MEASURING CUMULATIVE AND LOW-LEVEL BLAST OVERPRESSURE EXPOSURE OF AVALANCHE WORKERS
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ABSTRACT: Avalanche workers operate in complex environments with numerous hazards. One risk is exposure to blast overpressure (BOP) from explosive events. Explosives are inherently dangerous and no exposure is without risk. Research in military and law enforcement sectors has suggested that even relatively low levels of BOP, with peak overpressure of 0.25 psi (1.72 kPa) may be associated with physiologic and neurologic changes. Cumulative BOP exposure has been associated with increasing symptom severity. Reported symptoms include difficulty with memory and concentration, mood changes such as irritability and frustration, sleep disturbances, hearing difficulties, impaired reaction time and balance. Blast exposure among avalanche workers remains understudied. The work presented here expands upon published data by Thompson et al. (2023) in which avalanche workers wore pressure sensors to measure BOP during routine mitigation work. To improve the accuracy of measured exposures, the number of sensors worn by participants was increased from one to three. With this change, a blast event was ~1.6 times more likely to result in a recorded exposure. Data presented here was collected between 2024-2026 at four operations with 49 unique participants. In total 458 explosives were deployed, resulting in 48 recorded events (10.48%), with average peak overpressure exposure was 1.15 psi (7.9 kPa), maximum of 2.28 psi (15.72 kPa), and average positive impulse of 3.31psi·ms (22.82 kPa·ms). Sensor data also demonstrated that some participants experienced multiple exposures within minutes to hours. These values may be overstated due to the presence of atypical waveforms with uncertain significance. Despite this limitation, the measured exposures provide a framework for discussion and comparison with adjacent industries. Given the widespread use of explosives for avalanche mitigation, blast exposure remains an important topic in occupational hazard discussions. Awareness of blast exposures alone allows for adjustment of individual risk and recognition of symptoms. This work also provides support for avalanche programs to employ risk-reduction strategies applicable for their operation. Continued focus on the risk associated with cumulative blast exposure will guide safer explosives use practices and support longevity of career practitioners.

KEYWORDS: Worker Safety, Explosives, Blast Overpressure, Cumulative Low-Level Blast

1. INTRODUCTION

Explosives remain a critical part of successful avalanche mitigation, helping to reduce risk to critical infrastructure and protect human lives. Across many operations, the deployment of explosives relies heavily on trained personnel working in relatively close proximity to denotations. Explosives are inherently dangerous, and standoff distances may be limited by the complexity and numerous additional hazards present in an avalanche blasting environment. Safe explosives practices rely largely on industry norms, historical knowledge and perceived risk.

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Research within the avalanche industry related to explosives has historically focused on the effectiveness of blast on the snow surface. Notable examples include the work of Gubler (1977) who described the effectiveness of explosives deployed above the snow surface, as well as recent research including the work of Simioni (2017), and Meier (2024). Shifting the focus to explosives users — this group published the first study of its kind to measure levels of blast overpressure (BOP) in avalanche workers performing routine mitigation work (Thompson et al., 2023). Given ongoing interest from operations and individuals across the avalanche industry, data collection has continued. In the second phase of this study, the focus was shifted toward improving sensor use methods and evaluating risk associated with repeated and cumulative blast exposures

1.1 Blast Fundamentals
Blast is characterized by a sharp, and nearly instantaneous rise in air pressure to a maximum value known as peak overpressure (Figure 1). Following this maximum value, pressure rapidly decays during a positive phase, followed by a negative phase, before returning to ambient air pressure, as represented by the Friedlander waveform (Friedlander, 1946). Measurements of blast have historically focused on peak overpressure measured in psi/kPa. However, an additional metric, positive impulse (psi/kPa•ms) should also be considered. Impulse integrates blast duration with pressure to quantify total energy delivered by blast wave.

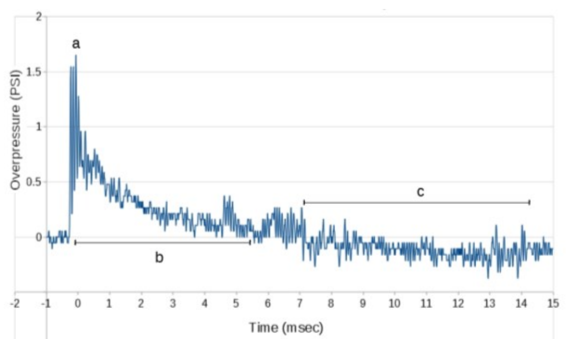

Figure 1: Blast wave recording from Blast Gauge Sensor. The resulting waveform is from a hand thrown explosive that aligns with the Friedlander waveform (a) Characteristic blast wave front, (b) positive phase decay, and (c) negative phase. The positive phase lasts roughly 6 milliseconds with a peak over pressure of 1.7 psi (11.7 kPa).

Blast propagates outward in all directions from the blast epicenter. In a flat field, BOP can be calculated at a given distance (UN SaferGuard, n.d.). However, avalanche workers operate in complex blasting environments in which blast waves are influenced by surrounding structures, natural features, and body position, which can amplify or attenuate pressure waves. These characteristics make BOP estimation difficult and highlight the need for measured BOP to better understand occupational exposure and associated risk.

1.2 Risk for Acute Blast Related Injury
Explosives are inherently and undoubtedly dangerous with multiple mechanisms for injury. Focusing on the acute impacts of BOP, primary blast injury can affect the ear, lungs and gastrointestinal tract (Ortega et al., 2024). The brain is also susceptible to BOP. Neurologic impacts were first described in *The Lancet* following World War I, where a description of "shell shock" included symptoms such as memory loss, difficulty concentrating, hearing difficulties, and dizziness (Myers, 1915). Even in modern times, blast exposure remains a primary cause of traumatic brain injury among military members (Bell et al., 2009).

The auditory system, specifically the tympanic membrane, is sensitive to relatively low levels of BOP (Mizutari, 2019). Historically, injury to the tympanic membrane has contributed to defining the threshold of 4psi (27.6kPa) as a single exposure guideline. More recently being cited only as an interim risk-management guideline, serving as a "useful first step to begin helping military personnel reduce their overpressure exposures using an easy-to-understand metric" (North Atlantic Treaty Organization Science and Technology Organization (NATO STO, 2026, p.35). Importantly, lower levels of BOP however are not necessarily benign, and there remains no universally established safe threshold for blast exposure.

1.3 Cumulative Low Dose Blast
Low-level blast exposures, typically characterized by the absence of immediately detectable injury, still pose an occupational hazard, particularly when considering repeated events and cumulative exposure over a career (Kamimori, 2017). Symptoms associated with even relatively low-level blast exposure include difficulty with memory and concentration, mood changes such as irritability and frustration, sleep disturbances, impaired reaction time, and balance disturbances. (Sajja et al., 2019; Defense Health Agency, 2026). The severity of these symptoms has been associated with greater cumulative blast exposure (McEvoy et al., 2024; Carr et al., 2015). In addition to self-reported symptoms, emerging research has identified measurable changes in cognitive function, balance and eye movement following repeated low level blast exposure (Kemmerer et al., 2026; Sutherland et al., 2026).

It should be emphasized that individuals may have a varying physiologic response to blast (Sutherland et al., 2026). Workers may be more sensitive to the effects of blast for a number of reasons that are incompletely understood.

1.4 Acoustic Pressure
Cumulative effects of blast exposure have also been demonstrated to affect the auditory system (Shea et al., 2025). These effects can include damage to the external structures of the ear, as well as the cochlea, auditory nerve and central auditory pathways that transmit sound within the

brain. (Mizutari, 2019). Importantly, blast-related auditory dysfunction may not be detected by standard audiograms. Individuals may still experience difficulty understanding speech, mishearing parts of sentences, and trouble hearing in noisy environments despite having normal results on a standard hearing test (Fausti et al., 2009; Mizutari, 2019).

Blast overpressure is the increase in air pressure caused by an explosion, while acoustic pressure is the rapid fluctuation in pressure that produces sound. Both occur during an explosive event but are distinct components. Acoustic energy may contribute to the neurologic and audiologic symptoms associated with cumulative low-level blast exposure (Sajja et al., 2019). Even without significant measured blast exposures, substantial acoustic pressure levels exceeding 150dB have been measured (Sajja et al., 2019). Because blast results in both an overpressure wave and a high-amplitude acoustic component, measuring only peak BOP may not fully characterize the auditory exposure of an explosive event.

2. METHODOLOGY

2.1 Sensors

Generation 7 Blast Gauge sensors were purchased from BlackBox Biometrics. These sensors are small, body mounted pressure sensors, worn as a set of three sensors recommended to be worn on the head, chest and shoulder (Figure 2). These sensors were selected given their established use across military and law enforcement groups allowing for useful comparisons to published data.

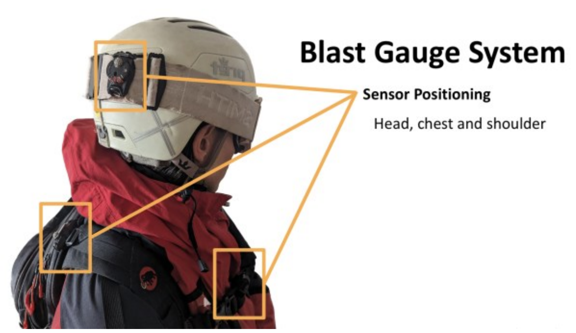

Figure 2: Configuration of Blast Gauge sensors worn by an avalanche worker. Sensors are positioned on the head, chest and shoulder to increase the likelihood of capturing blast exposure in various orientations and changing body positions.

Per the manufacturer specifications, these sensors sample pressure at 100 kHz with a resolution of 0.05 psi (0.4 kPa). The system can be configured to record blast overpressure between 0.5–100 psi (3.5 kPa–689.5 kPa). Additionally, this system records positive impulse (psi·ms) and peak acceleration magnitude (g). Proprietary sensor software reports event summaries including peak overpressure (psi) and event time. Additionally raw data summaries can be downloaded and analyzed independently.

It should be noted that Blast Gauge sensors measure pressure at the sensor location on the body, and do not directly measure incident pressure. Wiri et al, (2022) details that collected measurements can be influenced by sensor orientation, body positioning, shielding by equipment, and reflections from nearby surfaces. (Figure3).

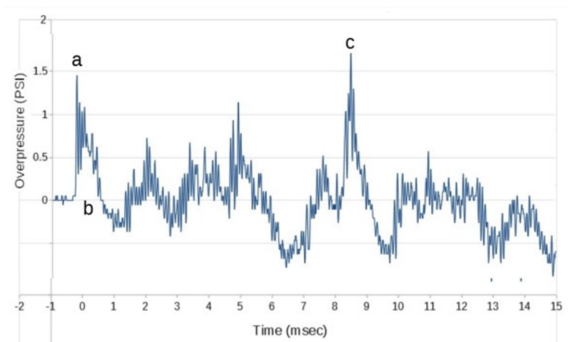

Figure 3: Example of a recorded blast event from Howitzer round. Personnel are within a concrete shelter with a retractable metal garage door exposing the gun barrel. This waveform demonstrates the reflective nature of blast with multiple pressure peaks readings exceeding 1psi all within 10msec.

2.2 Data Collection

Preliminary data collected using the Blast Gauge System between 2020 and 2023 were published in the 2023 International Snow Science Workshop (ISSW) proceedings from Bend, Oregon (Thompson et al., 2023). This initial phase included 25 participants across five operations, with 769 hand deployed explosives resulting in 45 recorded pressure events, with an average peak overpressure of 1.2 psi (8.27kPa).

In Phase II of this study (2024-2026), modifications were made to sensor use to improve event capture. Participants wore three sensors positioned on the chest, shoulder, and back of the head. Attempts were made to standardize placement across operations by providing a graphic detailing appropriate sensor locations. Sensors were worn by 49 participants across four unique operations, including Alta, Big Sky Resort and Solitude Mountain Resort. All operations are located in the Intermountain region.

avalanche mitigation work and included 458 deployed explosives.

Following the completion of their mitigation duties, participants were asked to provide information regarding the type, size, and total number of explosives deployed. Additionally, demographic data including age, years of avalanche experience and subjective symptomatic reporting were collected. Events recorded by the Blast Gauge system were compared with available operational route data using date and time stamps to identify corresponding blast events, calculate exposure rates, and provide the following analytics. When multiple pressure peaks were recorded for a single blast event, the highest peak overpressure was used for analysis, consistent with the approach used in previous studies.

3. RESULTS

Given the alterations to the data collection methods, only data collected between 2024-2026 are presented in the following results. The dataset includes 87 individual avalanche control routes with 458 explosives deployments. Data represents hand thrown explosives, air blasts, and bomb trolley deployments. Explosives used were almost exclusively pentolite cast boosters (2-6lbs), with the exception of five Delta-K Avalauncher rounds. All recorded overpressure readings were included in the analysis; no events were excluded based on waveform characteristics. A total of 48 recorded exposures exceeded the sensor threshold of 0.5psi (3.45kPa)

- Overall exposure rate of 10.48% (48/458 deployments).
- Median number of exposures per day: 1, mean of 1.62 exposures/day. Range of 1-5 recorded exposures.
- Mean peak BOP: 1.15psi (7.9 kPa)
- Maximum BOP: 2.28psi (15.72 kPa)
- Mean positive impulse: 3.31 psi·ms (22.82 kPa·ms)

Exposure rates (recorded events/number of deployments) across the four unique operations ranged from 7.0% up to 25.0%. The rates were 7.0% (9/128) for Operation 1, 7.1% (6/85) for Operation 2, 13.3% (32/241) for Operation 3, 25% (1/4) for Operation 4. Rate estimate from Operation 4 should be interpreted very cautiously as it is based on only four total explosives deployments,

Data was collected during routine
resulting in substantial uncertainty for the estimated rate.

3.1 Repeated Exposures

A concept we paid particular attention to in our data included circumstances in which individuals had multiple recorded exposure events in one day. Three examples are detailed in (Figure 4) including the time of recorded event, peak overpressure and positive impulse.

User A

Time	Peak Overpressure	Positive Impulse
8:04:02	0.76 psi (5.24 kPa)	1.45 psi·ms (10.00 kPa·ms)
8:15:29	0.91 psi (6.27 kPa)	1.16 psi·ms (8.00 kPa·ms)
8:22:52	2.28 psi (15.72 kPa)	1.89 psi·ms (13.03 kPa·ms)

User B

Time	Peak Overpressure	Positive Impulse
8:03:15	0.73 psi (5.03 kPa)	2.18 psi·ms (15.03 kPa·ms)*
8:50:55	0.91 psi (6.27 kPa)	1.16 psi·ms (8.00 kPa·ms)
9:19:01	0.73 psi (5.03 kPa)	0.87 psi·ms (6.00 kPa·ms)
10:13:36	1.27 psi (8.76 kPa)	5.08psi·ms (35.02 kPa·ms)*
11:31:31	1.16 psi (8.00 kPa)	10.15 psi·ms (69.98 kPa·ms)*

User C

Time	Peak Overpressure	Positive Impulse
10:53:48	0.65 psi (4.48 kPa)	0.76 psi·ms (5.24 kPa·ms)
11:08:47	0.65 psi (4.48 kPa)	1.02 psi·ms (7.03 kPa·ms)

Figure 4: User A had three measured exposures within 18 minutes. User B had the highest number of exposures in one day with five measured events, however this included atypical waveforms, detonated by *. Significance of these events in detailed within discussion. User C is included given their over 20-year career in the avalanche industry to highlight those at greatest risk of cumulative blast related effects.

4. DISCUSSION

4.1 Comparative Data

Data from this study allow for some contextual comparison with military personnel who are exposed to occupational BOP. The most comparable occupational uses of explosives include grenade training, explosive breaching, and mortar operations. Studies use a variety of measurement systems, reporting methods and analytics. These comparisons are intended only to provide context rather than direct comparison to adjacent populations. Many of these studies report peak overpressure readings exclusively, while including impulse is a newer scientific focus. Both metrics are included when available. See Figure 5.

	Peak Overpressure	Cumulative Impulse
Avalanche Workers	0.51–2.28 psi (3.52–15.72 kPa)	3.31–16.55 psi·ms (22.82–114.08 kPa·ms)
Grenade Training	0.14–1.4 psi (0.97–9.65 kPa)	None available
Explosives Breachers	1.3–9.17 psi (8.96–63.23 kPa)	15.05–47.2 psi·ms (103.75–325.43 kPa·ms)
Mortar Operations (60mm, 80mm and 120mm)	1.2–7.8psi (8.27–53.78 kPa)	~91–131 psi·ms (~627.42–903.21 kPa·ms)

Figure 5: Peak overpressure values reflect reported values including minimum/maximum, means and medians. Cumulative daily impulse was estimated and not directly reported in many studies. Grenade range data was reported by Medda et al. (2021), Sajja et al. (2019), and Pickett (2026). Mortar operations data was reported by Woodall et al. (2023), and Wiri et al. (2023). Breacher Exposure data was reported by LaValle et al. (2019), McEvoy et al. (2024), and Nakashima et al. (2022).

Given gaps in the scientific understanding of cumulative blast exposure and its effects on brain health, NATO and the U.S. Department of Defense have established interim guidelines to guide risk-reduction strategies for both peak overpressure and cumulative impulse.

A peak on-body pressure of 4 psi (27.6 kPa) is cited by Hicks (2024) and NATO STO (2026) as an exposure threshold for a single exposure event. This threshold should not be interpreted to indicate that repetitive exposures below 4 psi are without risk. Peak on-body overpressure is best viewed as an exposure metric not a direct measure of injury.

Positive impulse provides a measure that incorporates both the magnitude and duration of a pressure event. Two blast events may have similar peak pressure but substantially different durations, making impulse a critical value when characterizing blast exposure. NATO STO (2026) provides a recommendation to limit cumulative positive impulse to less than 31.7 psi·ms (219 kPa·ms) within a single day. This recommendation is based on levels of exposure associated with acute cognitive effects. These guidelines explicitly state that these recommendations do not account for successive days of exposure.

Although exposures recorded in this study are below the DoD/NATO interim risk-management thresholds, there remains no established level of blast exposure that can be considered “safe”. Populations with a history of blast exposure have demonstrated adverse neurologic outcomes; however, the relationship of peak overpressure, positive impulse, exposure frequency and interval is not yet defined. For this reason, it remains critical to proactively integrate risk reduction strategies for explosives users.

4.2 Risk Reduction for Avalanche Workers

The most effective way to reduce the potential for long term neurocognitive impacts associated with blast is to reduce blast exposure. Risk management framework should consider both magnitude of individual events, and cumulative burden. A standardized metric to quantify cumulative blast exposure and its effects has not yet been established. However, the concept of “dose” used in ionizing radiation provides a potential analogous risk-management framework. ALARA “As Low as Reasonably Achievable” principle as outlined by the U.S. Department of Defense (2024) emphasizing the reduction in exposure whenever practical. Concepts adapted for avalanche workers may include:

- Increasing standoff distance as much as possible.
- Minimizing the number of personnel near detonation; for example, positioning your route follower further from blast when feasible.
- Reducing the duration and frequency of explosives work, minimizing back-to-back routes, or sequential days of explosives work for the same user when practical.
- Rotating staff between “heavy” and “light” routes based on number and size of explosives used.
- Reduce total number of explosives used
- Consider keeping individual records to track cumulative exposures over time.

Particular attention should be paid to workers with historically greater explosives exposure, such as snow safety teams, career long explosives users, and gun teams. Additional efforts to reduce exposures may be particularly important during prolonged storm cycles or first openings.

Recognition of the potential risk associated with cumulative blast exposure, combined with appropriate education and risk reduction strategies can help reduce an individual’s exposure. Shared responsibility among employers, common agencies, and the workers themselves provides an opportunity to develop an industry wide approach to management of cumulative blast exposure.

Future recommendations surrounding blast exposure should be cautiously interpreted and integrated into the avalanche industry. Much of the research focuses on military and law enforcement. Readiness for war requires an inherently different level of acceptable risk, in which risk to an individual may be acceptable when necessary to accomplish a mission objective. Acceptable risk should reflect the intention of the explosives work.

4.3 Personal Protective Equipment

The unprotected ear is anatomically designed to amplify the transmission of sound. In-ear and over-ear protection work by reducing acoustic energy entering the external auditory canal, up to 90% with some devices (Gan et al., 2019). However, hearing protection cannot completely prevent auditory injury given that at high acoustic pressures, and with blast overpressure energy is transmitted through the skull affecting the cochlea and central auditory system directly.

Additional PPE, including helmets, are primarily designed for blunt impact protection, and only marginally mitigate risk related to the effects of BOP. Performance is impacted by a variety of factors including fit, design, coverage, padding. (Li et al., 2024; Thams et al., 2026;). Protection provided is influenced by blast orientation and may result in localized pressure amplification beneath or around the helmet.

4.4 Blast Gauge Software

Raw data tracings from each recorded exposure event are available for review within the integrated Blast Gauge software. Blast Gauge sensors measure pressure at the sensor's location on the body and are affected by reflection, diffraction and shielding (Wiri et al., 2023). Body mounted sensors do not provide a measure of undisturbed incident pressure, such as that measured by a sensor in a free field before the blast wave interacts with the body or surrounding objects. This presents a challenge when interpreting overpressure measurements obtained from body mounted sensors. Recorded tracings can lack a typical sharp rise in overpressure, such as those seen in Figure 6.

Because waveform morphology can be influenced by many factors, the significance of these atypical waveforms remains uncertain. Exclusion or inclusion of these tracing introduces subjectivity with direct influence on reported blast metrics. This represents an important limitation of using the body mounted Blast Gauge System.

A proposed algorithm (FAST) has been developed to address the complexity of these outputs from body mounted sensors and develop processing tools that can better quantify and support the analysis of key blast metrics that will be available for future use with Blast Gauge Sensors (Wiri et al., 2022). Reanalysis of this data set may be warranted, as these tools become available.

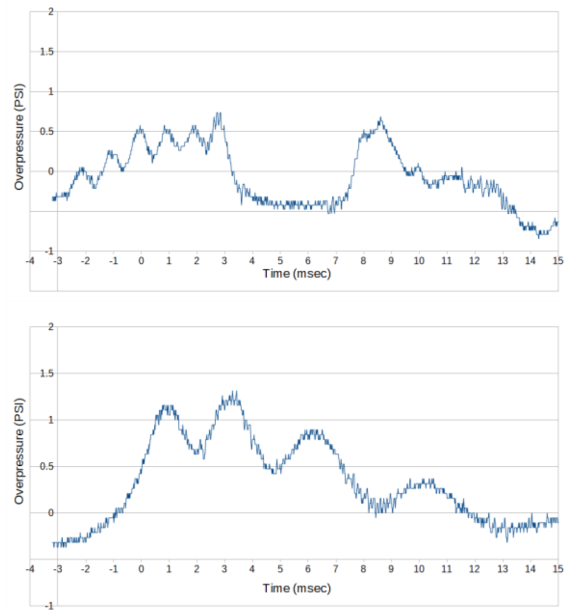

Figure 6: Examples of recorded waveforms that lack typical blast characteristics including a sharp rise in overpressure. These tracings have an extended positive phase and result in relatively high calculated positive impulse values.

4.5 Sensor Use and Limitations (1v.3 sensors)

Increasing the number of sensors worn by participants from one sensor to three sensors was associated with a greater proportion of known blast events producing a recorded exposure. A known blast event was approximately 1.6 times more likely to result in a recorded exposure using the 3-sensor system. This corresponds to a relative increase of 58% (one sensor design: 51 recorded exposures from 769 known blast events [6.63%] vs. three sensor design:48 recorded exposures from 458 known blast events [10.48%]). However, interpretation of this difference is complicated by the frequency of atypical waveforms. Among the 48 recorded exposures obtained using the 3-sensor configuration, up to ~20 exhibited some atypical characteristic. If all atypical tracings are excluded the relative difference in recorded exposure is substantially reduced, to approximately 5-10%. This further highlights the need for better standardization of pressure recordings and waveform classification from body mounted sensors. Of interest 34 of the 48 recorded exposures only registered on one of the three sensors worn, this is most likely due to shielding effects of various body positions. Single sensor events were relatively evenly distributed across sensor locations, 11 events from head sensor, 11 from chest sensor, and 12 from shoulder sensor.

Sensors are only capable of recording events >0.5 psi (3.45 kPa) due to the factory settings. This is important given that studies have reported symptoms (Sajja et al., 2019) and measured physiologic changes (Kemmerer et al., 2026) below this threshold. Events below 0.5 psi (3.45 kPa) likely do still contribute to cumulative blast exposure but are not captured in this dataset, resulting in an underestimation of total exposure. Future work may benefit from the integration of additional recording devices such as pencil probes, or sound meters to better capture low-level events.

5. CONCLUSION

Explosives remain an effective and routinely used tool that continues to aid in the success of the avalanche industry. There undoubtedly remains a need for hand deployed explosives. This study quantifies blast exposures (peak overpressure and positive impulse) of workers performing routine avalanche mitigation work. Consistent with previously published work from this group in 2023, recorded peak overpressures were below levels typically associated with acute and immediately apparent physical injury. However, adjacent research demonstrates that focusing exclusively on BOP of single events does not adequately define risk and that repeated exposure to any level of blast poses a cumulative risk.

Repeated blast exposures should be considered as an occupational hazard of avalanche work. Reframing blast exposure to a cumulative exposure measure — including peak overpressure, positive impulse, number of exposures, and interval between exposures is a more informative approach to characterize occupation risk and align with ongoing research. Thus far there is no universally accepted metric for cumulative blast dose or formal recommendations defining “safe” explosives use. Cited thresholds function only as practical interim limits until additional research is better developed. Risk reduction strategies must be employed proactively given that adverse effects of blast may not be immediately apparent and may manifest only with additional time/exposures.

Practically, this work provides support of blast related education related to cumulative risk of blast exposure. Simple awareness allows for informed individual and operational risk decisions by identifying practice patterns that may pose greatest risk for avalanche workers. However, within our industry at large, to our knowledge, there is no common agency actively investigating or providing updated recommendations to align with risk for injury related to cumulative blast exposure.

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