WHAT IF WE ARE WRONG? RETHINKING AVALANCHE FATALITIES: TRAUMA, BURIAL PRESSURE, AND THE LIMITS OF HYPOXIA-FOCUSED MITIGATION

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ABSTRACT**:** Avalanche fatality research has traditionally identified asphyxia as the leading cause of death among fully buried victims, with trauma accounting for approximately one-quarter of fatalities. A frequently cited Canadian study of 204 avalanche deaths reported that 75% were attributed to asphyxia and 24% to trauma. These figures have subsequently been incorporated into wilderness medicine guidelines, avalanche education, and the rationale for technologies intended to prolong airway patency during burial. However, the underlying mortality data is more than a decade old, and substantial regional variation exists in the relationship between trauma, snow climate, burial conditions, and survival. This raises an important question: what if the prevailing interpretation of avalanche mortality is incomplete?

Emerging research using special sensors on a girdle over a mannequin in simulated burials is examining partial pressures exerted by avalanche debris on the thoracic and pelvic regions. This is providing a different perspective on the mechanisms of death following burial. If avalanche debris can generate sufficient pressure to produce clinically significant blunt thoracic or pelvic trauma, some deaths currently conceptualized primarily through the lens of hypoxia may instead involve traumatic pneumothorax, internal haemorrhage, or other life-threatening injuries. This distinction is medically important because maintaining a patent airway cannot prevent death from injuries sustained during the avalanche or burial process. The possibility is especially relevant to maritime and transitional snow climates, where denser snowpacks and forested or irregular terrain have been associated with greater traumatic injury rates.

This paper reviews the established evidence concerning avalanche mortality, snow climate, trauma, airway-preservation technologies, and blunt traumatic injury. It argues that avalanche safety education should continue to emphasize rapid rescue and airway management while simultaneously recognizing that avoidance and exposure-based terrain selection remain the most fundamental forms of trauma prevention. If ongoing pressure research confirms that burial forces can independently generate severe thoracic or pelvic injury, avalanche medicine and mitigation strategies may require a broader model of survivability, one that treats trauma prevention and asphyxia prevention as interconnected but distinct objectives.

KEYWORDS**:** trauma, asphyxia, hypoxia, pneumothorax, pelvic fracture, haemorrhagic shock

1. INTRODUCTION

Avalanches present a distinctive medical problem because the environment itself can simultaneously create mechanical injury, respiratory failure, hypothermia, and delayed access to definitive medical care. For decades, avalanche medicine has emphasized the rapid deterioration of critically buried victims because of asphyxia. The established survival model describes a relatively high probability of survival during the first portion of burial, followed by a rapid decline as oxygen is depleted and carbon dioxide accumulates. Consequently, rapid companion rescue has become one of the central principles of avalanche safety.

The commonly cited distribution of avalanche causes of death comes largely from a landmark Canadian study by Boyd et al. (2009). Reviewing 204 avalanche fatalities in western Canada, the investigators determined that asphyxia accounted for 154 deaths, or 75%, while trauma accounted for 48 deaths, or 24%. Importantly, however, the study also found that major trauma was present in a subset of victims whose primary cause of death had been classified as asphyxia. Among autopsied asphyxia victims, 13% had major trauma. When trauma was considered as either a primary or significant contributing factor, the authors concluded that major trauma contributed to approximately one-third of deaths in the study population, Boyd et al. (2009).

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These findings complicate the simple statement that three-quarters of avalanche victims die from hypoxia while one-quarter die from trauma. Cause of death is not always an either-or distinction. A victim can sustain severe trauma, lose consciousness, become unable to protect the airway, and subsequently die from asphyxia. Similarly, a victim may sustain thoracic trauma that initially produces a pneumothorax and later develops into severe hypoxemia. The final physiological pathway may involve hypoxia, while the initiating event is traumatic. This is supported by the fact that avalanche involvement constitutes exposure to blunt force trauma by physiological definition via the mechanism of injury, Grossman MD et al (1989).

This distinction becomes increasingly important as new technologies seek to extend survival during burial. Devices such as the AvaLung and newer artificial-airway or air-management systems are designed to delay hypoxemia and hypercapnia. Recent clinical research involving the Safeback system, for example, demonstrate that an airflow device could substantially delay severe oxygen desaturation during simulated avalanche burial, SBX Avalanche Survival System. Such technologies have relevant medical value. Nevertheless, their effectiveness depends upon the assumption that the buried person remains sufficiently uninjured for additional time to translate into additional survival. The central question, therefore, is not whether hypoxia matters. It clearly does. The more important question is whether current avalanche mortality models adequately distinguish between deaths caused by respiratory failure and deaths initiated by mechanical trauma. If they do not, avalanche education and mitigation strategies may be overemphasizing the extension of airway survival while underemphasizing the prevention of traumatic injury.

2. THE ESTABLISHED MODEL OF AVALANCHE MORTALITY

The current medical understanding of avalanche burial is strongly influenced by survival data from Switzerland and Canada. The traditional avalanche survival curve demonstrates that survival remains relatively high during the early period of burial and then declines sharply as asphyxiation develops. Current Wilderness Medical Society guidelines continue to identify asphyxia as the most common cause of avalanche death, generally citing approximately 75% of fatalities, with trauma responsible for approximately 25%, v. Tilburg et al (2025).

This model has considerable clinical value. Once a person is critically buried, time becomes an essential determinant of outcome. The 2024 Wilderness Medical Society guidelines report that critically buried victims have greater than 90% survival when extricated within approximately 15 minutes, whereas survival decreases to approximately 30% after about 30 minutes, Wilderness Medical Society (2017). Beyond approximately 35 minutes, survival increasingly depends on a patent airway and an adequate air pocket. The physiology is straightforward. A buried individual continues to consume oxygen while exhaling carbon dioxide. If exhaled gas accumulates around the face, inspired oxygen decreases, and carbon dioxide rises. Snow can also obstruct the airway directly or create an ice mask around the face. These mechanisms can cause progressive hypoxemia, hypercapnia, unconsciousness, cardiac arrest, and death.

Research into airway patency supports the importance of this mechanism. A recent scoping review identified 566 critically buried avalanche cases and found that airway patency was documented in 41% of cases, while airway obstruction was reported in 12%. An air pocket was present in 19% of cases. The authors also noted substantial gaps in documentation, emphasising that the available evidence concerning airway status remains incomplete, Boyd et al. (2009). The traditional model is therefore not incorrect. Rather, it may be incomplete. The distinction is important because the mechanisms of trauma and asphyxia can overlap, and because the existing percentage estimates originated from historical populations and specific geographic regions.

3. TRAUMA IS NOT DISTRIBUTED UNIFORMLY ACROSS AVALANCHE ENVIRONMENTS

One of the strongest reasons to reconsider a universal avalanche mortality percentage is that trauma rates vary substantially according to activity, terrain, and snow climate, Boyd et al. (2009) found that trauma accounted for 24% of deaths overall, but the proportion varied dramatically by activity. Trauma was responsible for approximately 9% of deaths among snowmobilers and 42% among ice climbers. The authors also found that only 48% of victims whose primary cause of death was trauma were completely buried, Boyd et al. (2009). This observation is significant because traumatic death does not necessarily require prolonged burial. A person can die from the avalanche impact itself before burial-related asphyxia becomes relevant.

Canadian survival research further demonstrates the influence of snow climate, Haegeli et al (2011). compared 301 Canadian complete burials with 946 Swiss cases and found that Canadian survival declined more rapidly during the early stages of burial, Haegeli, P et al (2011). Survival was particularly reduced when trauma-related deaths were included and in denser snow climates. The researchers concluded that differences in snow climate contributed to differences between Canadian and Swiss survival patterns.

This is especially relevant to transitional and maritime environments. A review of avalanche medicine and climate change reported that maritime Canadian climates have historically demonstrated higher rates of trauma than continental climates, with wet snow and forested terrain contributing to the risk. In one Canadian analysis, collisions with trees accounted for 68% of traumatic avalanche deaths, while impacts with rocks, ice, and the crushing or churning forces of avalanche debris also produced serious injuries, Haegeli, P et al (2011). Consequently, a single percentage describing trauma-related avalanche fatalities may obscure important geographic differences. A skier buried in relatively soft continental snow in open terrain may experience a substantially different mechanical environment from a skier carried through dense maritime snow and into trees, rocks, or other terrain features.

4. THE POTENTIAL ROLE OF BURIAL PRESSURE

The proposed pressure-sensor research introduces a different question: can the avalanche debris itself generate sufficient pressure against the human body to cause severe internal (traumatic) injury after the moving avalanche has stopped? Simply by mechanism of injury as evidenced in Grossman et all (1989) with respect to avalanche dynamics and blunt force trauma, the preliminary answer is yes. This question is distinct from conventional avalanche trauma research. Historically, discussions of traumatic avalanche deaths have focused heavily on collisions with trees, rocks, ice, terrain irregularities, and other external objects. However, an avalanche is also a large moving mass. During flow, deceleration, deposition, and subsequent settlement, that mass can interact mechanically with the body.

A pressure-sensor system positioned around the thoracic and pelvic cavities provides quantitative information that is otherwise difficult to obtain from retrospective accident investigations. Sensors would distinguish between transient dynamic loading during avalanche movement and sustained pressure after deposition. This distinction matters because the physiological effects of a short-duration impact may differ from those produced by prolonged compression. The thorax is particularly important because significant blunt chest trauma can produce rib fractures, pulmonary contusion, haemothorax, pneumothorax, or other injuries that compromise ventilation. A pneumothorax may initially be relatively subtle but can progress depending on the nature of the injury and surrounding physiological conditions. In an avalanche burial, the ability to recognize or treat such an injury is extremely limited.

The pelvis presents a different concern. Pelvic fractures are recognized in modern trauma medicine as potentially life-threatening because they can produce substantial internal haemorrhage. Contemporary trauma literature describes pelvic fractures as a major source of morbidity and mortality following blunt trauma, particularly when associated with hemodynamic instability and uncontrolled bleeding, Baker J, et al (2024). Furthermore, the pelvis requires slightly less force than what is required to fracture a femur, which is the strongest bone in the human body. At a minimum of 4000 newtons of force (900 pounds), when a femur fractures in an avalanche burial, it should be assumed that the pelvis is also likely to fracture with 'pretzel' characteristics. A key physiological factor that must be evaluated is that in many cases of avalanche fatalities, subjects are found with femoral fractures. This suggests significant blunt or penetrating force trauma in the avalanche dynamics which, if the femur is fractured, is likely that the pelvic cavity would also fracture. This would result in an increased likelihood of internal haemorrhage and haemorrhagic shock prior to hypoxia, Cullinane, D. C. et al (2011).

If avalanche debris were demonstrated to generate pressures capable of producing major pelvic injury without a collision with an external object, the implications would be substantial. A buried victim could theoretically maintain an open airway yet continue to deteriorate because of internal bleeding. In such a situation, extending airway survivability would not address the primary mechanism of death.

It is important, however, to distinguish between pressure measurement and proof of injury. Demonstrating that a snowpack generates a certain pressure does not automatically establish that the pressure causes a specific fracture, organ injury, pneumothorax, or fatal haemorrhage. Continued research would need to establish appropriate biomechanical thresholds, exposure duration, body position, snow density, temperature, loading rate, and individual variability. Cadaveric, anthropomorphic, computational, and clinical evidence may ultimately be required to establish a reliable relationship between measured snow pressure and actual human injury. Cullinane, D. C., et al (2011).

5. TRAUMA VERSUS HYPOXIA: WHY THE CLASSIFICATION MATTERS

At first glance, distinguishing traumatic death from hypoxic death may appear primarily academic. Clinically, however, the distinction affects prevention, rescue priorities, product development, and public education. Consider a hypothetical buried victim who sustains a blunt thoracic injury during avalanche movement. The injury produces a pneumothorax. The victim remains conscious, maintains an airway, and possesses an effective air-management device. Nevertheless, progressive respiratory compromise develops because of the chest injury. The eventual physiological endpoint may be hypoxemia and cardiac arrest. Calling this death “hypoxia” is physiologically understandable but potentially misleading from a prevention standpoint. The initiating event was traumatic. Improving airway duration may have limited benefit because the fundamental problem is structural injury to the respiratory system.

The same principle applies to pelvic trauma. A victim with a severe pelvic fracture may remain oxygenated for a period while blood accumulates internally. As haemorrhage progresses, circulating blood volume decreases, tissue perfusion fails, and haemorrhagic shock develops. Ultimately, cellular hypoxia occurs. Yet the cause is still traumatic haemorrhage rather than primary burial asphyxia.

This distinction is fundamental to trauma medicine. A patient may die from hypoxic cellular injury secondary to haemorrhage, airway obstruction, pulmonary injury, or cardiac dysfunction. Describing the final physiological state does not necessarily identify the initiating cause. Therefore, future avalanche mortality research should consider a more detailed classification system that distinguishes primary asphyxia, primary trauma, trauma contributing to asphyxia, and trauma producing secondary respiratory or circulatory failure.

6. IMPLICATIONS FOR AVALANCHE SAFETY TECHNOLOGY

The development of airway-preservation technologies remains justified by the evidence. The AvaLung was developed to allow buried victims to draw air from the surrounding snow while directing exhaled carbon dioxide away from the airway, Saurabh Sud et all (2020). Experimental research demonstrated that such technology can significantly prolong oxygenation during simulated burial.

More recent evidence provides similar support for newer technologies. A randomized clinical trial involving the Safeback system found that participants using the device maintained substantially better oxygenation and lower carbon dioxide concentrations during simulated critical burial than controls. The study supports the conclusion that the technology can delay hypoxemia and hypercapnia, SBX Avalanche Survival System. These findings should not be interpreted as evidence that such devices are ineffective. Instead, they demonstrate why avalanche safety should be understood as a layered system.

An airway-management device addresses one pathway to death. An avalanche airbag addresses another by reducing the probability of complete burial. An avalanche transceiver, probe, and shovel facilitate rapid location and extrication. Education, terrain assessment, weather evaluation, group management, and conservative decision-making reduce the probability of entering a dangerous avalanche path in the first place. If pressure research confirms significant burial-related trauma, the hierarchy becomes even more important. A technology that extends airway survival may increase the time available for rescue, but it cannot eliminate blunt force traumatic injuries sustained before or during burial. Consequently, an airway device should never be interpreted as a substitute for avoidance.

7. AVOIDANCE IS THE PRIMARY MEDICAL INTERVENTION

The most important implication of the proposed research may be that avalanche avoidance remains the most effective trauma intervention. The 2024 Wilderness Medical Society guidelines explicitly identify avalanche avoidance as the primary method for mitigating injury and death, v.Tilburg et al (2024). When an avalanche occurs, companion rescue, appropriate resuscitation, and advanced medical care become essential. Avoidance is unique because it can prevent both major categories of avalanche mortality simultaneously. A person who never enters an avalanche path cannot be buried and therefore cannot develop burial asphyxia. The same decision also prevents the mechanical forces associated with avalanche movement, collisions, crushing, and burial pressure. This has implications for avalanche education. If the public is taught that the primary danger of burial is loss of oxygen after approximately 15 to 35 minutes, there is a risk of unintentionally encouraging a technology-focused approach to survival. Individuals may begin to view an air-management device as an insurance policy that makes entering avalanche terrain more acceptable.

This is a potential heuristic trap. Safety equipment can change risk perception even when the equipment itself provides a genuine reduction in risk. The appropriate message should therefore be that rescue and survival technologies are layers of protection, not permission to accept greater exposure. Terrain selection should consequently remain central to avalanche education. Understanding avalanche forecasts, recognizing avalanche terrain, evaluating slope angle and terrain traps, identifying exposure to trees and rocks, maintaining appropriate group spacing, and choosing conservative travel routes are not secondary strategies. They are mechanisms for preventing the traumatic and respiratory consequences of avalanche involvement before they occur.

8. FUTURE RESEARCH PRIORITIES

The pressure-sensor research described within will contribute substantially to avalanche medicine if it is able to establish a reliable relationship between snowpack pressure and human injury.
Future research should address several questions.

First, pressure should be measured across multiple snow climates and densities. Results from maritime snow should not automatically be generalized to continental snow, and vice versa.

Second, measurements should distinguish dynamic loading from static or settling pressure. The rate at which force is applied may be as important as the maximum pressure itself.

Third, thoracic and pelvic measurements should be correlated with validated biomechanical injury thresholds. Pressure alone is insufficient to establish clinical injury.

Fourth, body position should be incorporated into testing. A prone, supine, or flexed individual may experience substantially different loading patterns.

Finally, avalanche fatality databases should improve the classification of trauma. Cause-of-death investigations should distinguish between trauma as the initiating event, trauma as a contributing factor, and asphyxia as the primary mechanism. More precise classification would allow future survival models to reflect the complexity of avalanche deaths.

9. CONCLUSION

The established view that approximately 75% of avalanche fatalities are caused by asphyxia and approximately 25% by trauma remains supported by current wilderness medicine guidelines. However, the evidence behind these percentages is historical, regional variation is substantial, and trauma is highly likely to contribute to a larger proportion of deaths than a simple cause-of-death classification suggests. The possibility that avalanche debris can generate clinically significant thoracic or pelvic pressures deserves careful investigation. If ongoing research demonstrates that burial pressure can produce blunt chest injury, pneumothorax, pelvic fracture, or internal haemorrhage, the implications for avalanche medicine will be significant. Such findings would not invalidate the importance of airway management. Instead, they would demonstrate that airway preservation addresses only one component of the survival problem.

The central lesson is therefore not that avalanche survival technology is misguided. It is that technology must be understood within the broader context of risk management. An airway device may provide additional time. A transceiver may shorten the time to rescue. An airbag may reduce the probability of complete burial. None of these tools, however, can guarantee protection from traumatic forces generated during an avalanche. The most reliable way to prevent avalanche trauma remains preventing avalanche involvement. Avoidance, appropriate terrain selection, conservative decision-making, and effective avalanche education therefore remain the foundation of risk reduction.

The question “What if we are wrong?” should not be interpreted as a rejection of established avalanche medicine. It should be interpreted as an invitation to improve it. Scientific progress depends upon challenging assumptions when new measurements become possible. If emerging research demonstrates that trauma plays a greater role in avalanche mortality than previously recognized, avalanche medicine should adapt accordingly. A more complete understanding of death in avalanches may ultimately lead to better prevention, more appropriately designed safety equipment, more accurate medical training, and most importantly, less fatalities

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