ORIGINAL RESEARCH

Normal oxygenation and ventilation during snow burial by the exclusion of exhaled carbon dioxide

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Objective.—To confirm that the accumulation of exhaled carbon dioxide (CO₂) is the principal cause of nonmechanical asphyxiation during avalanche burial by demonstrating that complete exclusion of exhaled CO₂ during experimental snow burial results in normal oxygenation and ventilation utilizing the air within the snowpack.

Methods.—In the experimental group, 8 healthy volunteers (mean age 32 years, range 19–44 years) were fully buried up to 90 minutes in compacted snow with a density ranging from 300 to 680 kg/m³ at an elevation of 2385 m. The 6 men and 2 women breathed directly from the snow utilizing a device containing no air pocket around the inhalation intake, in addition to an extended exhalation tube running completely out of the snowpack to remove all exhaled CO₂. Continuous physiologic monitoring included oxygen saturation, end-tidal CO₂, inspired CO₂, electrocardiogram, rectal core temperature, and respiratory rate. As controls, 5 of the 8 subjects repeated the study protocol breathing directly into a small, fist-sized air pocket with no CO₂ removal device.

Results.—In the experimental group, the mean burial time was 88 minutes, despite the absence of an air pocket. No significant changes occurred in any physiologic parameters in this group compared to baseline values. In contrast, the controls remained buried for a mean of 10 minutes ($P = .003$) and became significantly hypercapnic ($P < .01$) and hypoxic ($P < .02$).

Conclusions.—There is sufficient oxygen contained within a densified snowpack comparable to avalanche debris to sustain normal oxygenation and ventilation for at least 90 minutes during snow burial if exhaled CO₂ is removed. The prolonged oxygenation observed during CO₂ exclusion is irrespective of the presence of an air pocket.

Key words: snow burial, asphyxiation, displacement asphyxia, carbon dioxide, avalanche

Introduction

Carbon dioxide (CO₂), produced as a consequence of cellular respiration and exhaled as an inert gas, has long been recognized as an asphyxiant if rapidly accumulated in poorly ventilated areas, such as mines or silos.¹ Its contribution in asphyxiation during avalanche burial, on the other hand, has been poorly appreciated and remained uninvestigated prior to recent work by our group that suggested a principal role of CO₂ in nonmechanical asphyxiation after snow burial.² Furthermore, our experience with the artificial air pocket vest (AvaLung,

Black Diamond Equipment Ltd, Salt Lake City, UT), a device that diverts exhaled CO₂ away from the inspired air during snow burial, revealed that the air pocket is not as critical for normal oxygenation as is the diversion of CO₂. We hypothesized that there is sufficient oxygen in snow of similar density to avalanche debris to support normal oxygenation and ventilation, independent of an air space, if CO₂ is completely removed from the burial environment.

Methods

The subjects were healthy paid volunteers (6 men and 2 women), 19 to 44 years of age (mean age 32 years), who were experienced backcountry enthusiasts and climbers comfortable with the winter environment. Each

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subject was studied physiologically immediately prior to snow burial as a baseline. Measurements were made breathing ambient air and included oxygen saturation by pulse oximetry (SpO₂), end-tidal CO₂ (ETCO₂), inspired CO₂ (PICO₂), respiratory rate, electrocardiogram, and core body temperature by deep rectal probe. Subjects were allowed a clear liquid breakfast and were clothed in mid-weight synthetic underwear under a 1-piece Gortex shell with hood, goggles, face mask, hat, warm gloves, and boots. The experimental setup consisted of a large mound of snow that was boot-packed and age-hardened to a density consistent with avalanche debris. Snow density was measured using a 250-cm³ wedge density cutter (Snowmetrics, Ft Collins, CO) and reported in kg/m³. An average of 3 readings from various areas of the inner pit walls and the snow used to complete the burial was recorded. The density range of 300 to 680 kg/m³ (mean 370 kg/m³) was consistent with known avalanche deposition densities that typically range from 300 kg/m³ for a moderate dry snow avalanche to 600 kg/m³ for a wet snow avalanche.³ A shoulder-width trench was dug into the mound and a platform created to seat the subject during burial.

Each subject breathed via a modified version of a commercially available artificial air pocket vest (Avalung), a device that allows a person to breathe air contained in snow through a mouthpiece connected to a self-contained plastic 500-cm³ air pocket. Expired air passes through a separate circuit by 1-way valves and exits around the back, away from the air pocket. Modifications of the device used by the experimental group included removal of the artificial air pocket, leaving only the inhalation intake orifice (surface area 4 cm²) in direct contact with the snow. In addition to the absence of an air pocket, the expiratory tubing was extended, running completely out of the snowpack to remove all exhaled CO₂ (Figure 1). Physiologic parameters were observed continuously and were recorded every minute, including SpO₂, ETCO₂, PICO₂, respiratory rate, electrocardiogram, and core body temperature.

Burial time 0 was recorded when the head was completely covered by the compacted snow, which was carefully and tightly placed to avoid air channels. The snow was then piled over the subject and hand packed to achieve a depth to the head of 30 to 100 cm (Figure 2). The planned study duration of 90 minutes could be aborted at the subject's request or if the SpO₂ fell below 84% or core body temperature dropped below 35°C.

Subjects communicated with the surface team via an intercom buried next to the face. Safety precautions available at the site included advanced airway management equipment and resuscitative medications. An emergency oxygen backup line was attached to the device

Figure 1. The experimental device utilized to exclude exhaled CO₂ from the surrounding snowpack while inhaling directly from the snow. The subject breathes in and out through the mouthpiece while capnometers (A, B) record PICO₂, ETCO₂, and respiratory rate. Inhaled air enters through the mesh-protected orifice (E) where an emergency oxygen line is attached to the system (C). A series of 1-way valves (D) diverts exhaled air through a separate circuit out of the snowpack via an extended tube (F). The subject and device are tightly buried in place without an air pocket. In contrast, the control device lacked D and F, with the subjects breathing into a 500-cm³ air pocket surrounding E.

mouthpiece and could immediately deliver 15 L/min of 100% oxygen to the buried subject.

As controls, 5 of the 8 subjects repeated the study protocol without the CO₂ removal circuit on the device, breathing directly through the mouthpiece and tubing into an approximately 500-cm³ air pocket in the snow (surface area 290 cm²). Three subjects did not wish to perform control burials, which typically followed the experimental burial. The same member of the surface team consistently formed the air pocket by creating a void in

the snowpack during burial around his clenched fist that measured an approximate volume of 500 cm³. Control studies were terminated at the subject's request or if the SpO₂ fell below 84% or core body temperature dropped below 35°C.

The study site was located in the Wasatch Mountains of Utah at 2385 m elevation. Written informed consent was obtained from each of the volunteers, and the LDS Hospital Research and Human Rights Committee approved the study.

Baseline measurements were compared to end-study data by Mann-Whitney *U* test. Experimental end-study data also were compared to control end-study measurements by Mann-Whitney *U* test. Statistica (StatSoft, 1999 edition, Tulsa, OK) was used for all statistical analysis. A *P* value less than .05 was considered statistically significant. Data are reported as means and ranges.

Results

All but 1 of the 6 men and 2 women were able to remain buried for the entire 90-minute experimental period (mean 88 minutes, range 73–90 minutes). One male subject dropped below our threshold for core body temperature of 35°C and was removed at 73 minutes with an end-study SpO₂ of 96%. No respiratory symptomatology developed in this group, and physiologically there were no significant changes in the respiratory parameters compared to baseline (Table 1). In marked contrast, however, the control group remained buried for a significantly shorter mean of 10 minutes, with a range of 4 to 19 minutes (*P* = .003), as they rapidly became hypercapnic and experienced symptoms of headache, panic, breathlessness, and agitation. These symptoms resulted in the subjects' request to be removed prior to reaching physiologic endpoints in 3 out of the 5 control burials. Objectively, a significant drop in oxygen saturation was observed in this group compared to the prolonged normal oxygenation that characterized the normocapnic (experimental) burials (*P* = .004) (Figure 3). In no instance was an ice lens found surrounding the air pocket of the control group subjects during removal from snow burial.

Statistical comparisons examining baseline versus end-study values for both groups are presented in Table 2. No statistically significant changes in mean SpO₂, PICO₂, or ETco₂ were noted in the experimental group from baseline to end-study values, while in the control (hypercapnic) group, a significant drop in mean oxygen saturation (*P* < .02) and increases in mean CO₂ indices (*P* < .01) were observed.

Core body temperature decreased at a mean rate of 0.7°C/h (range 0.3–1.7°C/h), extrapolated from 90 min-

Figure 2. The compacted snow mound with a subject in sitting position partially extricated after completed burial.

utes of burial. Mild to moderate subjective shivering was present in most of the experimental subjects by the end of the burial, and only 1 subject described violent sustained shivering.

Discussion

Survival data from the United States and Europe demonstrate that asphyxia occurs swiftly after burial and accounts for up to 80% of all avalanche deaths.^{4–6} However, there are dramatic reports of survival after prolonged burials, which are consistently related to the presence of a large air space or channel. Avalanche snow debris, although highly compacted and densified, still contains 40% to 60% air, which can be breathed after burial. The lifesaving air space functions as a gas exchange environment involving the air-snow interface, where oxygen and CO₂ move across the porous surface by diffusion.

When the physical properties of the surrounding

Figure 3. Mean values and ranges for SpO₂ versus burial time. Mean values and ranges are shown for oxygen saturation (SpO₂) at baseline with subjects breathing ambient air, during device burials (CO₂ exclusion), and during control burials. Some ranges toward the end of the control burial are missing because of subject dropout (burial times of 4–19 minutes, mean 10 minutes).

snowpack impair diffusion, CO₂ will accumulate and function as an asphyxiant in a closed space, resulting in hypoxia. In addition, if an ice lens forms on the interface as a consequence of the freezing of exhaled moisture, diffusion ceases and asphyxia is rapidly accelerated.

In a preliminary study,⁷ the effect of restricting gaseous exchange between the air space and snowpack was examined. Mesh bowls functioned as “open” air spaces compared to plastic bowls, which were effective “closed” or noncommunicating spaces, both of known size and volume. In both open and closed systems, the larger the air space, the longer the time to critical oxygen desaturation, supporting previously empiric assumptions. More importantly, the open air spaces allowed considerably longer oxygenation than the closed spaces for any given size and volume, suggesting that gaseous communication with the snowpack is a vital dynamic for adequate respiration during snow burial.

Such communication allows diffusion of oxygen into the air space and CO₂ out to the snowpack to proceed across their respective concentration gradients, probably affected by such variables as the porosity, temperature, water content, and structural characteristics of the sur-

rounding snow. In addition, the localized warmth generated during live burial, which could enhance diffusion and vapor gradients, may augment gas movement. Eventually, the snow becomes saturated with CO₂ as production exceeds diffusion, and deleterious effects of hypercapnia commence. Any impedance to diffusion of CO₂ away from the air space, such as creation of an ice lens or low-porosity snow,⁸ will accelerate this buildup. Likewise, a process that enhances diffusion, such as the greater surface area of a large air pocket, will retard hypercapnia.

A rapidly lethal condition develops when a high concentration of an inert gas is present in an enclosed space due to its ability to displace oxygen from the inspired air. The term *displacement asphyxia* characterizes this mechanism⁹ and involves the progressive crowding of the partial pressure of oxygen by the addition of an asphyxiant such as methane, nitrogen, or CO₂. Clinical entities involving CO₂ include poorly ventilated brewery vats or silos, combustion of firedamp in coal mining, and large-scale volcanic emission clouds.¹ A recent report attributed death of a cross country skier to this mechanism after falling into a “snow well” contaminated by

Table 1. Baseline versus end-study data for experimental and control groups*

Subject No.	SpO ₂ , %		ETCO ₂ , mm Hg		PiCO ₂ , mm Hg		RR, breaths/min		Burial time, minutes
	Baseline	End	Baseline	End	Baseline	End	Baseline	End	
Experimental (CO ₂ exclusion) group									
1	95	93	40	45			9	7	90
2	98	99	39	35	3	4	14	12	90
3	92	96	41	37			9	9	73
4	94	97	37	36	0	4	9	5	90
5	96	95	43	38	9	10	12	8	90
6	96	96	42	28	6	9	10	8	90
7	95	96	43	41	4	5	7	12	90
8	92	96	32	30	4	5	19	19	90
Control group									
1	95	83	34	53	2	44	22	33	11
2	97	84	33	53	2	43	13	61	10
4	94	76	37	57	0	38	9	13	4
5	96	79	43	70	9	56	14	32	5
8	92	93	32	61	4	41	20	39	19

*SpO₂ indicates oxygen saturation as measured by pulse oximetry; ETCO₂, end-tidal carbon dioxide; PiCO₂, partial pressure of inspired carbon dioxide; and RR, respiration rate.

Table 2. Baseline versus end-study means in experimental (CO₂ exclusion) and control groups*

Subjects	Mean burial time, min (range)	Baseline mean SpO ₂ , %	End study mean SpO ₂ , %	Baseline mean PICO ₂ , mm Hg	End study mean PICO ₂ , mm Hg	Baseline mean ETCO ₂ , mm Hg	End study mean ETCO ₂ , mm Hg
Experimental (n = 8)	88† (73–90)	95	96‡	4	6§	40	36
		<i>P</i> = .17		<i>P</i> = .23		<i>P</i> = .14	
Controls (n = 5)	10† (4–19)	95	83‡	3	44§	36	59
		<i>P</i> < .02		<i>P</i> < .01		<i>P</i> < .01	

*Baseline means are compared with end-study means in the experimental and control groups for oxygen saturation (SpO₂), partial pressure of inspired CO₂ (PiCO₂), and end-tidal CO₂ (ETCO₂).

†*P* = .003.

‡*P* = .004.

§*P* = .006.

||*P* = .003.

locally high levels of CO₂ from underlying volcanic emission.¹⁰

After snow burial, as exhaled CO₂ accumulates in the surrounding snowpack, gaseous displacement of oxygen results in a progressively hypoxic burial environment. Our previous data² suggest that this is the predominant effect of CO₂ after avalanche burial and that, according to the alveolar gas equation, a critical degree of arterial hypoxemia will occur before hypercapnia is severe enough to cause CO₂ narcosis (PaCO₂ ≥ 70 mm Hg).¹¹ This process would be expected to occur more rapidly at higher altitudes.

In this study, we have effectively isolated the contribution of CO₂ to the asphyxiation process by removing it completely as a variable from our experimental snow burial model. The sustained normal oxygenation consistently observed during CO₂ exclusion, as compared to the rapid hypoxia seen in hypercapnic control subjects, confirms that there is sufficient oxygen available in the dense snow similar to avalanche debris to sustain adequate respiration for prolonged periods during burial.

Interestingly, the control subjects quickly became hypercapnic, and 4 of 5 became hypoxic despite a small air pocket, whereas during the normocapnic experimental burials, they remained normoxic without any air pocket. Therefore, it appears that the lifesaving air space does not enhance oxygen extraction from the snow, but rather promotes removal of CO₂ from the immediate respiratory environment. An increased surface area for enhanced diffusion may be the mechanism that operates in an adequately sized air space, but this remains to be determined.

The control burials likely demonstrate physiologic responses that simulate those occurring during actual avalanche burial. Understandably, these data are derived

from a controlled experimental setup that excludes asphyxiation from mechanical chest compression, airway obstruction, and awkward positioning, in addition to the physiologic effects of trauma and preburial struggle. However, the obvious limitations due to safety concerns mandate an extrapolation of our findings as the best nearest approximation from which to draw conclusions.

The importance of slowing the rate of hypercapnia was previously confirmed during physiologic trials with the artificial air pocket vest, which diverts CO₂ away from the inhalation circuit, thereby delaying hypercapnia and hypoxia for up to an hour. The present data suggest that complete removal of CO₂ from the burial environment, which can be accomplished by a scrubbing agent in the exhalation circuitry of the artificial air pocket vest, would greatly prolong adequate oxygenation using this device.

We conclude that in our experimental simulation of avalanche burial, there is sufficient oxygen in the densified snowpack comparable to avalanche debris to sustain normal oxygenation and ventilation for at least 90 minutes if exhaled CO₂ is removed. Remarkably, as no air pocket was necessary for the prolonged oxygenation observed during CO₂ removal, the function of the air pocket in extending survival after avalanche burial is likely in its ability to accommodate increased levels of exhaled CO₂ or by enhancing egress of CO₂ into the snowpack by diffusion. Hopefully, these results will help stimulate the development of improved survival devices designed to eliminate exhaled CO₂ after snow burial.

References

1. Hamilton A, Hardy HL. *Industrial Toxicology*. 3rd ed. Acton, MA: Publishing Sciences Group; 1974:235–237, 263–269.

2. Grissom CK, Radwin MI, Harmston CH, Hirshberg E, Crowley TJ. Respiration during snow burial using an artificial air pocket. *JAMA*. 2000;283:2266–2271.
3. McClung D, Schaerer P. *The Avalanche Handbook*. Seattle, WA: Mountaineers; 1993:115.
4. Logan N, Atkins D. *The Snowy Torrents: Avalanche Accidents in the United States 1980–1986*. Denver, CO: Colorado Geological Survey; 1996:240–243.
5. Falk M, Brugger H, Adler-Kastner L. Avalanche survival chances. *Nature*. 1994;368:21.
6. Grossman MD, Saffle JR, Thomas F, Tremper B. Avalanche trauma. *J Trauma*. 1989;29:1705–1709.
7. Radwin MI, Keyes L, Radwin DL. Avalanche air space physiology. In: *Proceedings of 1998 International Snow Science Workshop*. Seattle, WA: Washington State Department of Transportation; September 27–October 1, 1998; Sunriver, OR. 1998:296.
8. Sommerfeld RA, Mosier AR, Musselman RC. CO₂, CH₄, N₂O flux through a Wyoming snowpack and implications for global budgets. *Nature*. 1993;361:140–142.
9. Baum GL, Wolinsky E. *Textbook of Pulmonary Diseases*. Vol 1. 5th ed. New York, NY: Little, Brown & Co; 1993: 901–906.
10. Hill PM. Possible asphyxiation from carbon dioxide of a cross-country skier in eastern California: a deadly volcanic hazard. *Wilderness Environ Med*. 2000;11:192–195.
11. Nunn JF. *Applied Respiratory Physiology*. 3rd ed. London, England: Butterworths; 1987:226, 475.