Project Report
TIP-191

Field Measurements of Blast Overpressure in the Context of Ballistic Helmet Wear: FY23 Biomedical Sciences and Technologies Technical Investment Program

MAJ K.G. Gruters
H.M. Rao
CJ. Smalt
L. Kent
SFC A. Anderson
K. Spradley
S. Thomas
COL P.J. Depenbrock

22 January 2024

Lincoln Laboratory
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LEXINGTON, MASSACHUSETTS

This material is based upon work supported by the Department of the Air Force under Air Force Contract No. FA8702-15-D-0001.

This report is the result of studies performed at Lincoln Laboratory, a federally funded research and development center operated by Massachusetts Institute of Technology. This material is based upon work supported by the Department of the Air Force under Air Force Contract No. FA8702-15-D-0001. Any opinions, findings, conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Department of the Air Force.

Massachusetts Institute of Technology
Lincoln Laboratory

Field Measurements of Blast Overpressure in the Context of Ballistic Helmet Wear: FY23 Biomedical Sciences and Technologies Technical Investment Program

MAJ K.G. Gruters
U.S. Army John F Kennedy Special Warfare Center and School

H.M. Rao
C.J. Smalt
MIT Lincoln Laboratory

L. Kent
1st Special Forces Command (Airborne)

SFC A. Anderson
COL P.J. Depenbrock
K. Spradley
S. Thomas
U.S. Army Special Operations Command

Project Report TIP-191

22 January 2024

This material is based upon work supported by the Department of the Air Force under Air Force Contract No. FA8702-15-D-0001.

Lexington Massachusetts

ABSTRACT (U)

Explosive breaching instructors in special operations military and law enforcement are exposed to a substantial volume of low-level (~0.5-3 psi) blasts. This population tends to report greater discomfort and negative cognitive impacts when wearing versus not wearing ballistic combat helmets during blast training. Simulation modeling and laboratory assessment of high-pressure blasts support these reports by indicating that blast pressures inside a helmet are higher than those outside. However, these findings have yet to be tested in a real-world study of low-level blasts like those used in training.

We conducted a limited-scope study on helmet wear in the context of blast exposure at a military training range for urban combat and breaching. Two participants were exposed, in accordance with range safety protocols, to n = 58 low-level blasts while observing routine training from an overhead catwalk. Data were collected as part of a training protocol assessment for process improvement and so were IRB-exempt; regardless, both participants were informed of the risks and agreed to participate. We recorded acoustic pressures simultaneously from inside and outside of a combat helmet during a blast training exercise using a pair of specialized high-amplitude microphones. Paired blasts were assessed by t-test and fit with a power series model to compare the pressures inside versus outside of the helmet.

We found that the pressure inside a helmet is considerably higher than outside during a blast event ($t(57) = 5.48$, $p << 0.001$). Power series modeling showed that at low-level blasts around 1 psi, the pressure inside the helmet was about 1.4 times that outside. Further, as the pressure outside the helmet got higher, the additive impact on pressure inside also grew larger.

This report confirms previously published modeling and empirical studies as well as anecdotal reports from training personnel using real humans in a real-world training environment. Specifically, this evidence indicates that blast pressures inside a combat helmet are increased relative to the external pressure. This likely increases the effects of blast exposure by subjecting the brain to higher intensity and more dynamic pressure waves, particularly when the angle of the blast does not meet the helmet straight on (e.g., when the blast originates below the helmet). Based on this evidence, we recommend considering the relative risk of increased brain injury from blast exposure compared to risk of projectile exposure when deciding to wear helmets in training.

ACKNOWLEDGMENTS (U)

The authors would like to acknowledge the dedication, patience, and professionalism of the Special Operations instructors involved in this work. Their feedback and support were instrumental to this project and greatly appreciated.

TABLE OF CONTENTS (U)

LIST OF FIGURES (U)

1. BACKGROUND (U)

1.1 (U) DYNAMICAL MODELING OF THE BLAST WAVE

The blast pressure wave from a breaching charge consists of an initial wave front that contacts then wraps around the head and reconnects on the other side. When wearing a helmet, the pressure wave can enter and travel inside the helmet along the skull. Further, the initial wave front reflects off the inside of the helmet and collides with the on-going wave causing dynamic reverberation in a phenomenon called under-wash [1]. Simulation modeling has found that the under-wash tends to enhance the wave pressure, up to double the impulse power for low-level blasts (ibid.).

The initial passage of the blast wave and its associated under-wash appear to drive strong pressure gradients between the skull and brain tissue, with intra-cranial cavitation occurring in particular with the reflection of the blast wave off the helmet and into the skull [2]. Models by Moss et al. [3] concurred, showing that the pressure inside the helmet is amplified compared to pressure outside, and that internal pressure is transferred first into the skull then into the brain.

Under-wash notwithstanding, the helmet does appear to protect the skull from the initial direct wave front [2]. However, Grujicic et al. [4] demonstrated that the pressure wave outside of the helmet can compress the foam inside, loading the foam like a spring. Upon release of the pressure, the foam itself drives the loaded pressure into the skull, potentially reversing at least some of the blast-mitigation conveyed by the helmet.

Finally, the pressure wave can reflect off of nearby objects and cause reverberant exposure. This reflection can enhance the pressure and expose an individual to secondary blasts during which all of the same above dynamics are at play. It should be noted that the above studies are conducted as simulation modeling, with the results being subject to the parameters and assumptions of the model. Despite this, there are generally consistent findings indicating increased pressure on the brain contingent on the blast wave entering the helmet.

1.2 (U) EMPIRICAL EVIDENCE

Understandably, there is little empirical evidence on the matter of blast exposure in the brain. However, the existing evidence is consistent with the simulation modeling. Skotak et al. [5] used a blast tube and anatomically accurate head form to demonstrate the dynamics of blast wave pressures in the context of no helmet or different types of helmets, including both ACH and Ops-Core helmets. They found that, in the context of a 10 PSI blast, wearing a helmet increased the overall pressure on the skull as compared to not wearing one by roughly 1.4 times. They found that each helmet had different hotspots which concentrated the pressure and under-wash, suggesting that the pressure dynamics are design dependent. Moreover, they found that helmet wear increased the pressure experienced by the eyes—one of the primary points of entry for pressure into the head and forehead due to the concavity created by the helmet and face.

The authors conclude that no helmet design provided better overall protection against blast exposure as compared to the bare headframe, and that all helmets tested cause increased surface pressures on the skull. This evidence is consistent with simulation modeling, demonstrating that blast pressure inside the helmet is greater than that outside. This presumably results in a greater transfer of energy into the brain through the skull and potentially even through the soft tissue of the face (e.g., the eyes).

However, the existing modeling and empirical research on this topic focuses on high-amplitude blasts, outside of the bounds normally seen during training, and no studies have been published using real human participants or training situations. We conducted a small-scale study during routine training at a course at the US Army John F. Kennedy Special Warfare Center and School (SWCS) to see if we could replicate Skotak et al. [5] in a real-world training situation.

2. METHODS (U)

We placed a pair of acoustic pressure microphones on the inside and outside of an ACH (test 1; figure 1a) and Ops-Core (test 2; figure 1b) helmet during a blast training day.

Both helmets were worn during a day of indoor breaching training by individuals as part of their routine routine military training. This research activitiy was found to be IRB exempt by Army Human Research Protections Office (AHRPO). Wearers were on a second-floor catwalk observing training from overhead. Multiple lanes of training were being conducted simultaneously, and all lanes used a combination of shotgun, flashbang, and door breaching charges. Blasts came from multiple directions laterally, but all below relative to the helmet. It is not feasible to reconstruct blast origins or calculate objective overpressure at origin.

The ACH was worn by a male with short, military-cut hair, and data were collected in August where the temperature was 106 F with 90% humidity. The Ops Core was worn by a female with long hair worn in a thick but flat braid. Data were collected in November with 76 F temperature and 97% humidity on test day. Both collection sessions lasted about two hours. Data collection was part of a safety protocol assessment for routine military training and was thus IRB-exempt; regardless, both participants were informed of and understood the risks involved in the data collection process.

The acoustic measurement system was designed by MIT Lincoln Laboratory (MIT LL), and produced by Creare, LLC [6], using a custom, high-amplitude microphone (GRAS Sound & Vibration). The microphones record acoustic events between 135-182 dB SPL as distinct impulses. Custom analysis code, supplied by MIT LL, was used to extract individual blast events from both microphones for comparison. Microphones were calibrated within one week prior to testing; analysis of blasts on intervening training days showed no indication of overall drift in their calibration.

UNCLASSIFIED

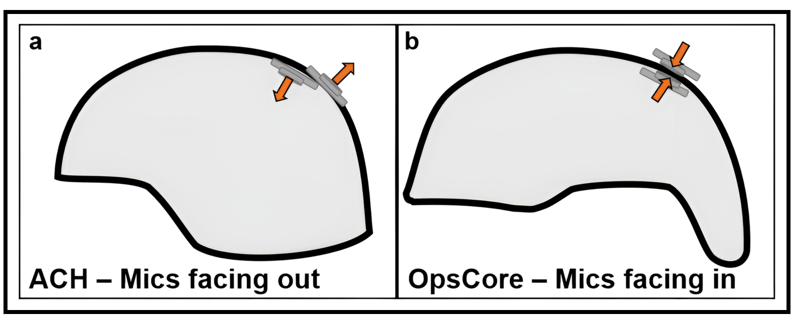

Figure 1. (U) Position of recording microphones in helmets. Schematic showing arrangement of the microphone with respect to the helmet during testing. Orange arrows indicate the recording face direction of the microphone. a. Advanced Combat Helmet (ACH), set up with microphone facing away from the helmet shell, either to open air (outside) or toward head (inside). b. The Ops-Core helmet set up with both the inside and outside microphones facing into helmet shell.

3. RESULTS (U)

We compared blast amplitudes from outside versus inside the helmet where both microphones recorded the same blast event. Test 1 (ACH) had 41 such paired events, while the test 2 (Ops Core) had 17. Figure 2 shows these paired events, with events recorded outside of the helmet in purple and inside in green. Outside-Inside pairs are joined with a line, colored purple if the event was of higher amplitude outside the helmet and green if the higher amplitude was inside. This figure shows that most events, particularly those of generally higher amplitude, had a higher blast overpressure inside than outside of the helmet.

UNCLASSIFIED

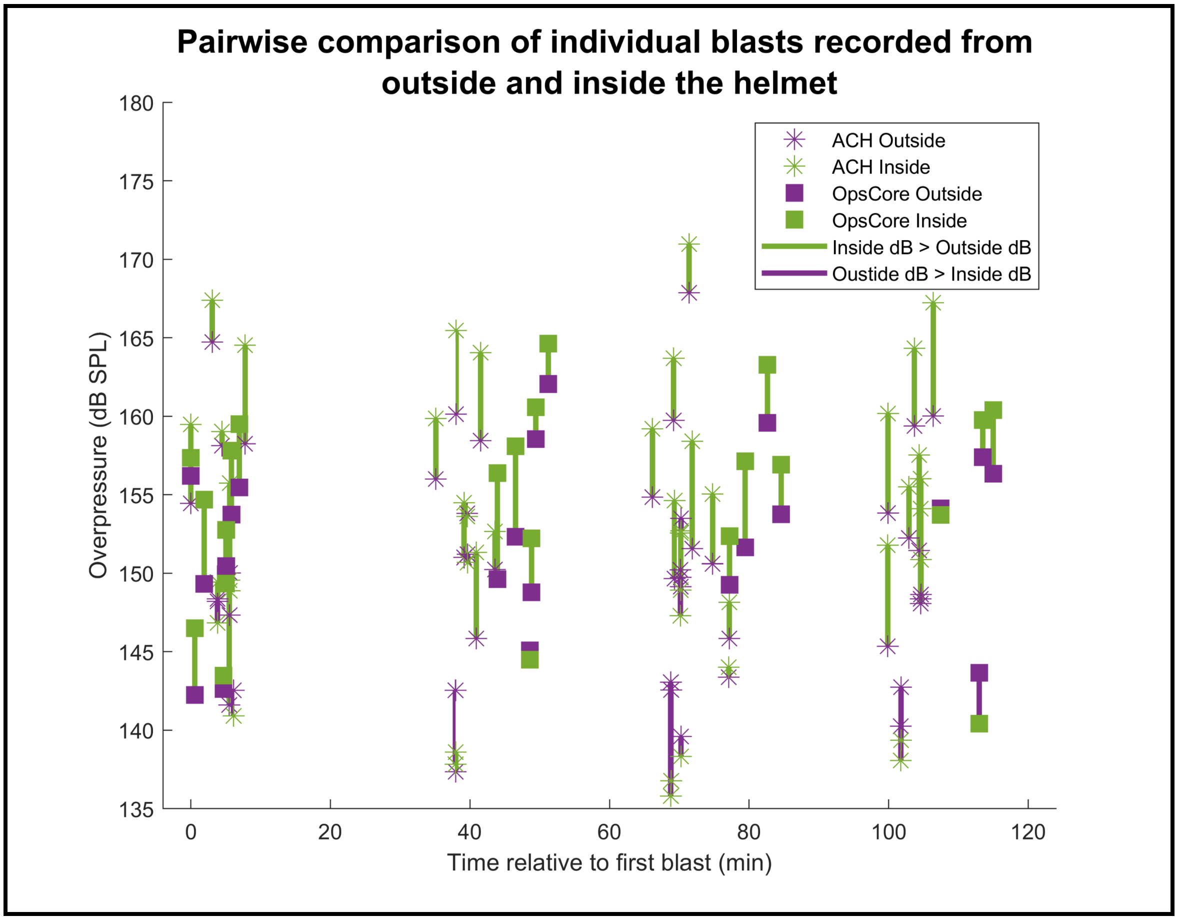

Figure 2. (U) Comparison of blast dual-recorded blast events. Visual comparison of blast events recorded both outside and inside the helmet for the ACH (Advanced Combat Helmet) and OpsCore helmets. Paired events were generally of higher amplitude inside the helmet, as indicated by green connecting line between the same event recorded outside (purple) versus inside (green) the helmet.

We conducted a pairwise t-test to compare the overpressure difference between recorded levels outside versus inside the helmets (figure 3) and found a highly significant difference ($p < 0.001$), with a mean difference of about 2.5 dB SPL. Notably, there appears to be a non-linearity such that if we consider points below 145 dB SPL, they are generally of higher amplitude outside the helmet, while if we consider those above 145 dB SPL, they are generally higher inside. Considering only impulses above 145 dB SPL, the amplitude inside the helmet is 3.6 dB SPL higher than outside the helmet on average.

Practically, we are interested in the additional pressure imparted on the head by wearing the helmet. Accordingly, we modeled the additional amount of pressure recorded inside the helmet relative to the baseline, external blast pressure (figure 4). Since blast exposure is typically discussed in psi, we converted from dB SPL to psi. We used a power series model of the form $y = a * x^b + c$, where x is the atmospheric (outside the helmet) amplitude of the blast in psi, and y is the additional blast pressure expected inside the helmet. This model was a good fit to the observed data ($R^2 = 0.57$, $RMSE = 0.06$ psi), and the power series model more effectively captured the purported non-linearity near 145 dB SPL as compared to a simple polynomial model. Notably, this model indicates that as the external pressure gets higher, the amount of additional pressure inside the helmet gets larger as well. For example, for a recorded external pressure of 1 psi, our model would predict an internal under-wash pressure of 1.38 psi.

UNCLASSIFIED

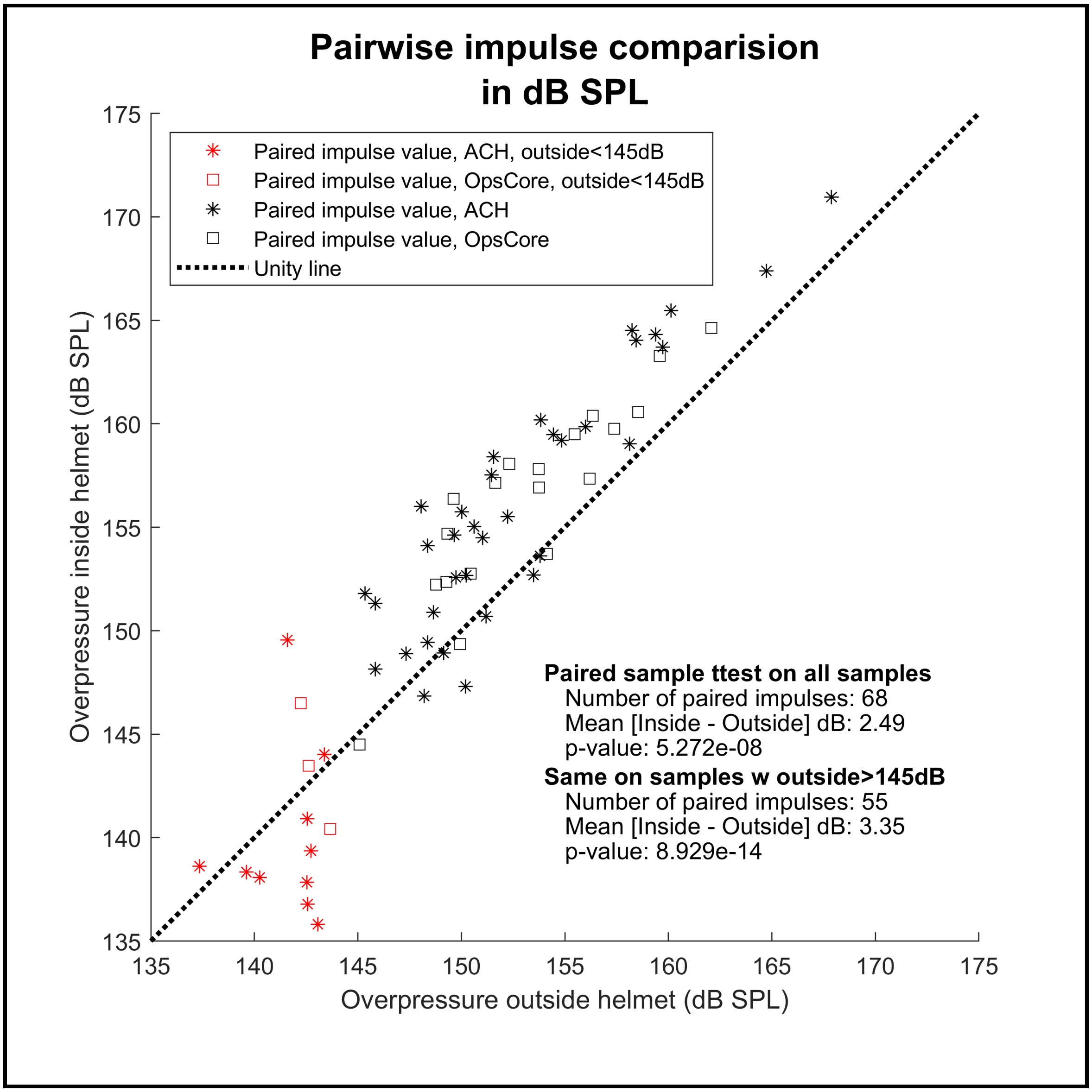

Figure 3. (U) Statistical assessment of dual-recorded blast events. Statistical assessment of the difference in amplitude of blast events recorded from both inside and outside the ACH (Advance Combat Helmet) and OpsCore helmet. Paired blasts are plotted with recorded overpressure (dB SPL) outside the helmet on the x-axis and inside on the y-axis. Unity line (black dotted line) is plotted for reference. Blasts $<$ 145 dB SPL tended to have higher amplitude outside the helmet, while those $\geq$ 145 dB SPL had significantly higher amplitude inside. This suggests a non-linearity with an inflection point around 145 dB SPL.

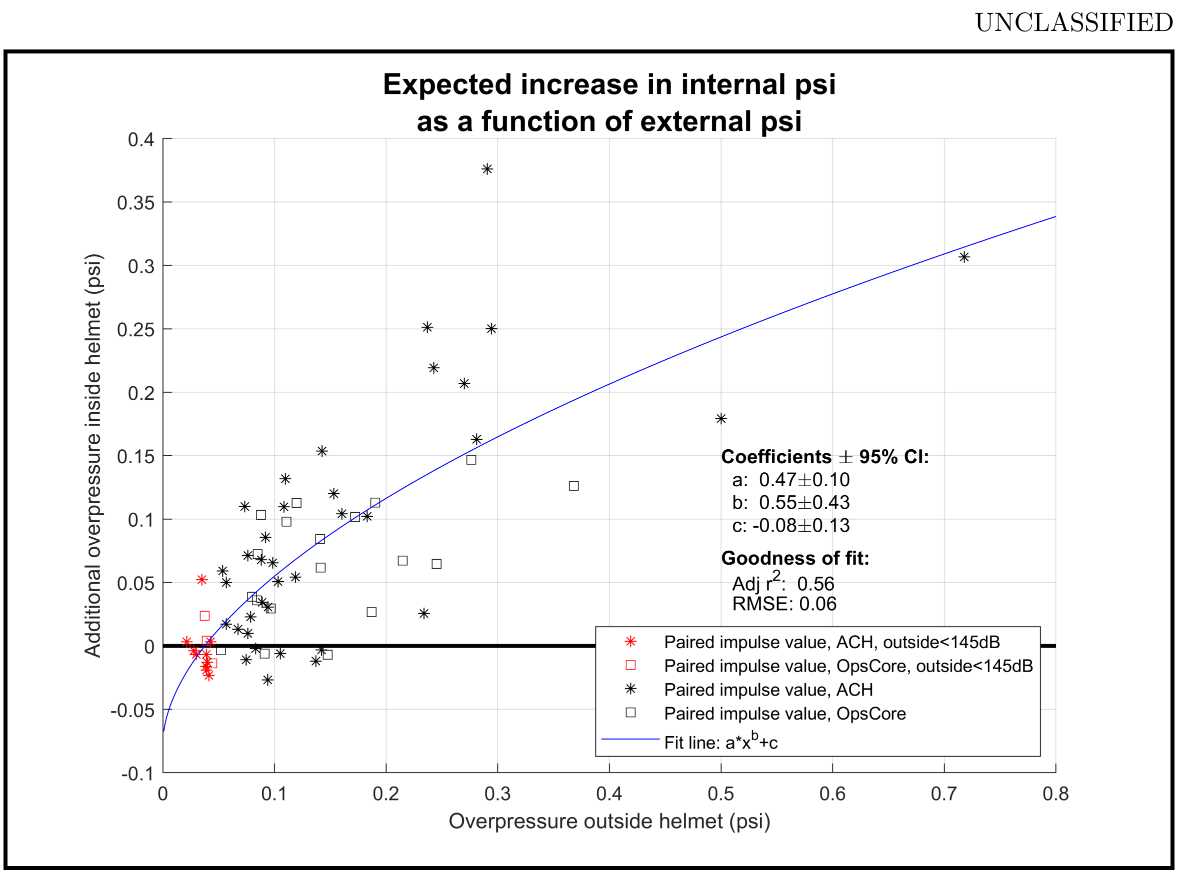

Figure 4. (U) Modeling pressure differential inside versus outside the helmet. Power series model showing additional psi inside relative to psi outside the ACH (Advanced Combat Helmet) and OpsCore helmets. Model was fit to paired blast recordings after converting from dB SPL to psi. Fit line (blue) shows that higher external psi yields increasing additional impact inside the helmet.

4. DISCUSSION (U)

We collected overpressure data inside and outside helmets as two service members performed training. Our results indicate that the overpressures recorded inside the helmet are higher than those recorded outside. These results are consistent with Skotak et al. [5], in which they find that the pressure inside of a helmet is significantly greater than that outside. Further, we find that the relative increase in under-wash pressure is higher for larger overpressure events. Meaning, this effect is particularly true when dealing with pressures above the very low end of small arms fire (∼145 dB; [7]).

The current study was performed in an operational training environment where the types of overpressures and the orientation of the head relative to the source could not be controlled. Therefore, a limitation of the results is that we cannot model the specific incidence of the blast pressure wave and its dynamics in and around the helmet. We refer to Skotak et al. [5] for systematic comparisons across helmet types and incidence angles. The value of the current study is the confirmation of laboratory results in an operational field setting.

This evidence should be weighed against the relative safety risks of not wearing a helmet during blast training. In particular, when the risk of projectile injury is low (e.g., on a second-floor observation deck), the risk assessment should weigh the current findings against that risk even though it may be in conflict with conventional practice and wisdom. More broadly, the accumulated evidence suggests that there may be room for development of a helmet with specific regard for pressure dispersion. This might be done through some combination of helmet geometry, venting, and padding materials.

5. CONCLUSIONS (U)

Converging evidence from anecdotal reports, simulation studies, and empirical evidence indicate that helmet wear may increases blast pressures on the brain in a training environment. Our data suggest increased pressure and under-wash inside the helmet as compared to outside. This apparent increase in pressure on the brain and skull are consistent with anecdotal reports of increased headaches, cognitive disruption, and sleep difficulties when wearing a helmet versus not wearing one during training. Importantly, these conclusions do not consider the risks of debris or other projectiles where helmets clearly provide undisputed protection.

In light of this convergence of evidence, we recommend that risk assessments in blast training consider the risk of increased blast pressure on the brain relative to the risk of projectile and debris exposure when deciding on helmet requirements. We believe this is particularly important when the blast wave originates below the helmet, effectively ensuring that the bulk of the blast wave is captured by the helmet while negating any deflection of the blast by the helmet.

GLOSSARY (U)

ACH	Advanced Combat Helmet
LL	Lincoln Laboratory
MIT	Massachusetts Institute of Technology
SWCS	US Army John F. Kennedy Special Warfare Center and School

NOTATION (U)

dB SPL	Sound Pressure Level
psi	Pounds per Square Inch

REFERENCES (U)

[1] H. Sarvghad-Moghaddam, A. Rezaei, M. Ziejewski, and G. Karami, "Evaluation of brain tissue responses because of the underwash overpressure of helmet and faceshield under blast loading," *International journal for numerical methods in biomedical engineering* 33(1), e02782 (2017).

[2] M.K. Nyein, A.M. Jason, L. Yu, C.M. Pita, J.D. Joannopoulos, D.F. Moore, and R.A. Radovitzky, "In silico investigation of intracranial blast mitigation with relevance to military traumatic brain injury," *Proceedings of the National Academy of Sciences* 107(48), 20703–20708 (2010).

[3] W.C. Moss, M.J. King, and E.G. Blackman, "Skull flexure from blast waves: a mechanism for brain injury with implications for helmet design," *Physical review letters* 103(10), 108702 (2009).

[4] M. Grujicic, W. Bell, B. Pandurangan, and T. He, "Blast-wave impact-mitigation capability of polyurea when used as helmet suspension-pad material," *Materials & Design* 31(9), 4050–4065 (2010).

[5] M. Skotak, J. Salib, A. Misistia, A. Cardenas, E. Alay, N. Chandra, and G.H. Kamimori, "Factors contributing to increased blast overpressure inside modern ballistic helmets," *Applied Sciences* 10(20), 7193 (2020).

[6] C.J. Smalt, E. Yuan, C. Audette, A. Bruzka, J. Russell, O. Clavier, Q. Hecht, and D. Brungart, "Development and evaluation of a body-worn dosimeter for continuous and impulsive noise," in *44nd Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC)*, IEEE (2022).

[7] J. Lankford, "Council for Accreditation in Occupational Hearing Conservation," (2014), URL OccupationalHearingConservation;2014.Availablefrom:https://www.caohc.org/UserFiles/file/ShotofPreventionextrahandout.pdf.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
22-01-2024

2. REPORT TYPE
Project Report

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE

Field Measurements of Blast Overpressure in the Context of Ballistic Helmet Wear: FY23 Biomedical Sciences and Technologies Technical Investment Program

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER
2232-4201

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHOR(S)

MAJ K.G. Gruters, H.M. Rao, CJ. Smalt, L. Kent, SFC A. Anderson, K. Spradley, S. Thomas, COL P.J. Depenbrock

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

MIT Lincoln Laboratory
244 Wood Street
Lexington, MA 02421-6426

8. PERFORMING ORGANIZATION REPORT NUMBER

TIP-191

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
MIT Lincoln Laboratory
244 Wood Street,
Lexington, MA 02421-6426

10. SPONSOR/MONITOR'S ACRONYM(S)
MIT LL

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
DISTRIBUTION STATEMENT A. Approved for public release. Distribution is unlimited.

13. SUPPLEMENTARY NOTES

13. ABSTRACT
We conducted a limited-scope study on helmet wear in the context of blast exposure at a military training range for urban combat and breaching. Two participants were exposed, in accordance with range safety protocols, to n = 58 low-level blasts while observing routine training from an overhead catwalk. Data were collected as part of a training protocol assessment for process improvement and so were IRB-exempt; regardless, both participants were informed of the risks and agreed to participate. We recorded acoustic pressures simultaneously from inside and outside of a combat helmet during a blast training exercise using a pair of specialized high-amplitude microphones. Paired blasts were assessed by t-test and t with a power series model to compare the pressures inside versus outside of the helmet.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT UNCLASSIFIED	**b. ABSTRACT** UNCLASSIFIED	**c. THIS PAGE** UNCLASSIFIED	None	22	**19b. TELEPHONE NUMBER** *(include area code)*