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Experimental paper

Avalanche airbag post-burial active deflation — The ability to create an air pocket to delay asphyxiation and prolong survival

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Abstract

Aim: The primary purpose of an avalanche airbag is to prevent burial during an avalanche. Approximately twenty percent of avalanche victims deploying airbags become critically buried, however. One avalanche airbag actively deflates three minutes after deployment, potentially creating an air pocket. Our objective was to evaluate this air pocket and its potential to prevent asphyxiation.

Methods: Twelve participants were fitted with an airbag and placed prone on the snow. Participants deployed the airbag and were buried in 1.5 m of snow for 60 min with vital signs including oxygen saturation (SpO2) and end-tidal CO2 (ETCO2) measured every minute. Participants completed a post-burial survey to determine head movement within the air pocket.

Results: Eleven of the 12 participants (92%) completed 60 min of burial. Preburial baseline SpO2 measurements did not change significantly over burial time ($P > 0.05$). Preburial baseline ETCO2 measurements increased over the burial time ($P < 0.02$); only one ETCO2 value was outside of the normal ETCO2 range (35–45 mmHg). Participants reported they could move their head forward 11.2 cm (SD 4.8 cm) and backward 6.6 cm (SD 5.1 cm) with the majority of participants stated that they had enough head movement to separate the oral cavity from opposing snow if necessary. Visual examination during extrication revealed a well-defined air pocket in all burials.

Conclusion: The avalanche airbag under study creates an air pocket that appears to delay asphyxia, which could allow extra time for rescue and improve overall survival of avalanche victims.

Keywords: Avalanche, Asphyxiation, Airbag, Air pocket

Introduction

Avalanches are a primary safety concern for those who travel in winter backcountry terrain. If not killed by traumatic injury, most victims can survive for 15–20 min before asphyxiation occurs. From 20 to 35 min after burial the rate of survival sharply declines from approximately 90%–35%. If the airway is not obstructed by snow and a pocket of air exists near the mouth, the victim may be able to survive longer.[1,2] A large air pocket[3] and/or lower density of the surrounding snow[4] will slow the onset of critical levels of hypoxia and hypercapnia. The combination of airway patency, presence of an air pocket, density of snow, and extent of burial[2] will influence victim survival after 20–35 min of burial.[1] These factors guide resuscitation protocols during avalanche rescue.[5,6]

An avalanche airbag is a backpack equipped with a packable bag that, upon pulling a trigger handle, rapidly inflates via a compressed gas cartridge or fan mechanism. The airbag approximately doubles the volume of the victim. Avalanche airbags work by the physical property of granular convection which, in a mixture of varying sized particles, propels relatively larger particles towards the top. This increased volume helps to keep the victim at the surface of the snow

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with the goal to prevent critical burial, which is defined as head under the snow and breathing impaired.

A European study published in 2014 found that 3.6% of individuals in a backcountry sample from South Tyrol, Italy, carried an avalanche airbag.[7] In 2015, 5% of recreationists in a sample of the North American Wasatch and Teton mountain ranges carried an avalanche airbag.[8] Although more recent data has not been published, anecdotal observations indicate that the number of airbag users is increasing.

Although most avalanche victims with an inflated airbag remain on the surface, approximately 20% of avalanche victims who have deployed airbags successfully still become critically buried.[9] One avalanche airbag (JetForce, Black Diamond Equipment, Ltd, Salt Lake City, UT) actively deflates three minutes after deployment by reversing the fan mechanism, thereby removing air that has entered the airbag during the inflation phase. Active deflation may create an air pocket in the snow in the event of a critical burial, which could delay asphyxiation and allow more time for rescue and ultimately increase chances of survival. This study examines active deflation as a secondary safety mechanism in an avalanche airbag. We hypothesized that the air pocket created by the JetForce airbag would maintain normal physiology for the 60 min study period.

Methods

The study was approved by the University of Utah Institutional Review Board and written informed consent was obtained from each participant prior to burial.

This study took place at 2100 m elevation in the the Wasatch Mountains, Utah, during February and March of 2019. The experimental setup simulated a critical avalanche burial. A 6 m × 6 m snow mound was pushed and built by a snowcat. A 190 cm high, 102 cm wide, and 190 cm length trough was dug from the side of the snow mound. Snow was piled on top of the mound near the trough and allowed age harden for 30–60 min before each burial trial.

Subjects were paid volunteers, 7 men and 5 women, mean age 32.4 years (ranges 26–39 years) without acute or chronic respiratory medical problems. Anthropomorphic details are described in Table 1. All subjects lived between 1500 to 2500 m elevation. The participants wore a thin base layer and were provided the same midlayer and snowsuit shell. A standardized set of hood, face mask, goggles, and helmet covered the head. The nose was occluded with an external nose plug. A device that separates inspired air from expired air using two one-way valves, subsequently called "inhalation/exhalation separator" (AvaLung, Black Diamond Equipment, Ltd, Salt Lake City, UT) was modified to allow for measurement of end tidal carbon dioxide (ETCO2). The ETCO2 monitor tubing was placed in-line with the respiratory tubing between the mouthpiece and the housing containing the two one-way valves. An emergency oxygen backup line was attached to the apparatus capable of delivering 15 L/min of 100% oxygen to instantly increase inspired partial pressure of oxygen and displace CO2. The setup positioned the inhalation/exhalation separator device within the air pocket once the airbag deflated. See Fig. 1 illustrating the experimental setup.

The most common position for an avalanche victim to be buried is prone with head downhill.[10] We elected to place participants in the prone position on a level surface. This level position avoided potential breathing restriction of the abdomen on the diaphragm and decreased participant anxiety. Body position is shown in Figs. 1 and 2.

Table 1 – Participant demographic data and anthropometric characteristics.

Subject No.	Sex	Age	Height (cm)	Weight (kg)
1	F	26	163	63.6
2	M	31	175	79.5
3	F	27	180	75.0
4	F	28	165	63.6
5	M	36	175	77.3
6	M	39	180	77.3
7	F	35	175	61.4
8	M	38	180	95.5
9	M	32	183	88.6
10	F	31	157	59.1
11	M	39	185	84.1
12	M	27	183	75.0

Once the participant was positioned, we started a countdown to mark time zero. At time zero, the participant pulled the airbag trigger. Simultaneously, two personnel shoveled the prepared snow onto the participant from above. The trough was filled with snow within the first 60 s, allowing 2 min for the snow to set. At 3 min, the airbag deflated thereby creating an air pocket. Burial depth was approximately 130 cm at the participant's head.

The participant was monitored with continuous pulse oximetry to measure percent saturation of hemoglobin with oxygen (SpO2%), ETCO2, respiratory rate (RR), and heart rate (HR) (ZOLL X Series monitor/defibrillator, ZOLL, Chelmsford, MA). Vital signs were recorded for 5 min pre-burial (baseline) and at 1-min intervals while buried. Participants had a radio to communicate at 5 min intervals and in an emergency, although verbal communication was limited to ensure that ETCO2 measurements were valid. Participants were unburied after 60 min, if heart rate fell below 50 bpm, SpO2 fell below 88%, or if the participant felt too distressed to continue. During the burial, water per cubic meter of snow was measured using a 1000 cm^3 wedge density cutter (Snowmetrics, Ft. Collins, CO). Snow/water density was reported as weight/volume and percentage (ie, 300 kg/m^3 is 30% density snow or 70% air). Snow densities measured between 300–520 kg/m^3 (30–52%) correlating well with typical avalanche debris (range: 300 kg/m^3 for a midwinter dry snow avalanche to 600 kg/m^3 or higher for a springtime wet snow avalanche).[11]

Participants completed a survey shortly after completion of burial with the following questions: (1) How many inches do you estimate you were able to tilt your head forward after the airbag deflated? (2) How many inches do you estimate you were able to tilt your head back after the airbag deflated? (3) After the airbag inflated, I could pull my face away from the snow in front of my face. Questions #3 was answered using a Likert scale with possible responses: Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree.

Baseline vital signs prior to burial were compared with those at the end of the burial period using a Wilcoxon matched pairs test (Microsoft Excel, Redmond, WA). Data from this airbag study was compared to historical results obtained by Grissom et al.[12] which examined the AvaLung inhalation/exhalation seperator device during snow burial. This comparison was performed using generalized additive mixed models with participant-level random effects to compare outcomes

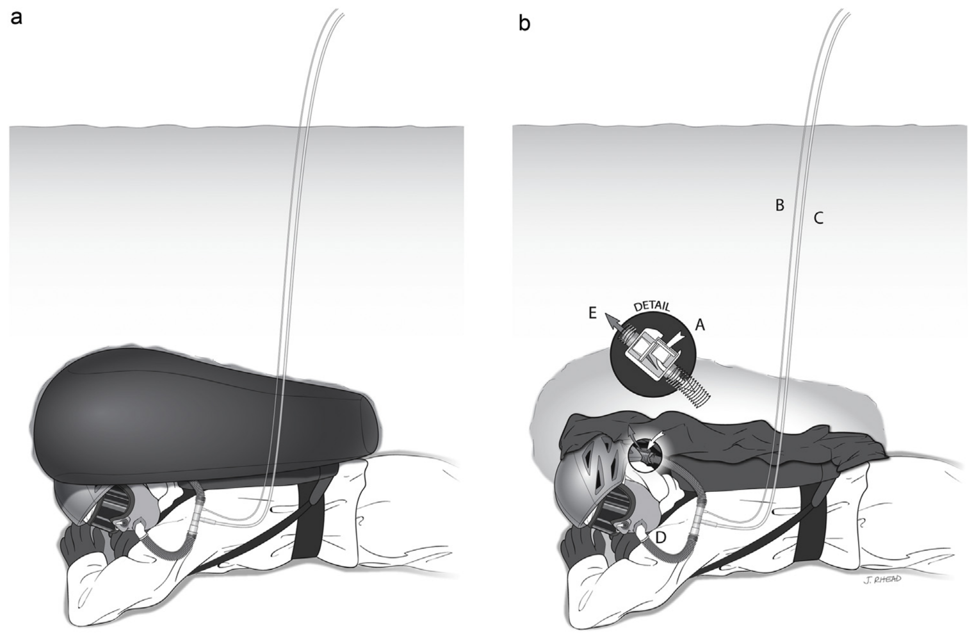

Fig. 1 – Experimental setup. (a) Depicts conditions after inflation of the airbag at time 15 s–3 min after trigger. (b) Depicts conditions after deflation of the airbag at 3 min.
On inspiration, air from the air pocket enters the inhalation/exhalation separator through the first of two 1-way valves (A) (see detail). Air then flows through the respiratory tubing past the in-line capnometer sampling tubing (B) and emergency oxygen tubing (C) to the mouthpiece (D). On exhalation, air travels away from the mouthpiece, again past the emergency oxygen tubing and capnometer sampling tubing, through the inhalation/exhalation separator to exit out the exhalation port (E).

between burial types (R Project for Statistical Computing, Lucent Technologies, Murray Hill, NJ).[13]

Results

Eleven subjects remained buried for the entire 60 min. Participant 9 required extrication at 48 min for increasing heart rate, ETCO2, and anxiety. Overall mean baseline SpO2, RR, and HR measurements did not change significantly over burial time ($P > 0.05$, see Table 2). Mean preburial baseline ETCO2 measurements increased from 38 (SD 5.3) to 40 mmHg (SD 2.9) ($P < 0.02$, Table 2). All end-burial ETCO2 values were within the normal physiological range of 35–45 mmHg except that of Participant 9 whose value measured 50 mmHg upon extrication. In all burials, we observed a well-defined air pocket casted around the former position of the airbag. See Fig. 3.

Fig. 2 – Participant placement before burial (airbag deflated) and after inflation prior to being buried.

Table 2 – Baseline and end-point data from burials with avalanche airbag.

Subject No.	Burial time (min)	SpO2, %		ETCO2, mmHg		Respiratory rate, breaths/min		Heart rate, beats/min	
		Baseline	End	Baseline	End	Baseline	End	Baseline	End
1	60	95	96	37	40	11	8	99	73
2	60	94	97	37	40	13	12	92	66
3	60	96	95	39	40	13	13	74	50
4	60	97	99	34	36	8	9	99	81
5	60	98	95	35	38	7	7	101	58
6	60	97	98	37	39	9	4	97	56
7	60	98	99	38	35	6	8	108	92
8	60	93	97	44	43	5	5	85	86
9	48	98	96	35	50	6	23	62	81
10	60	99	100	39	40	8	14	88	65
11	60	97	99	39	42	21	7	97	87
12	60	99	99	40	41	7	7	122	79
Mean	59	97	98	38	40	10	10	94	73
P value			$P > 0.05$		$P < 0.02$		$P > 0.05$		$P > 0.05$

SpO2, oxygen saturation as measured by pulse oximetry; ETCO2, end-tidal carbon dioxide.
P values compare baseline and end point.

Fig. 3 – Example of the air pocket created by deflation of the airbag observed upon extrication.

Participants reported they could move their head forward a mean of 11.2 cm (SD 4.6) and backward 6.7 cm (SD 5.1). Five participants (42%) “Strongly agreed” that they had the ability to move their face away from snow, 6 (50%) “Agreed”, and 1 participant (8%) “Disagreed.”

Discussion

The results supported our hypothesis that the air pocket created by deflation of the airbag created conditions that could sustain normal physiology during 60 min of snow burial. The automatic deflation mechanism and resulting air pocket could allow extra time for companions or possibly a large search and rescue team to extricate the victim before succumbing to asphyxiation.

Under these ideal and experimental conditions, our data suggest that critical hypoxia and hypercapnia would be delayed significantly. We compared our airbag data with data from historical controls which used an inhalation/exhalation separator in its intended fashion during avalanche burial.[12] This comparison is shown in Fig. 4 and is provided as an exploratory analysis. The comparison demonstrates that SpO2 and ETCO2 were better maintained while breathing within the air pocket after avalanche airbag deflation. Although experimental conditions, body position, and participants were different, we expect that the air pocket from the deflated airbag would likely delay asphyxia much longer than that of the inhalation/exhalation separator studied by Grissom et al.[12] We anticipate that the air pocket would improve survival chances in avalanche accidents in the proper conditions, however the exact survival benefit is unknown.

The European Resuscitation Council (ERC) guidelines avalanche algorithm uses the presence of a patent airway to help determine whether a victim should continue to be resuscitated or attempts ceased during rescue.[5] The guidelines instruct the rescue team to note the presence or absence of an air pocket to help determine whether the victim may have a longer potential for suvival because of delayed asphyxiation. An air pocket created by the deflation of an airbag could create circumstances that could improve survival based on the ERC algorithm and avalanche burial survival curves.[1,2]

Even though the air pocket created by airbag deflation appears to delay asphyxia under our experimental scenario, this potential benefit would not be realized in all conditions. If the mouth, nose, or upper airway are obstructed by inhaled snow or debris, an air pocket would not delay asphyxia nor serve any survival adavantage.[6] In many burial situations, a victim is unable to move because of snow packing around the head or neck. The victim may be unconscious and unable to move the head and neck to access the air pocket. Trauma may prevent head and neck movement. An air pocket from a deflated airbag would similarly be of limited or no benefit in these situations. Airbags that inflate from compressed gas from a canister do not actively deflate. These airbags will not create an air pocket and therefore not provide the potential survival benefit that the airbag under study would. A properly deployed and inflated airbag that prevents critical burial will always be superior to strategies aimed to prolong survival after burial.

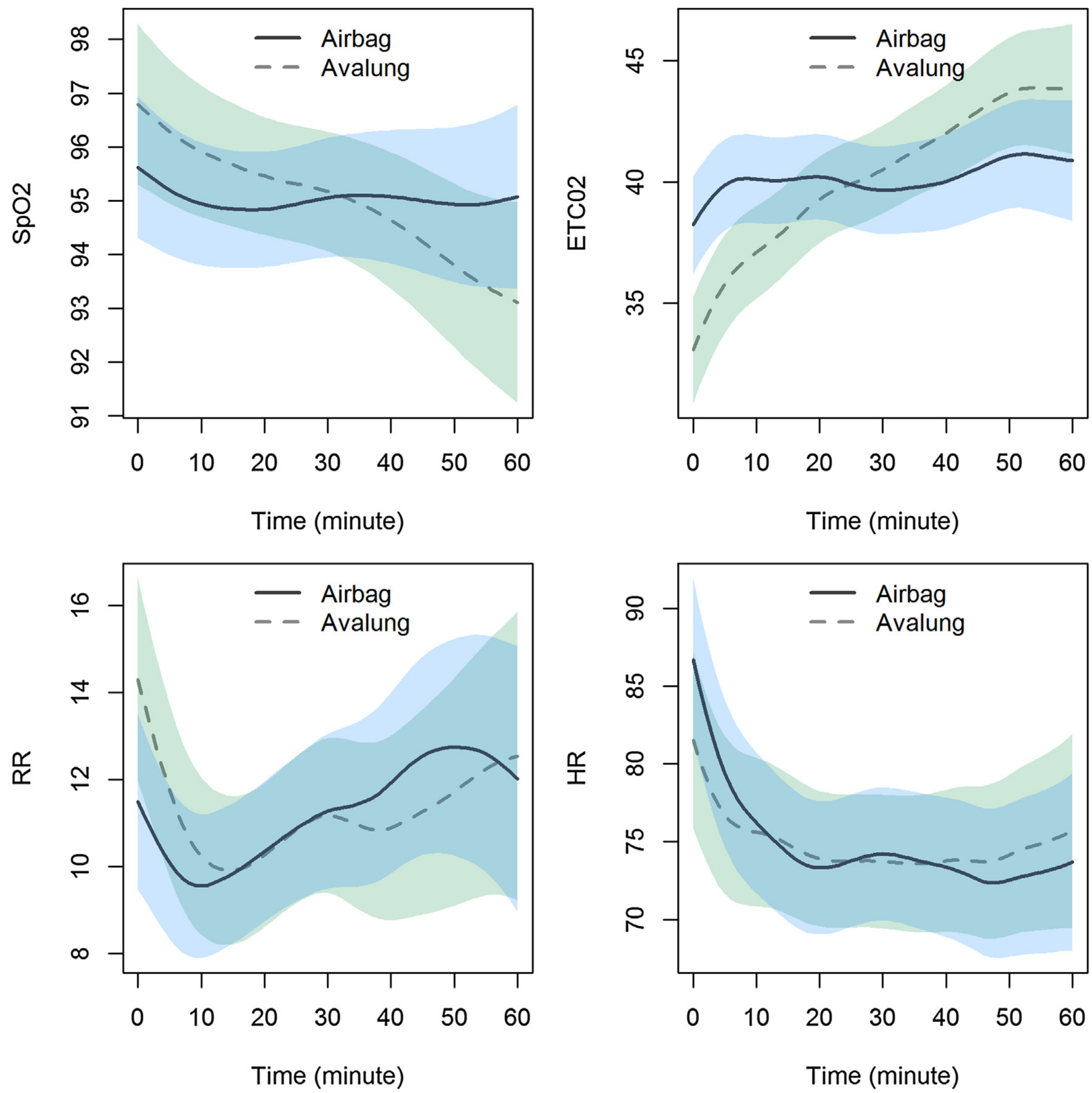

Fig. 4 – Vital sign comparison of data from current study vs historical controls using an inhalation/exhalation separator (Avalung).
Airbag = data from current study; Avalung = data from Grissom et al.[12]. Burial methods of the current avalanche airbag study paralleled those of Grissom with differences in body position, equipment, and participant characteristics.

We defined normal physiological variables as the following: heart rate 60–100 bmp, respiratory rate between 12–20 bpm, SpO2 88–100%, and ETCO2 between 35–45 mmHg. Although the increase in ETCO2 was statistically significant overall, only one ETCO2 value was outside of the normal physiological range at the end of burial. Perhaps the inhalation/exhalation device was not completely within the air pocket or snow fell onto the device during deflation of the airbag. Either of these scenarios could have explained the increase in ETCO2 and respiratory rate observed.

A control arm would consist of similar experimental circumstances with an avalanche airbag that remained inflated for the 60 min of burial, ie a canister-inflated system. We believe that these conditions would be very similar to studies already researched and published of the AvaLung.[12] The only difference between the potential control arm (with continuously inflated airbag) to conditions published by Grissom et al.[12] is that an inflated airbag would occupy much of the potential diffusion space normally occupied by snow. We believe that these conditions would skew the results towards *faster* asphyxiation because the airbag fabric would provide no area for gases to diffuse. We did not study these conditions specifically, however, and would be an area of further research.

Avalanche avoidance strategies are the primary method to stay safe in avalanche terrain. These strategies should employ a foundation of proper avalanche education and good decision-making. Travelers in avalanche terrain should carry essential avalanche gear and be efficient in rescue techniques. Avalanche airbags add a potential layer of safety to the above strategies to prevent burial if one is caught. Avoiding burial via an inflated airbag may be the best possible outcome during an avalanche. In the scenario of critical burial while using an avalanche airbag, the air pocket created by airbag deflation may delay asphyxiation and improve survival.

Limitations

We did not use real time controls as was done in Grissom et al.[12] and relied on historical controls for comparison, allowing us to enroll more participants. These historical controls may not be completely representative of a control group. We placed participants in the prone position with the inhalation/exhalation separator on the posterior of the helmet to simulate inhalation/exhalation in the air pocket. Other burial positions (eg, supine position) might not provide the extent of head movement that would result in communication between the victim's airway and the air pocket. Subsequent studies placing the air exchange device anteriorly nearer to the subject's airway could examine this more fully. In addition, other positions or burial circumstances in which a victim did not have a mouthpiece, tubing, and one-way valve housing could result in rebreathing of expired air in front of their mouth which would significantly decrease time to asphyxiation.

Conclusions

Avalanche airbags have the potential to keep a victim on top of the avalanche debris, thereby preventing critical burial and improving survival. Even when avalanche airbags are deployed correctly, however, approximately 20% of victims are critically buried. The avalanche airbag under study appears to create a large air pocket after actively deflating 3 min after deployment. Results from our study indicate that victims may be able to maintain normal physiology for 60 min if the airway is not obstructed and head movement allows access to the air pocket. This study should be repeated with different body positions to determine if head movement can access the air pocket in other scenarios. Airway impaction and other variables not tested in this experimental setting should be considered and caution heeded when translating our results to real avalanche burials.

Conflict of interest statement

The authors have no financial relationship to Black Diamond Equipment, Ltd. The company supplied snow safety equipment, including airbags, for the study but did not provide any other equipment or funding. Black Diamond Equipment, Ltd. did not review the manuscript prior to submission. None of the authors are financially involved in the production or sale of avalanche airbags nor have they received any related grants, stock ownership, or patents.

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