MEASURING BLAST OVERPRESSURE EXPOSURE TO AVALANCHE WORKERS INTERNATIONAL SNOW SCIENCE WORKSHOP 2023, BEND, OREGON

Ken Thompson[1*], Mandy Geisler[2], Mark Saurer[2], Allie Fredbo

[1] *Monument Cat Skiing, Eden UT, USA*
[2] *Park City Mountain Resort Snow Safety, Park City UT, USA*

ABSTRACT: Blast overpressure (BOP) produced by explosives used for active avalanche mitigation poses a risk to users and the exposure remains unquantified. Complex blasting environments create difficulty in estimating worker exposure. Exposure levels are relevant as various studies have identified exposure to explosive events as a source of brain injury. To our knowledge a study of this kind has not been done in the avalanche industry.

Six sensors were purchased in 2020 specifically designed to measure pressure waves experienced by personnel in the area of a blast event. Throughout the winters of 2020 to 2023 data was collected from active avalanche mitigation missions at five operations in the western United States representing different snow climates and explosive types. In this novel study, data was collected from over 50 separate control missions, representing 769 deployed explosives and 103 howitzer rounds (105mm). A large ski area avalanche program may deploy an average of 5,000 explosives in one season. Measured maximum exposure was 2.7 psi (18.6kPa) which is below maximums reported in related industries. Related industries remain invested in identifying risks of repetitive low level blast exposure. These cumulative effects of low-level blasts may pose the greatest risk to avalanche workers, as they may be exposed to dozens of detonations in a single day. Refinement of future data collection will aid in better defining the exposure of avalanche workers.

KEYWORDS: Worker Safety, Explosives, Avalanche Mitigation, Overpressure

1. INTRODUCTION

Avalanche professionals deploying explosives in avalanche terrain are exposed to many hazards. This study concentrates on workers' exposure to blast overpressure (BOP), a sharp rise in air pressure produced by an explosion. The strength of the BOP wave may be influenced by surrounding terrain and structures. When using hand deployed explosives, workers must choose a safe and practical location to await detonation. An additional source of exposure is military artillery used by several programs in North America in which gunners are in close proximity to the weapon while firing. In both situations workers are exposed to blast overpressure.

Active and prior research in the avalanche industry has focused on the effects of blast on the snowpack. This includes work by Binger & Miller, 2016, Wooldridge et al., 2012, Frigo et al., 2012. Additional work in this area is well summarized in a comprehensive review from Simioni, 2017. However, BOP effects on avalanche workers has not been evaluated to date. The goal of this project is to gain insight into an aspect of the avalanche industry which has previously been understudied. The findings, in combination with research produced from related industries, can help avalanche practitioners make informed decisions regarding BOP exposure.

Explosive blast waves are characterized by rapid rise in air pressure to a peak overpressure followed by positive phase and negative phase before returning to ambient air pressure (Stuhmiller et al., 1990). These characteristics can be seen in blast event recorded in this study. Depending on the size and composition of the explosive BOP can be calculated at a given distance in a flat field hemispheric explosion ("Kingery-Bulmash blast parameter calculator," n.d.). However, in more complex blasting environments, blast waves may reflect off of surrounding structures or natural features amplifying their effects. These variables create difficulty in estimating BOP exposures for avalanche workers in the field.

BOP has the potential to damage organs of the body through multiple mechanisms (Champion et al., 2009). Specifically, blast is well characterized to cause brain injury of varying severity. Even in populations without diagnosable concussion, professionals routinely exposed to blast endorse headache, tinnitus, sleep disturbances, and memory dysfunction. (DeKosky et al., 2010). Prevalence and severity of these symptoms proportionally increased with history of blast exposure (Carr et al., 2016).

* *Corresponding author address:*
Ken Thompson;
Logan UT, USA 84341;
tel: +1 207-468-9120;
email: kenthompson.maine@gmail.com

The auditory system is sensitive to the lowest level of BOP. (Mizutari, 2019). Damage to the peripheral structures including the eardrum is routinely evaluated and successfully managed through surgery, rehab, and hearing aids. Veterans with blast exposure who have passed hearing sensitivity testing still endorse hearing impairments. A suggested mechanism includes blast damage to the structures of the inner ear (sensorineural hearing loss) including the neurons of the central auditory pathway within the brain (Fausti et al., 2009). Exposure thresholds for this type of injury are not well defined, and overlapping symptoms with brain injury make diagnosis difficult. Initial symptoms of sensorineural dysfunction include hearing loss, tinnitus, and sensitivity to sound. If these symptoms persist this type of hearing loss is permanent, life altering and untreatable. (all from Saunders & Echt, 2012)

Acceptable exposure thresholds are often cited at 3-4 psi (20.7-27.6 kPa) by US and Canadian military operations based on associated gross injury to the human eardrum (Kamimori et al., 2017), (Nakashima et al., 2021). However even with these published thresholds there is a growing body of evidence to support injury to the brain and auditory system at lower levels of blast exposure. Research aims to identify a reliable diagnostic tool to reveal those at greatest risk for additional injury and symptom progression.

Individuals with subtle presentations and undetected brain injury may continue to expose themselves to repeated blasts (Edlow et al., 2022). These cumulative effects of low-level blast may pose the greatest risk to avalanche workers, as they may be exposed to dozens of detonations in a single day.

2. METHODOLOGY

2.1 Sensors

In January 2020 six *Generation 7 Blast Gauge System* sensors were purchased for use in this study. (Figure 1) These sensors are designed and routinely used by military and law enforcement personnel (Borkholder, 2015). These small and wearable sensors have made the type of data collection used in this study practical.

Per the manufacturer specifications these sensors have a sample rate of 100 kHz with a resolution of 0.05 psi (0.4 kPa) and can be configured to record

Figure 1: Blast Gauge sensor being worn on the chest strap of an avalanche worker.

changes in ambient air pressure level between 0.5 and 100 psi (3.5 kPa to 689.5 kPa). Proprietary sensor software reports data summaries for event peak pressure (psi) with a timestamp for each blast event. Raw data summaries are available for each recorded event. Although not utilized for this study, software can also report data summaries for event impulse (psi*ms) and peak acceleration magnitude (g).

Pressure sensors will record a different level of pressure for a given blast wave depending on how they are oriented. For a sensor oriented parallel to a blast wave, the resulting measurement will be the incident pressure. If the sensor is oriented facing the blast wave higher measurements are expected, defined as the reflected pressure (Stuhmiller et al., 1990). See Figure 2.

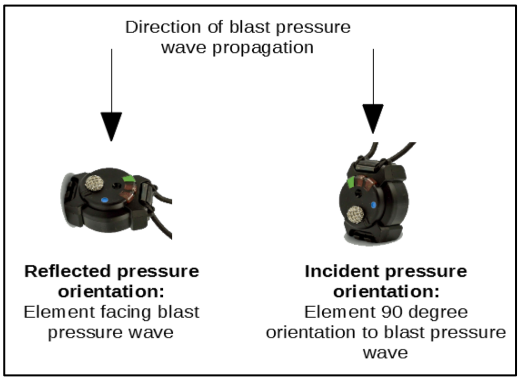

Figure 2: Sensor orientation effects on recorded pressure. Photos reproduced from Black Box Biometrics material.

Other studies by convention may describe the pressure wave by its incident pressure. In this study, recorded peak pressures are uncontrolled for incident angle and may be a combination of reflected and incident pressure. One study has demonstrated that Blast Gauge sensors underestimate peak overpressure when in the reflected pressure orientation (Misistia et al., 2020).

2.2 Control Field Test

To evaluate the Blast Gauge sensors in a controlled environment, explosives were detonated 1m off the snow surface. Sensors 1.5m off the ground were oriented in the reflected position at various distances. The recorded peak pressures of our flat field tests are within the expected ranges estimated by the Kingery-Bulmash blast calculation stated previously. See Figure 3. Further results of these tests support findings that Blast Gauge sensors may record lower peak reflected pressures. (Misistia et al., 2010)

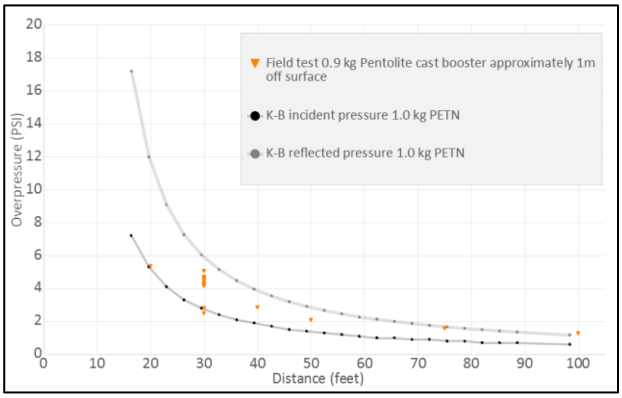

Figure 3: Results of flat field tests compared to estimated incident and reflected pressures based on Kingery-Bulmash (K-B) blast parameters. Pentolite is typically composed primarily of PETN in combination with other compounds to optimize explosive characteristics.

2.3 Data Collection

From January 2020 - April 2023 Blast Gauge sensors were distributed to avalanche workers across five operations. In total 25 participants wore sensors while performing routine explosives mitigation both on hand routes and artillery missions. Participants provided route data detailing type, size, and total number of shots or rounds deployed.

Initially participants wore three separate sensors following the manufacturer specifications (head, shoulder, chest). For the deployments where three sensors were worn, the reading from the highest SPE was chosen for analysis. They were initially configured with a default sensor threshold of 1 psi (6.9 kPa) to record a significant pressure event (SPE), without raw data recording for all events. To maximize data collected and minimize data redundancy with only six sensors, we instructed participants to wear a single sensor. Sensors were also re-configured to a minimum SPE threshold of 0.5 psi (3.5 kPa) and were set to record raw data for all SPE events.

For hand deployed explosives the peak overpressure recorded for each SPE was matched to the associated route data and characterized by the study team. SPEs with available raw data were analyzed to determine if it matches the characteristic blast wave form. SPEs that did not match the characteristic blast wave were excluded. See Figure 4.

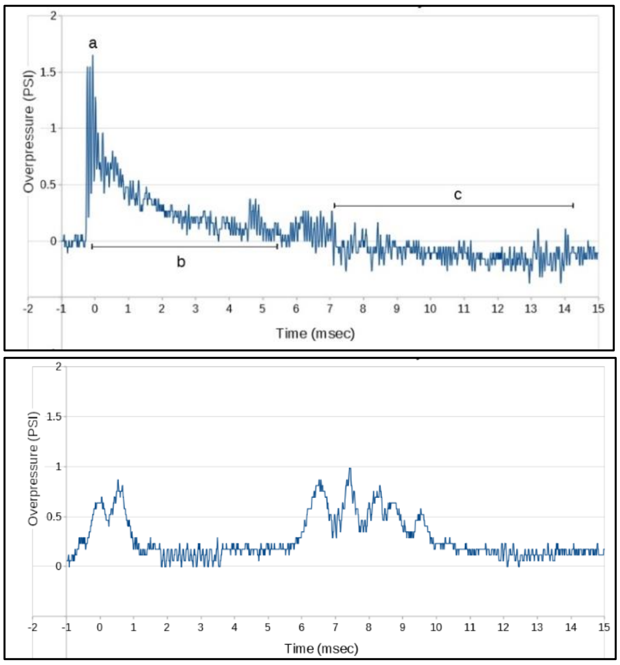

Figure 4: Top: Example of raw blast wave data recorded by a sensor showing a typical waveform from a hand thrown explosive. (a) Characteristic blast wave front, (b) positive phase decay, and (c) negative phase. The positive phase lasts roughly 6 milliseconds with a peak of 1.7 psi (11.7 kPa). Bottom: Example of raw data from SPE that did not match the typical presentation of a blast wave and was excluded from analysis.

3. RESULTS

3.1 Hand Deployed Explosives

Data was collected from 769 explosives deployed during 78 hand routes. Peak event pressure for blast wave events recorded by avalanche workers on route during this study was **2.7 psi (18.6 kPa)** with a mean of **1.2 psi (8.3 kPa)**. The highest peak pressure recorded was from a route where only 0.9 kg (equivalent to 2 pounds) explosives were deployed. For a summary of evaluated data, refer to Table 1, Chart 1 and Chart 2 below.

Total SPEs	Total Routes	Total Explosives Deployed	SPEs per 100 Deployments
45	78	769	5.5

Table 1: Summary of data results aggregated from operations with hand deployed explosives. Only SPEs with available route data are used to calculate SPEs per 100 deployments. Route data was unavailable for three SPEs. Raw data was available for 34 SPEs. Events with no raw data available are categorized as blast wave events. 10 SPEs were recorded with the participant wearing three sensors. The remainder were collected with the participant wearing one sensor. Six potential SPEs were excluded per procedure discussed in methodology. Explosive types used include: pentolite cast booster, AP Dyno +, Ultrex. ANFO.

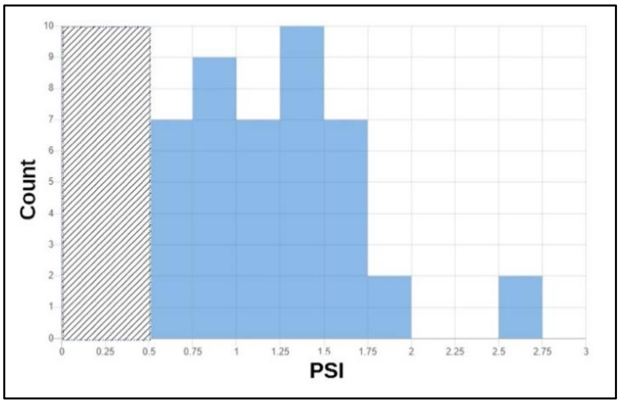

Chart 1: Distribution of recorded SPEs. Shaded area represents the PSI level below the minimum threshold for recording SPE (0.5 psi; 3.5 kPa). Mean = 1.2 psi (8.3 kPa); StdDev = 0.5.

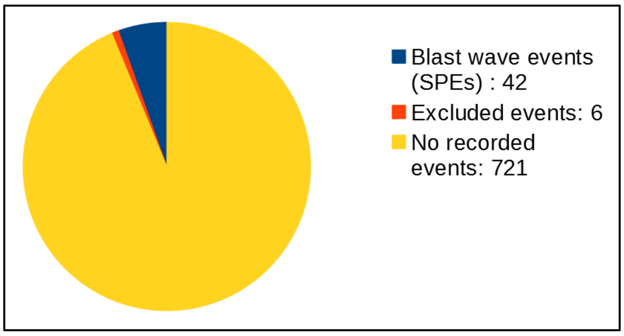

Chart 2: Distribution of results from all hand deployed explosive (n=769) data. Includes only SPEs with associated route data.

Our data demonstrates a notable difference in registered exposure rates between operations. Table 2 compares rates of SPE with available route data from four different operations. Operation 2 contributed a large percentage of the total deployments, yet a minimal number of SPEs. Considering only operations 1,2, & 4 yields an exposure rate of 11.2 per 100 explosives deployed.

	SPEs per 100 deployments
Operation 1	14
Operation 2	0.3
Operation 3	10.7
Operation 4	5.9

Table 2: Hand route data from four separate operations showing rates of SPEs per 100 deployed explosives.

3.2 105mm Howitzer Missions

This study collected 105mm howitzer data from seven missions from two operations firing a total of 103 rounds at charge four (four bags of propellant). The maximum recorded SPE was **1.7 psi (11.7 kPa)** with a mean SPE of **0.9 psi (6.2 kPa)**. See Table 3 and Chart 3.

Position	Rounds	SPEs	SPEs per 100 rounds	Max SPE
Gunner	78	12	15.4	1.5 psi (10.3 kPa)
Assistant Gunner	66	17	25.8	1.7 psi (11.7 kPa)
Observer	61	17	27.9	1.2 psi (8.3 kPa)

Table 3: Results from 105mm howitzer control missions by operator position. 103 rounds fired. Gunner and Assistant Gunner remain in fixed positions for every round fired. The location of the observer may not be consistent between missions or rounds fired.

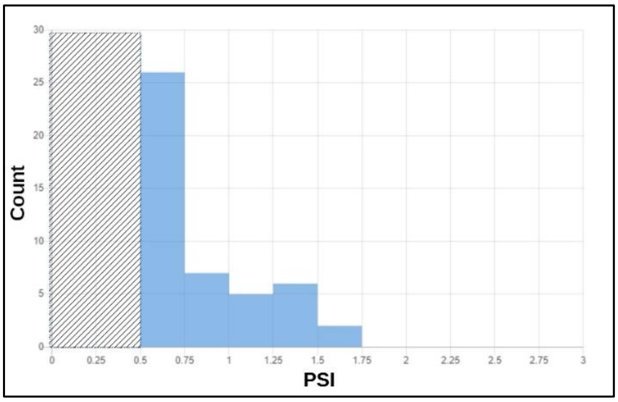

Chart 3: Distribution of recorded SPEs during 105 mm howitzer control missions. Aggregated for all positions: Gunner, Assistant Gunner, and Observer. Shaded area represents the PSI level below the minimum threshold for recording SPE (0.5 PSI; 3.5 kPa).

Chart 4 shows distributions of SPEs from different users in the same position.

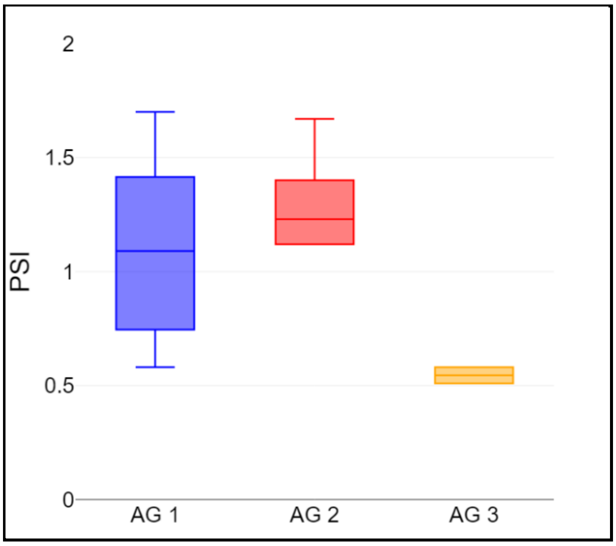

Chart 4: Three different workers at the Assistant Gunner (AG) position on different days. AG 1 & 2 show consistency among their recorded SPEs. However, the data for AG 3 shows a noticeably different range of results. AG 1: rounds fired= 26, SPE = 8; AG 2: rounds fired= 14, SPE = 5; AG 3 rounds fired= 26, SPE = 4.

Weapons fired by artillery programs in this study are within enclosed structures. These environments produce more complex waveform. Figure 5 presents an example of a captured waveform from the 105mm howitzer. This waveform demonstrates multiple positive peaks for a single round fired. These peaks may represent increased BOP exposure per round.

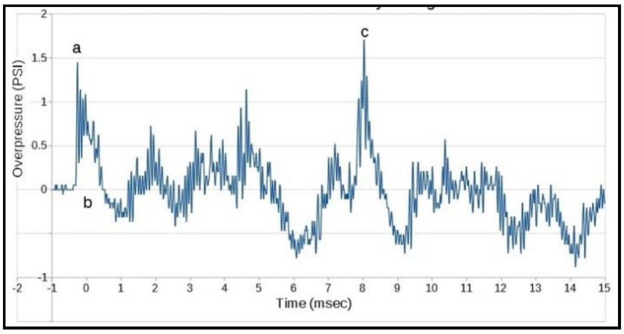

Figure 5: Raw data of the pressure wave produced by a single howitzer round. (a) Initial wavefront similar to a typical hand charge detonation. (b) There is a noticeably shorter positive phase. Most notable however is the multiple reverberated overpressure peaks likely resulting from the enclosure in which the guns are fired. (c) The peak recorded pressure is one of three distinct peaks above 1 psi (6.9 kPa).

4. DISCUSSION

This is the first study of its kind in the avalanche industry that seeks to quantify the levels of BOPs experienced by workers. Across all data collected, the recorded maximum exposure was 2.7 psi (18.6 kPa). This was the result of a single 0.9 kg deployment. While at first this seems counterintuitive, a simple explanation could be that avalanche workers tend to stand closer to smaller shots and seek shelter from larger shots.

Compared with other industries that rely on explosives, results from this initial study indicate avalanche workers have overall lower maximum BOP exposure as detailed in Tables 4 and 5. It is however critical to mention the significant amount of active research focused on identifying the effect of low level blasts, and cumulative exposure as a mechanism for brain injury. Published studies are quite limited and results remain mixed (Belding et al., 2021).

	Mean Exposure	Max Exposure
Hand Deployed Explosives (this study)	1.2 psi (8.3 kPa)	2.7 psi (18.6 kPa)
Military and Law Enforcement	1.1–6.2 psi (7.6–42.7 kPa)	3.8–13 psi (26.2–89.6 kPa)

Table 4: Aggregated mean and max exposures from industry studies using Blast Gauge sensors. Studies included are Kamimori et al. 2017, LaValle et al., 2019, Boutté et al., 2019, Nakashima et al., 2021, and Thangavelu et al., 2020.

	Mean Exposure	Max Exposure
105mm howitzer (this study)	0.9 psi (6.2 kPa)	1.7 psi (11.7 kPa)
Military and Law Enforcement	1.3 psi (9.0 kPa)	2.0 psi (13.8 kPa)

Table 5: Comparative exposures from a military training environment with 105mm howitzer (charge 4 and 5). Published study utilizing Blast Gauge sensors by Kamimori et al. 2017.

4.1 Limitations in Data Collection

Despite having consistent BOP measurements between all sensors used in early flat field data collection, there remains evidence that the sensors may be underreporting SPEs during operations. Examining the howitzer data suggests a rate of underreporting as high as 78%. Due to the fixed location and repeatable nature of howitzer missions, each round fired is expected to produce a similar pressure wave. However, data shows a rate of only 22 SPEs recorded per 100 rounds fired.

One potential source for this underreporting may include different tendencies amongst personnel. In a limited sample, this is evidenced by variation in exposure distribution level between operators for the same gun position (see Chart 4). With each user in this study wearing one sensor, there remains a possibility that this sensor may not have been positioned to capture the blast wave. This could be a result of body or sensor position, clothing, and/or equipment.

These same mechanisms could explain some of the large variation in recorded event rate between operations. Operation 2 had an event rate that is an order of magnitude smaller than the others. This may be attributed to variation between users, but may also suggest systemic differences including deployment methods, explosive type, and institutional practices. Additionally, obtaining informed consent per Institutional Review Board requirements removed the opportunity to collect blinded data. Participant awareness of the presence of a senor may have influenced behavior.

5. CONCLUSION

This novel study was intended to quantify BOP exposure amongst avalanche workers and compare to available research from related industries. Data collected using Blast Gauge sensors provided an average exposure level below 1.5 psi (10.3kPa) and a peak exposure below 3 psi (20.7kPa). The highest exposure recorded was the result of a single 0.9 kg deployment. Regardless of explosive size, all detonations are capable of causing bodily injury to a varying degree.

Our data set only represents a small fraction of the total explosives deployed across the avalanche industry. The data collection limitations outlined in this study could be eliminated or at least reduced in any future studies by:

- Purchasing & distributing additional sensors.
- Including additional operations.
- Standardizing how and where sensors are worn, including multiple sensors on each worker.
- Refining the route data collection method to allow for insights into other factors such as weather and snow conditions.

Although recorded levels of exposure in this study are lower than for workers from other industries, low levels of blast exposure and cumulative effects may still pose a risk to workers. Research continues to evolve in this area. Combining this study with future work will continue to inform avalanche workers about risks associated with explosive use. Awareness of blast overpressure effects alone may help reduce exposure.

CONFLICT OF INTEREST

Black Box Biometrics Inc. did not support this study financially or materially. The products used for this study were acquired at fair market price through normal distribution channels. The authors have not and will not benefit financially from the production or sale of Black Box Biometrics products.

ACKNOWLEDGEMENTS

The four of us would like to extend our deepest appreciation to the American Avalanche Association for the research grant which helped us get this project from an idea to a reality.

Thanks to Dave Richards and the Alta Avalanche Office for their time and support. We thank all the avalanche professionals who volunteered to participate in this study and provided us with good information and feedback.

Thank you to Dr. Scott McIntosh from the University of Utah for his contributions and assistance in this study receiving IRB approval for the University of Utah.

And finally, a special thanks to our family, friends, and peers who have supported us the last few years.

REFERENCES

Belding, J.N., Englert, R. M., Fitzmaurice, S., Jackson, J. R., Koenig, H. G., Hunter, M. A., Thomsen, C. J., & Da Silva, U. O.: Potential health and performance effects of high-level and low-level blast: A scoping review of two decades of research. *Frontiers in Neurology*, *12*. https://doi.org/10.3389/fneur.2021.628782, 2021.

Binger, J. B., & Miller, D. A., Soft and hard slab snow dynamic response to explosives used in avalanche hazard mitigation. *Journal of Cold Regions Engineering*, *30*(2). https://doi.org/10.1061/(asce)cr.1943-5495.0000096, 2016.

Borkholder, D.: Concept to commercialization of a MEMS-based blast dosimetry system. *2015 Transducers - 2015 18th International Conference on Solid-State Sensors, Actuators and Microsystems (TRANSDUCERS)*. https://doi.org/10.1109/transducers.2015.7180916, 2015.

Boutté, A. M., Thangavelu, B., LaValle, C. R., Nemes, J., Gilsdorf, J., Shear, D. A., & Kamimori, G. H.: Brain-related proteins as serum biomarkers of acute, subconcussive blast overpressure exposure: A cohort study of military personnel. *PLOS ONE*, *14*(8), e0221036. https://doi.org/10.1371/journal.pone.0221036, 2019.

Carr, W., Stone, J. R., Walilko, T., Young, L. A., Snook, T. L., Paggi, M. E., Tsao, J. W., Jankosky, C. J., Parish, R. V., & Ahlers, S. T.: Repeated low-level blast exposure: A descriptive human subjects study. *Military Medicine*, *181*(5S), 28-39. https://doi.org/10.7205/milmed-d-15-00137, 2016.

Champion, H. R., Holcomb, J. B., & Young, L. A. : Injuries from explosions: Physics, biophysics, pathology, and required research focus. *Journal of Trauma: Injury, Infection & Critical Care*, *66*(5), 1468-1477. https://doi.org/10.1097/ta.0b013e3181a27e7f, 2009.

DeKosky, S. T., Ikonomovic, M. D., & Gandy, S.: Traumatic brain injury — Football, warfare, and long-term effects. *New England Journal of Medicine*, *363*(14), 1293-1296. https://doi.org/10.1056/nejmp1007051, 2010.

Edlow, B. L., Bodien, Y. G., Baxter, T., Belanger, H. G., Cali, R. J., Deary, K. B., Fischl, B., Foulkes, A. S., Gilmore, N., Greve, D. N., Hooker, J. M., Huang, S. Y., Kelemen, J. N., Kimberly, W. T., Maffei, C., Masood, M., Perl, D. P., Polimeni, J. R., Rosen, B. R., … Dams-O'Connor, K.: Long-term effects of repeated blast exposure in United States special operations forces personnel: A pilot study protocol. *Journal of Neurotrauma*, *39*(19-20), 1391-1407. https://doi.org/10.1089/neu.2022.0030, 2022.

Elder, G. A., Stone, J. R., & Ahlers, S. T.: Effects of low-level blast exposure on the nervous system: Is there really a controversy? *Frontiers in Neurology*, *5*. https://doi.org/10.3389/fneur.2014.00269, 2014.

Fausti, S. A., Wilmington, D. J., Gallun, F. J., Myers, P. J., & Henry, J. A., Auditory and vestibular dysfunction associated with blast-related traumatic brain injury. *The Journal of Rehabilitation Research and Development*, *46*(6), 797. https://doi.org/10.1682/jrrd.2008.09.0118, 2009.

Frigo, B., Chiaia, B., & Cardu, M.: Snowpack Effects Induced by Blasts: Experimental Measurements vs Theoretical Formulas. Proceedings of the International Snow Science Workshop, Anchorage, AK, 16-21 September 2012, 923-947, 2012.

Kamimori, G. H., Reilly, L. A., LaValle, C. R., & Olaghere Da Silva, U. B.: Occupational overpressure exposure of breachers and military personnel. *Shock Waves*, *27*(6), 837-847. https://doi.org/10.1007/s00193-017-0738-4, 2017.

Kingery-Bulmash blast parameter calculator. (n.d.). UN Saferguard - International Ammunition Technical Guidelines. https://unsaferguard.org/un-saferguard/kingery-bulmash

LaValle, C. R., Carr, W. S., Egnoto, M. J., Misistia, A. C., Salib, J. E., Ramos, A. N., & Kamimori, G. H.: Neurocognitive performance deficits related to immediate and acute blast overpressure exposure. *Frontiers in Neurology*, *10*. https://doi.org/10.3389/fneur.2019.00949, 2019.

Misistia, A., Skotak, M., Cardenas, A., Alay, E., Chandra, N., & Kamimori, G. H.: Sensor orientation and other factors which increase the blast overpressure reporting errors. *PLOS ONE*, *15*(10), e0240262. https://doi.org/10.1371/journal.pone.0240262, 2020.

Mizutari, K., Blast-induced hearing loss. Journal of Zhejiang University-SCIENCE B, 20(2), 111-115. https://doi.org/10.1631/jzus.b1700051, 2019.

Nakashima, A., Vartanian, O., Rhind, S. G., King, K., Tenn, C., & Jetly, C. R.: Repeated occupational exposure to low-level blast in the Canadian Armed Forces: Effects on hearing, balance, and ataxia. *Military Medicine*, *187*(1-2), e201-e208. https://doi.org/10.1093/milmed/usaa439, 2021.

Saunders, G. H., & Echt, K. V., Blast exposure and dual sensory impairment: An evidence review and integrated rehabilitation approach. *The Journal of Rehabilitation Research and Development*, *49*(7), 1043. https://doi.org/10.1682/jrrd.2010.08.0157, 2012.

Simioni, S., *The effects of explosives on snow* [Doctoral dissertation]. https://www.research-collection.ethz.ch/handle/20.500.11850/156254, 2017.

Stuhmiller, J. H., Phillips, Y. Y., & Richmond, D. R.: The physics and mechanisms of primary blast injury. In C. C. Moore (Ed.), *Conventional warfare: ballistic, blast, and burn injuries* (pp. 241-270). Office of the Surgeon General Department of the Army, United States of America, 1990.

Taber, K. H., Hurley, R. A., Haswell, C. C., Rowland, J. A., Hurt, S. D., Lamar, C. D., & Morey, R. A.: White matter compromise in veterans exposed to primary blast forces. *Journal of Head Trauma Rehabilitation*, *30*(1), E15-E25. https://doi.org/10.1097/htr.0000000000000030, 2015.

Thangavelu, B., LaValle, C. R., Egnoto, M. J., Nemes, J., Boutté, A. M., & Kamimori, G. H.: Overpressure exposure from .50-caliber rifle training is associated with increased amyloid beta peptides in serum. *Frontiers in Neurology*, *11*. https://doi.org/10.3389/fneur.2020.00620, 2020.

Wooldridge, R. E., Hendrikx, J., Miller, D. A., & Birkeland, K. W. (2012). The Effects of Explosives on the Physical Properties of Snow. Proceedings of the International Snow Science Workshop, Anchorage, AK, 16-21 September 2012, 1033-1039, 2012.