain, especially when the helmet is worn. It is suspected that if pressure waves are allowed under the helmet at an upward angle, they can 'bounce' and magnify in intensity, increasing potential for negative consequences. See Figure 1 for further details.

Figure 1 – NHBM June 2017 Results

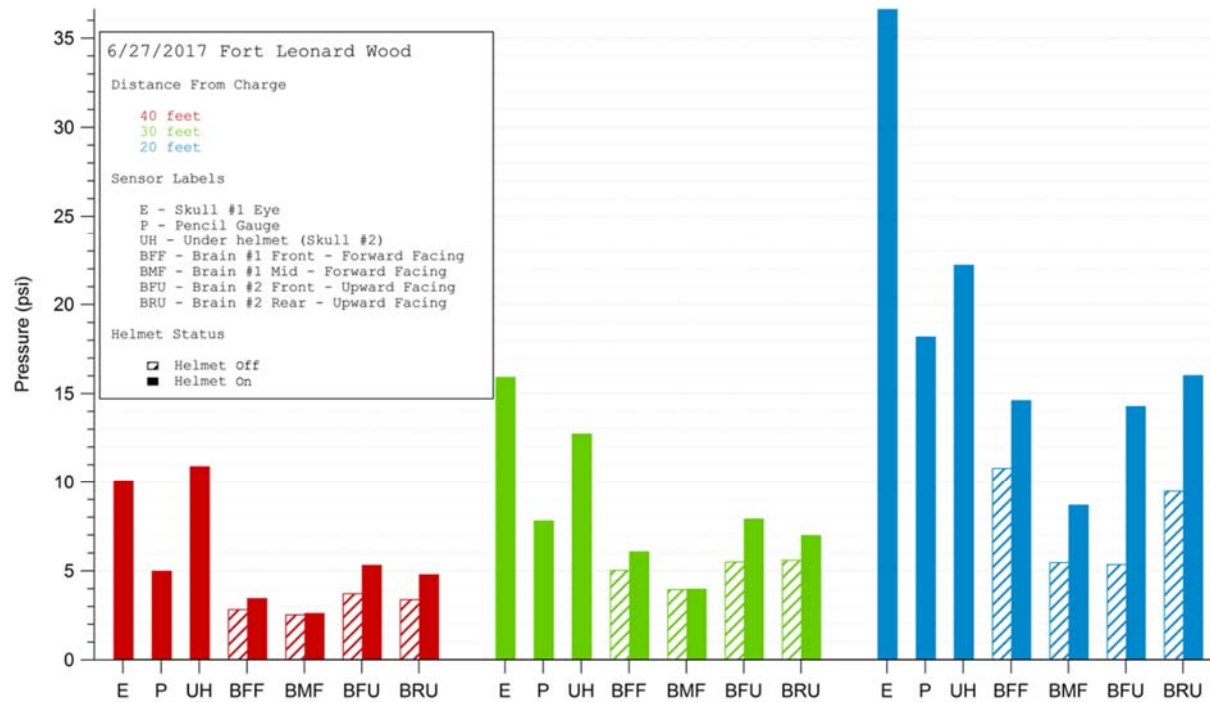


Figure 1. Eye pressures are reflective measurements. Brain pressures with the helmet on were slightly elevated compared to helmet off, however, at the closest distance this difference was significantly larger.

DISCUSSION

Blast gauges are a necessary component to the accurate evaluation of overpressure resulting from breaching and various weapons systems. Black box biometric blast gauges (Rochester, NY USA) have been used in various studies of blast overpressure, and with known orientation of sensors, have provided quality data. [17] [18] This study contributes to a growing body of results that demonstrate some individuals experience consequences to low and moderate blast overpressure. This study found a notable, but not concrete, trend where lower blast courses (in terms of impulse, max overpressure, and average overpressure) had fewer performance consequences than higher blast courses.

Moving on to the NHBM portion of the study, it is notable that the maximum distance of the NHBM represents the minimum safe distance (MSD) used by personnel for a charge of that construction type and weight. Cinderblock walls represent blasts with higher NEWs (10 lbs is common) allowing for the investigation of moderate or data collection on moderate or greater charges and their effects on various elements of the human head. Consistently, data supported the idea that ballistic helmets can exacerbate blast effects depending on recipient orientation.

Future works need to continue to investigate the components of blast to understand the relative contribution of the various components (average or max overpressure, cumulative impulse, acoustics, etc.) to understand where practitioner benefits can be efficiently and as dramatically as possible be implemented to mitigate risks. Moreover, refining the understanding of different blast factors on performance (and furthering understanding of health consequences that may also exist) is necessary to better understand individuals who may be at elevated risk.

REFERENCES

1. Tate, C.M., Wang, K.K.W., Eonta, S., Zhang, Y., Carr, W., Tortella, F.C., Hayes, R.L., & Kamimori, G.H., *Serum brain biomarker level, neurocognitive performance, and self-reported symptom changes in soldiers repeatedly exposed to low-level blast: A breacher pilot study*. Journal of Neurotrauma, 2013. **30**(19).
2. Carr, W., et al., *Repeated Low-Level Blast Exposure: A Descriptive Human Subjects Study*. Military Medicine, 2016. **181**(suppl_5): p. 28-39.
3. Littlefield, P.D., Pinto, R.L., Burrows, H.L., & Brungart, D.S., *The vestibular effects of repeated low-level blasts*. Journal of Neurotrauma, 2015. **33**(1).
4. Moldovan, M., Lupoae, M., Baciuc, C., & Constantin, D., *breaching in light obstacles*. Constructii, 2015. **6**(3): p. 35-44.
5. Lathan, C., Spira, J.L., Bleiberg, J., Vice, J., & Tsao, J.W., *Defense automated neurobehavioral assessment (DANA) - psychometric properties of a new field-deployable neurocognitive assessment tool*. Military Medicine, 2013. **178**(4): p. 365-371.
7. Di Battista, A.P., Rhind, S.G., & Baker, A.J., *Application of blood-based biomarkers in human mild traumatic brain injury*. Frontiers in Neurology, 2013. **4**(1): p. 1-7.
8. Shahim, P., Tegner, Y., Wilson, D.H., et al., *blood biomarkers for brain injury in concussed professional ice hockey players*. JAMA Neurology, 2014. **71**(6): p. 684-692.
9. Agoston, D.V., & Elsayed, M., *Serum-based protein biomarkers in blast-induced traumatic brain injury spectrum disorder*. Frontiers in Neurology, 2012. **3**(1): p. 1-10.
10. Van Geel, W.J.A., Rosengren, L.E., & Verbeek, M.M., *An enzyme immunoassay to quantify neurofilament light chain in cerebrospinal fluid*. Journal of Immunological methods, 2005. **296**(1-2): p. 179-185.
11. Gaiottino, J., Norgren, N., Dobson, R., Topping, J., Nissim, A., Malaspina, A., Bestwick, J.P., Monsch, A.U., Reginiter, A., Lindberg, R.L., Kappos, L., Leppert, D., Ptzold, A., Giovannoni, G., & Kuhle, J., *increased neurofilament light chain blood levels in neurodegenerative neurological diseases*. PLOSone, 2013.
12. Ahmed, F., Plantman, S., Cernak, I., & Agoston, D.V., *The temporal pattern of changes in serum biomarker levels reveals complex and dynamically changing pathologies after exposure to a single low-intensity blast in mice*. Frontiers in Neurology, 2015. **6**(114): p. 1-14.

13. Pelinka, L.E., Kroepfl, A., Leixnering, M., Buchinger, W., Raabe, A., & Redl, H. , *GFAP versus S100B in serum after traumatic brain injury: relationship to brain damage and outcome*. Journal of Neurotrauma, 2004. **21**(11): p. 1553-1561.
14. O'Shaughnessy, T.J., Chen, Y., Kamimori, G.H., Horner, D.M., Doherty, M.J., & Bagchi, A., *Assessing Effects of Repeated Blast Overpressure Effects in Breaching Training Exercises Utilizing NRL Head-Brain Models*. Naval Research Laboratory, N.D.
15. Chen, Y., Bagchi, A., Kamimori, G.H., O'Shaughnessy, T., *Shockwave pressure transmission through the ear canal*. Protective Armour Systems Symposium, 2018, Washington D.C., 2018.
16. O'Shaughnessy, T.J., Chen, Y., Horner, D.M., Doherty, M.J., Kamimori, G.H., & Bagchi, A., *Influence of helmet system on blast overpressure transmission into the brain*. Protective Armour Systems Symposium, 2018, Washington D.C., 2018.
17. Ostertag, M.H., Kenyon, M., Borkholder, D.A., Lee, G., Da Silva, U., & Kamimori, G.H., *The blast gauge system as a research tool to quantify blast overpressure in complex environments*. The American Society of mechanical Engineers, NOV 2013, 2013.
18. Bennet, S., Fintelman, G., Patchell, M., Webb, A., Wynen, B., Costello, J., & Wallace, D. , *PROJECT CEREBRO: An evaluation of blast gauges in the Australian defense force*. Journal of Military and Veterans' Health, 2015. **23**(3).

Appendix L: Published MABS paper, Kamimori et al.

OCCUPATIONAL BLAST EXPOSURE DURING MILITARY AND LAW ENFORCEMENT TRAINING

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ABSTRACT

Key words: overpressure, occupational exposure, blast

Occupational overpressure (OP) exposures were previously characterized and reported for mortar crew members (81 and 120 mm), artillery crew (105 mm Howitzer), and explosive breaching personnel. This work will be reviewed and new data from exposure to 50 caliber sniper rifle (2 classes), M3 Carl Gustaf recoilless rifle, and instructor grenade range exposure will be presented. OP data was collected using blast gauges (Gen6; Black Box Biometrics, Rochester, NY) attached to operators and in fixed static positions; where possible industry standard pencil probes were also used to collect data for comparative purposes. Operator OP on the left (non-dominant) shoulder firing the 50 Cal rifle was 4.7 ± 1.6 psi (mean $\pm$ SD) for the first class and 4.5 ± 0.5 (mean $\pm$ SD) psi for the second class. OP for the Gustaf gunner firing the training round was 4.1 ± 0.9 psi (mean $\pm$ SD). Acoustic data was also collected on the grenade range using a Larson Davis LxT sound meter with 1/4" mic (max 178 dB for a frequency range of 4 Hz-20 KHz) which meets the U.S. MIL-STD-1474E guidelines to record acoustic/noise exposure. Recorded measures using both the acoustic meter and calculated from pencil probe data indicate that mid-range exposure was 155 ± 3.0 dB for each detonation. Laboratory (blast tube) and field data which focuses on the effect of sensor orientation (incident vs reflective) to the overpressure source magnitude will also be presented to illustrate the magnitude of reporting errors (100%) if sensor orientation and the blast environment are unknown (e.g. internal detonation, location of walls, type of charge, etc). These data characterize repetitive low-level overpressure exposures commonly experienced by U.S. military and law enforcement personnel from a variety of training environments. This presentation will also emphasize essential factors that must be considered when measuring overpressure exposure which are critical for investigating the effects of occupational overpressure exposure from blast.

This work was supported by the U.S. Army Medical Research and Materiel Command Military Operational Medicine Research Program (Research Area Directorate 3) and Office of the Assistant Secretary of Defense for Health Affairs, Broad Agency Announcement Award No. W81XWH-16-2-0001. Opinions, interpretations, conclusions and recommendations are those of the author and are not necessarily endorsed by the Department of Defense.

INTRODUCTION

Occupational blast exposure is characterized as the repeated exposures to explosive blast events to personnel that occur as part of training and operational activities. These personnel most often have specialized roles in the military and law enforcement communities and operate weapons systems or execute tactics and techniques that involve exposure to heavy weapon systems and explosives. A growing body of literature is focused on the potential consequences for personnel in terms of readiness and long-term health resulting from blast exposure. [1][2] [3] [4] [5] A critical component to the understanding of any blast consequences regardless of severity, potential for comorbidities, or duration of effects is the proper characterization of the actual blast exposure. Generally, low-level blast exposures on humans are characterized as blasts that have a peak overpressure of <4 psi. [1] [5] [3] However, characterizing blasts beyond low-level has been difficult, and often focuses on the severity of injury rather than the nature of the exposure. [6] For

the purposes of this investigation, peak overpressures between 4 psi and 8 psi are considered moderate-level blast exposures.

The purpose of this manuscript is two-fold. First, this work characterizes blast across low-level and moderate-level exposures from a variety of overpressure inducing mechanisms like mortars, artillery, explosive breaching, 50 caliber rifle systems, M3 Gustaf Rifles, and hand grenades. Second, this work discusses methods of measurement and potential setbacks in generating measurements that are comparable across datasets.

CHARACTERIZATION OF BLAST FROM VARIOUS WEAPON SYSTEMS

Unless otherwise noted, B3 blast gauge sensors (black box biometrics, Rochester NY) were used for all pressure measurements. The data reported here was collected at five different sites between 2014 and 2016 for a total of six different overpressure exposure mechanisms. Previous works have used B3 blast gauges to good effect, [1] with results comparable to pencil gauges. All reported values in this study represent incident pressure measurements.

Mortar Measurements – Mortars are man-portable devices capable of launching muzzle-loaded explosives across moderate distances (several hundred yards to a few miles). Measurements here were of the 81 mm and 120 mm mortar systems. Notably, mortars emphasize use of high-arc parabolas (angle of fire) and varied charge weights (amount of propellant) to aim their payloads over distance and are generally operated by five-man crews.

Two mortars, an M252 81 mm bore mortar (length 56'') and an M120 120 mm bore mortar (length 69''), were fired during training. Twelve rounds of charge level 4 (moderate propellant) were fired from the 81 mm mortar followed by twelve rounds of charge level 3 (lower propellant) from the 120 mm mortar. Crew members were outfitted with sensors on the back and front of their helmets, as well as along both sides. Visual analysis of crew member position dictated reported sensor value to ensure incident pressure values were being reported.

Mortar crew positions for the 81 mm mortar (squad leader, gunner, assistant gunner, and ammo bearer) all had similar pressure readings, with ammo bearers being the lowest ($M=2.0$ psi, $SD=0.3$), squad leaders being the highest ($M=3.0$ psi, $SD=0.3$), and gunners ($M=2.4$ psi, $SD = 0.4$) and assistant gunners ($M=2.3$ psi, $SD=.4$) coming in between them.

The larger 120 mm mortars use five-man crews (add-in a range safety officer to the previous four man crew) and experience generally higher pressures. Range safety officers averaged 6.0 psi ($SD=1.2$), whereas squad leaders ($M=5.2$ psi, $SD=.8$), gunners ($M=3.7$, $SD=.7$), assistant gunners ($M=3.4$ psi, $SD=.4$), and ammo bearers ($M=2.4$ psi, $SD=.3$) all experienced lower pressures, but still higher than on the 81 mm mortar system.

Artillery Measurements – artillery pieces have been a staple in modern warfare. Artillery operates similarly to the mortar, but on a larger scale while still using variable charge weights and firing angles. Firing 105 mm projectiles (other artillery fires 155 mm projectiles) from towed or self-propelled systems, modern artillery pieces in the United States Military arsenal extend accurate support-fire capabilities beyond that of traditional infantry portable weaponry. Ranges extend to over 20 miles depending on local terrain.

For this investigation, a six-man crew operating an M119 105 mm howitzer were evaluated. High Explosive (HE) rounds at charge level 4 (moderate propellant level) and level 5 (higher propellant

level) were fired at two elevation levels. Standard elevation (approximately 30 degrees above horizontal) and charge 4 was also fired at high elevation (approximately 70 degrees above horizontal). Gauges were placed on the fronts members' helmets. Crew members do not remain static during Howitzer operation so their exact position and orientation to the weapon do not remain constant throughout the collection. As such, results are reported as is, and should be approached with the knowledge that these values may not represent ideal incident measurements, and instead may have reflective components that likely result in overestimation of pressure.

Artillery measurements were divided across crew positions. Crew members are divided into the ammunitions team chief (stands to the left mid-gun), assistant gunner (mid-gun, right side), gunner (mid-gun, left side), loader (rear gun), radio operator (rear gun), and chief of section (mid-gun immediately behind gunner). Charge four and five measurements with the 105 mm howitzer regardless of angle did not exceed 2.3 psi for any crew member. Overall, assistant gunners and chief of section crew members received the highest pressures, averaging 1.6 psi. Other members had lower exposures at 1.4 psi for the ammunitions team chief, 1.4 psi for the loader, 1.5 psi for the radio operator, and 1.3 psi for the gunner.

Breaching Measurements – Explosive breaching is a technique that allows for the rapid entry of military/law enforcement personnel into a barricaded or otherwise inaccessible location through the application of controlled explosives. Breaching charge construction varies based on application and resources available but are common across types such that all require some mechanism of detonation, an appropriate amount of explosive, a method of applying that explosive to the barrier, and nearby personnel to capitalize on the soon-to-be created entry point immediately post-detonation.

A total of 6 charges were evaluated (four indoor, two outdoor), with sensors placed on stands and where possible, personnel during blasting. Sensors on personnel were placed on both shoulders and the helmets of breachers, with values being reported for best incident pressure as determined by visual inspection. For all measurements, sensor distance was Minimum Safe Distance (MSD) for each particular charge.

Indoor pressure measurements calculated for a 3.5 psi MSD averaged 4.4 psi (SD=0.4) with outdoor charges, 6.2 psi (SD=1.5) on fence and 5.0 psi (SD=1.4) on concrete obstacles. Results indicate parameters can regularly exist in field exercises that make standard MSD calculations insufficient with regards to categorizing approximate blast values at various distances.

50 Caliber Rifle Measurements – 50 caliber rifle systems here refer to bolt-action or semi-automatic, man-portable rifles used for anti-personnel/equipment purposes. For this investigation, 50 caliber machine guns like the M2 or similar are not considered. Equipment and ammunition varied, with most rifles having 20-29 in barrels in factory specified condition firing military or match ammunition from 600-770 grains in weight. Rifles and ammunition of this type are common in law enforcement and military applications to defeat vehicles, light armor, or extend marksmen capabilities out to ranges of over 2 miles.

A total of 313 shots were measured over two courses lasting 7 days (course 1 – three days, 224 measurements, course 2 – four days, 89 measurements). Blast gauges were affixed to shooters with gauges on the front of their hats, on both the right and left shoulders, and on both wrists along the distal radioulnar joint (the position people generally have a wrist watch). Visual analysis of shooter positioning determined which gauge provided the best incident OP measure. Incident OP was used because all known safety tables are tied to incident OP, as reflective OP can vary wildly from

experienced OP based on the orientation of the sensor. Shooters engaged targets from the seated/kneeling, prone, and standing positions while outside, as well as inside and on top of an armored vehicle, from the top of a fire training tower, and through a window in an enclosed room.

Results indicated several notable points of overpressure variation. Characterizing blast broadly, course one had an average overpressure 4.7 psi (SD=1.6, n=224), whereas course two had an average overpressure of 4.5 psi (SD=0.5, n = 89). Notably, barrel length had little effect on overpressure readings [24'' barrel M=3.6 psi, SD =0.3; 26'' barrel M=3.4 psi, SD=0.2; 27'' barrel M=3.8 psi, SD=0.4; 29'' barrel M=4.9 psi, SD=0.7], but shorter barrels (counterintuitively) did not create overpressure situations to the extent that longer barrels did. Firing position and muzzle brake/muzzle device however, did heavily impact results such that positions that placed the shooter in a seated, concave position (M=5.7 psi, SD=0.5) or prone position (M=5.6 psi, SD=1.0) were more conducive to higher overpressure results than standing positions (M=4.5 psi, SD=0.4). Muzzle devices, especially those with recoil mitigation properties like reward slanting chambers at 45-degree angles, were found to increase overpressure readings (M=5.2 psi, SD=0.9) as compared to no muzzle brakes (M=3.1 psi, SD=0.3), or flash hiders (M=3.5 psi, SD=0.7). Suppressors also showed significant promise for overpressure mitigation, but the sensor measurements were inconclusive and therefore are not presented here.

Gustaf Measurements – The Carl Gustaf (M3 MAAWS) is an 84 mm recoilless rifle in use throughout the United States Military. Recoilless rifles are (often but not exclusively) man-portable weapons systems that vent gases during firing such that the ‘recoil’, or impulse generated from the combustion of propellant that accelerate the projectile to its target. The Gustaf is a man-portable system operated by a two-man crew which fires both modified artillery shells (which do not accelerate past the end of the muzzle, similar to a traditional rifle or pistol) as well as rockets (which have sufficient propellant and are designed such that acceleration past the end of the muzzle is possible). With an extensive variety of munition capabilities and firing positions, the Gustaf presents high potential for a variety of pressure exposures to operators.

A total of 34 shots were fired by nine teams. Eight teams fired four rounds each, one team fired only two rounds. Each team consisted of two members, with a gunner and assistant gunner. Each team member was outfitted with sensors on the front, back, and sides of the helmet, as well as on their shoulders. Visual observation was used to determine which sensor had the best orientation for incident pressure and was used for reported measurements.

The outside helmet measurement for both the gunner and assistant gunner provided the best incident pressure measurement. Gunners averaged 4.1 psi (SD=0.9) with assistant gunners measuring similarly with 4.1 psi (SD=1.1).

Grenade Measurements – The M67 fragmentation grenade weighs approximately 14 oz with 6.5 oz of the total weight being explosive. Overall, the M67 is slightly smaller than a baseball and is detonated by a time-delay fuse which is activated after a pin is pulled from the firing mechanism, and the safety spoon is removed. At this point, the grenade is thrown and will detonate in 3-5 seconds.

A total of 23 grenade detonations were measured across two grenade ranges (range one – eight detonations, range two – fifteen detonations). Unlike previously discussed measurements, grenades were evaluated with pencil probes located perpendicular and parallel to the soldier throwing grenades, in addition to a Larson Davis LxT sound meter with 1/4" mic (max 178 dB for a frequency range of 4 Hz-20 KHz). The decision to use acoustic measurement techniques and

pencil probes located in two orientations was made because there was concern that the blast/acoustic waves from the grenades may be ‘bouncing’ back and forth in the pit, encountering the grenade throwers multiple times. This bounce would be difficult to detect with B3 blast gauges, and the decision to go with a higher fidelity instrument was made.

Range one pressures averaged 0.2 psi (SD = 0.03) on the soldier whereas range two pressures were 0.7 psi (SD = 0.5). Overpressure from grenade training was low due to existing safety protocols in place for the facilities with regards to pressure. Acoustic data indicated exposures from 157.6-160.3 dBP on range one and from 153.7-163.2 dBP on range two – both ranges experiencing acoustic readings regularly 30 dBP above the pain threshold for most humans. Despite low overpressure levels, acoustic exposures present a significant potential for deleterious impact on soldier readiness as a result of grenade training if adequate personal protective equipment (PPE) guidelines are not practiced.

THE INFLUENCE OF SENSOR ORIENTATION AND MEASUREMENT ERROR

A concerted effort to always use visual confirmation of the primary incident sensor for all above data collections was made. To investigate the extent to which this step is beneficial, an experiment was conducted using a shocktube set to 5 psi using the same B3 sensors that are deployed by the research team in the field. A total of 24 blasts were conducted, with 6 blasts each at 0-degree orientation to the sensor, 90-degree orientation, 180-degree orientation, and finally 270-degree orientation. Results indicated that with face on blasts (0-degree), average pressure readings were 6.2 psi (SD=0.2), 90-degree orientation averaged 4.8 psi (SD=0.5), 180-degree orientation averaged 3.6 psi (SD=0.3), and finally 270-degree orientation averaged 4.6 psi (SD=0.5). Results indicated that measuring incident pressure resulted in values that were accurate to under 10% of actual pressure exposure, whereas other orientations contaminated values from 14-20+%.

DISCUSSION

Overpressure resulting from weapons exposure varies greatly across platforms. Systems that have previously garnered significant scrutiny (MAAWS/Gustaf) as measured here are far less problematic than previously expected. Other weapons systems like the 50 caliber rifle have higher than anticipated potential for blast overpressure exposure.

Throughout the data collections conducted here, topography and local variation in weapon system operation, as dictated by personal preference or training doctrine, can have measurable effects on the overpressure experienced by weapons operators. As discussed, orientation of sensors can contaminate the extent to which this effect may exist, which drives home the need for observation of current pressure sensor systems to ensure the most representative incident measurements are used to characterize exposures. Future systems should consider methodologies that would allow for sensor data to contain sufficient information to determine orientation to blasts without supplemental visual aid.

Finally, blast exposure is complex. Measurements here focused on peak overpressure and some acoustic exposure. Other works from the research team seek to combine peak overpressure, with acoustic exposure, and total impulse experienced. As evidence accumulates in blast overpressure exposure research, it is becoming exceedingly clear that a more nuanced approach to blast measurement is necessary to better understand the extent to which deleterious short and long-term effects may be experienced by operators in these environments.

REFERENCES

- [1] F. Hirsch, "Effects of overpressure on the ear - a review," *Annual New York Academy of Science*, vol. 152, no. 1, pp. 147-162, 1968.
- [2] Kamimori, G. H., L. A. Reilly, C. R. LaValle, and UB Olaghere Da Silva. "Occupational overpressure exposure of breachers and military personnel." *Shock Waves* 27, no. 6 (2017): 837-847.
- [3] Carr, W., Taylor, M., LoPresti, M.L., Aurich, L., Walilko, T., Yarnell, A., Kamimori, G., da Silva, U., Polejaeva, E. and McCarron, R., 2015. Symptomology observed in humans following acute exposure to explosive blast. *J Neurotrauma*, 32, pp.A-109.
- [4] C. de Candole, "Blast Injury," *Canadian Medical Association Journal*, vol. 96(4), pp. 207-2014, 1967.
- [5] Levin, H.S., Wilde, E., Troyanskaya, M., Petersen, N.J., Scheibel, R., Newsome, M., Radaideh, M., Wu, T., Yallampalli, R., Chu, Z. and Li, X., 2010. Diffusion tensor imaging of mild to moderate blast-related traumatic brain injury and its sequelae. *Journal of neurotrauma*, 27(4), pp.683-694..
- [6] Littlefield, P.D., Pinto, R.L., Burrows, H.L. and Brungart, D.S., 2016. The vestibular effects of repeated low-level blasts. *Journal of neurotrauma*, 33(1), pp.71-81.

Evaluation of the Effects of High Level Overpressure (8+ psi) on Cognitive Performance, Brain Blood Biomarkers and Symptom Reporting

Log Number: 14029001

Award Number: W81XWH-16-2-0001

PI: Gary Kamimori, PhD

Org: The Geneva Foundation

Award Amount: \$1,670,352.00



Study/Product Aim(s)

- Characterize a wide range of individual (operator) blast exposure and training environment overpressure.
- Investigate immediate and/or acute effects of repeated and/or high OP exposures (> 8 psi) from training operations.
- Use anatomically correct human surrogates to measure pressure and strain within specific anatomical locations in the brain during replicate experiments that were performed by operators.

Approach

This is a multi-site observational study of military and law enforcement personnel that will occur in conjunction with occupational training exercises that involve operator exposure to high (> 8 psi) and/or repeated blast overpressure. Neurocognitive, physiological (e.g., blood-based biomarkers, eye-tracking, etc.), and/or symptom reporting data will be collected before and after exposure to determine effects of blast exposure. Blast characteristics will be recorded to determine individual and environmental OP levels.



Figure: Operational training exercise involving blast overpressure (L) and operator performing neurocognitive task (R).

Accomplishments: Data have been collected from 6 different occupational training environments; analyses and blood assays are underway.

Timeline and Cost

Activities	CY	1	2	3	4
Protocol preparation/submission. Site selection/approvals. Equipment acquisition.					
Data collection					
Data analysis					
Prepare reports					
Estimated Budget (\$K)		\$273K	\$560K	\$581k	\$254K

Goals/Milestones

CY1 Goal – Protocol preparation/submission.

- ☒ Receive WRAIR IRB approval

CY2 Goals – Data Collection

- ☒ Receive WRAIR IRB approval for site specific addendum(s)
- ☒ Collect data

CY3 Goal – Data Analyses

- ☒ Assay blood based biomarkers
- ☒ Perform data analysis

CY4 Goal – Write reports

- ☐ Finalize data analyses
- ☐ Complete final report

Comments/Challenges/Issues/Concerns

- No spending issues to report.

Budget Expenditure to Date

Projected Expenditure: \$1,438,143.12

Actual Expenditure: \$1,020,555.12

Updated: (29 January 2019)

Evaluation of the Effects of High Level Overpressure (8+ psi) on Cognitive Performance, Brain Blood Biomarkers and Symptom Reporting

Log Number: 14029001

Award Number: W81XWH-16-2-0001; MIPR 10874005 (2016); 10874004 (2017); 11274678 (2018)

PI: Amit Bagchi, PhD (NRL)/Gary Kamimori, PhD (WRAIR) Org: Naval Research Laboratory (NRL) Award Amount: \$1,099,638.00



Study/Product Aim(s)

- Characterize a wide range of individual (operator) blast exposure and training environment overpressure.
- Investigate immediate and/or acute effects of repeated and/or high OP exposures (> 8 psi) from training operations.
- Use anatomically correct human surrogates to measure pressure and strain within specific anatomical locations in the brain during replicate experiments that were performed by operators.

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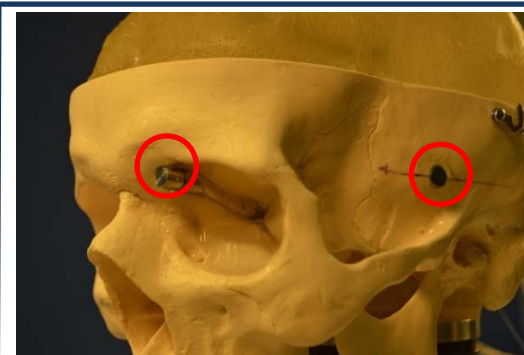


Figure: Instrumented surrogate head (L) and close up of surrogate head showing pressure sensors (red circles) on skull (R).

Accomplishments: Replicated data with instrumented NRL head-neck surrogates with different design configurations at Quantico and FLW. Continuing to obtain neuronal cell metabolism and response data at different blast levels. Continuing analysis of data collected for breaching.

Timeline and Cost

Activities	CY	1	2	3	4
Protocol preparation/submission. Site selection/approvals. Equipment acquisition.					
Data collection					
Data analysis					
Prepare reports					
Estimated Budget (\$K)		\$307K	\$324K	\$316K	\$152K

Goals/Milestones

CY1 Goal – Protocol preparation/submission

- ☒ Receive WRAIR IRB approval
- ☒ Develop and test surrogate instrumented head and cell pack head

CY2 Goals – Data Collection

- ☒ Receive WRAIR IRB approval for site specific addendum(s)
- ☒ Collect instrumented brain and cellular data at Quantico
- ☒ Collect instrumented brain data at Fort Leonard Wood, MO

CY3 Goal – Data Analyses

- ☐ Complete data collection, perform analysis

CY4 Goal – Write reports

- ☐ Finalize data analyses
- ☐ Complete final report

Comments/Challenges/Issues/Concerns

- Field testing planned for Q3 CY17 through Q2 CY 2019

Budget Expenditure to Date

Projected Expenditure: \$1,099,638

Actual Expenditure: \$948,786

Updated: (16 Jan 2019)