PROLONGED OXYGENATION DURING SNOW BURIAL; THE ROLE OF CARBON DIOXIDE EXCLUSION

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ABSTRACT: Asphyxiation, the cause of death in more than seventy five percent avalanche burial victims, is greatly accelerated by the rapid accumulation of exhaled carbon dioxide in the surrounding air space and snowpack. We hypothesized that complete exclusion of exhaled carbon dioxide during snow burial would allow prolonged oxygenation utilizing the air within the snowpack. Eight healthy volunteers were fully buried for greater than 90 minutes in compacted snow with a density ranging from 300-680kg/m^3 at an elevation of 2560m. The 6 men and 2 women breathed on a device containing no air pocket around the inhalation intake and a greatly extended exhalation tube running completely out of the snowpack to remove all exhaled carbon dioxide. Continuous physiologic monitoring included oxygen saturation (SpO2 %), end-tidal CO2 (ETCO2 in mmHg), inspired CO2 (PICO2 in mmHg), ECG, core temperature and respiratory rate. As controls, we studied 5 matched subjects under identical conditions breathing into a small fist-sized air pocket but no carbon dioxide removal device. In the experimental group, the mean burial time was 89 minutes despite the absence of an air pocket. No significant changes occurred in any physiologic parameters in this group compared to baseline. In contrast, the controls remained buried for a mean 10 minutes and became significantly hypercapnic and hypoxic. We conclude that there is sufficient oxygen in a densified snowpack comparable to avalanche debris to sustain normal oxygenation and ventilation for at least 90 minutes during snow burial if exhaled CO_2 is removed.

KEYWORDS: Snow Burial, Asphyxiation, Carbon Dioxide

1. INTRODUCTION

Carbon Dioxide, an inert gas exhaled as a byproduct of carbohydrate metabolism, has long been recognized as a simple asphyxiant if rapidly accumulated in poorly ventilated areas such as mines or silos (Hamilton 1974). Its relative contribution during asphyxiation after avalanche burial, on the other hand, has been poorly appreciated and to date uninvestigated. Preliminary work by our group suggested a principle role of carbon dioxide in non-mechanical asphyxiation after snow burial (Grissom 2000). Furthermore, exclusion of carbon dioxide from our experimental burial model resulted in prolonged normal oxygenation even in the complete absence of an air space for up to an hour. We hypothesized that there is sufficient oxygen in snow consistent with avalanche debris to support prolonged oxygenation, independent of an air space, if carbon dioxide is completely removed.

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2. METHODS

Eight healthy volunteers (6 males and 2 females), ages 19-44, were physiologically studied immediately prior to burial as a baseline. Measurements were made breathing ambient air and included: oxygen saturation (SpO_2 in %), end tidal CO_2 ($ETCO_2$ in mm Hg), inspired CO_2 ($PICO_2$ in mm Hg), respiratory rate, ECG and core body temperature by deep rectal probe. They were allowed a clear liquid breakfast and were clothed in light weight synthetic underwear under a one-piece shell with a hat, face mask, warm gloves and boots. The subjects were seated into the burial trench, which was fashioned out of an age and boot hardened mound of snow. The density range was 300-680 kg/m^3 as determined by an average of three readings from various areas of the inner pit walls and the snow used to complete the burial. A 250-cc wedge density cutter (Snowmetrics, Ft Collins, CO) measured snow density.

Each subject breathed on a modified artificial air pocket device (AvaLung™, Black Diamond Equip. Ltd., Salt Lake City, Utah) in which the air pocket was removed with only mesh covering the inhalation intake. In addition, the expiratory tubing was greatly extended running completely out of the snowpack to remove all exhaled carbon dioxide. Continuous physiologic monitoring was performed including: SpO_2, $ETCO_2$, $PICO_2$, respiratory rate, ECG and core body temperature.

The burial was initiated at time zero when the device was completely covered by the compacted snow which was carefully and tightly placed to avoid air channels. The snow was then piled over to achieve a depth to the head of 30-100cm. The planned study duration of 90 minutes could be aborted at the subject's request or if the SpO_2 fell below 80%.

Communication with the subjects was accomplished by the use of an intercom. Safety precautions included advanced airway management equipment and resuscitative medications. An emergency oxygen backup line was attached to the device mouthpiece and could immediately deliver 15 L/min of 100% oxygen to the buried subject.

Control burials were performed on 5 matched subjects under identical conditions and monitoring except for breathing into a fist-sized air pocket with no carbon dioxide removal device utilized. The control burials were terminated at the subject's request or if the SpO_2 fell below 80%.

The study site was located in the Wasatch Mountains of Utah at 2560m 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 were compared to control end study measurements by Mann-Whitney U test. Statistica (StatSoft, 1999 edition, Tulsa, Okla) was used for all statistical analysis. $P<0.05$ was considered statistically significant. Data were reported as means.

3. RESULTS

All but one of the 6 men and 2 women were able to remain buried for the entire 90 minute experimental period (mean 89 minutes). One male subject dropped below our cutoff for core body temperature of 35° C and was removed at 73 minutes with an end study SpO_2 of 96%. No symptomatology developed in this group and physiologically there were no significant changes in the respiratory parameters followed compared to baseline (Table 1).

In marked contrast, however, the control group could only remained buried for a significantly shorter mean of 10 minutes ($p=0.003$), as they were rapidly overcome by hypercapnia with its attendant symptomatology of headache, panic, breathlessness, and agitation. This resulted in the subjects' frequent request to be removed prior to reaching physiologic endpoints.

Objectively, a precipitous drop in oxygen saturation was observed in this group compared to the prolonged normal oxygenation that characterized their matched normocapnic (experimental) burials (Fig 1).

TABLE 1. Baseline vs. End Study Values

A. Experimental Group

subject #	SpO_2 %		$ETCO_2$ mm Hg		$PICO_2$ mm Hg		Tc °C
	Baseline	End	Baseline	End	Baseline	End	°C/ hr
1	95	93	40	45			-0.6
2	98	99	39	35	3	4	-0.6
3	92	96	41	37			-1.7
4	94	97	37	36	0	4	-0.5
5	96	95	43	38	9	10	-0.3
6	96	96	42	28	6	9	-0.8
7	95	96	43	41	4	5	-0.4
8	92	96	32	30	4	5	-0.5

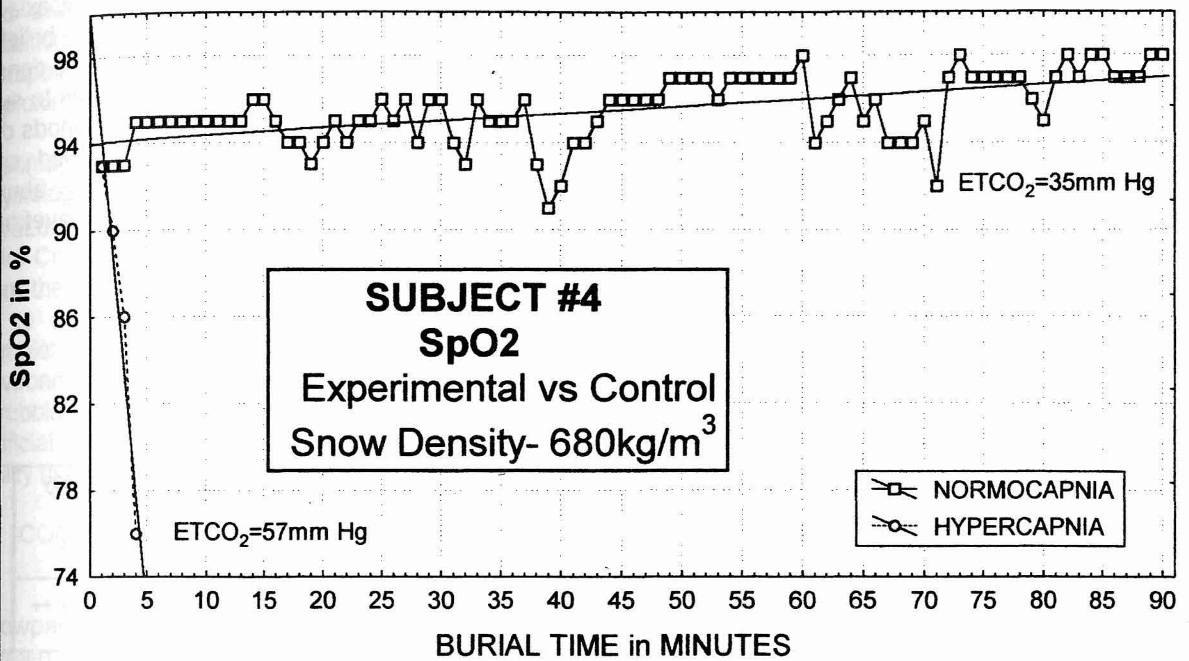
B. Control Group

subject #	SpO_2 %		$ETCO_2$ mm Hg		$PICO_2$ mm Hg	
	Baseline	End	Baseline	End	Baseline	End
1	95	83	34	53	2	44
2	97	84	33	53	2	43
4	94	76	37	57	0	38
5	96	79	43	70	9	56
8	92	93	32	61	4	41

Statistical comparisons of baseline vs. end study and end study vs. end study means are presented in Table 2. No statistically significant changes in mean SpO_2, $PICO_2$, or $ETCO_2$ were noted in the experimental group while in the control (hypercapnic) group a significant drop in mean oxygen saturation and increases in mean carbon dioxide indices were observed.

space functions as a gas exchange environment involving the air-snow interface where oxygen and carbon dioxide freely move by simple diffusion. The deposition snowpack, although highly compacted and densified, contains abundant air that is readily available for adequate respiration. Exchange of gases will continue as long as the

FIGURE 1. Example of Carbon Dioxide's Effect on Oxygen Saturation



Core body temperature decreased at a mean rate of 0.7°C/hr with a range of 0.3-1.7°C/hr extrapolated from 90 minutes of burial. Mild to moderate subjective shivering was present in most of the experimental subjects by the end of the burial and only one subject described violent sustained shivering.

4. COMMENTS

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 (Logan 1996, Falk 1994). Dramatic reports of survival after prolonged burials are consistently related to the presence of a large air space or channel. The life-saving air interface remains porous.

However, once an ice lens forms on the interface as a consequence of the freezing of exhaled moisture, diffusion ceases and death ensues rapidly.

In a preliminary study (Radwin 1998), 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 non-communicating spaces, both of known size and volume. Within both groups, 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 carbon dioxide out to the snowpack to proceed across their respective concentration gradients affected by the porosity, temperature, water content and structural aberrations of the surrounding snow. Eventually, the snow becomes saturated with carbon dioxide as production exceeds diffusion and deleterious effects of hypercapnia commence. Any impedance to diffusion of CO2 away from the air space, such as ice lensing or low porosity snow (Sommerfeld 1993), will accelerate this build up. Likewise, a process that enhances diffusion, such as the greater surface area of a large air pocket, will retard hypercapnia.

with asphyxia occurring rapidly as the concentration rises in the surrounding snowpack prior to levels high enough to produce death from stupor and coma, known as "CO_2 narcosis."

In this study, we have effectively isolated the contribution of carbon dioxide to the asphyxiative process by removing it completely as a variable from our experimental snow burial model. The sustained normal oxygenation consistently observed during carbon dioxide exclusion as compared to the rapid hypoxia seen in hypercapnic controls, confirms our belief that there is sufficient oxygen available in the dense snow associated with avalanche debris to sustain adequate respiration for prolonged periods during burial. However, accumulating exhaled carbon dioxide prevents utilization of the abundant oxygen in the snow by an advancing wavefront of

TABLE 2. Baseline vs. End Study Means in Experimental 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	89 * (73-100)	95	96 +	4	6 **	40	36 ++
		p=0.17		p=0.23		p=0.14	
Controls N=5	10 * (4-19)	95	83 +	3	44**	36	59 ++
		p<0.02		p<0.01		p<0.01	

* p=0.003 + p=0.004 ** p=0.006 ++ p=0.003

The most significant deleterious effect encountered with high concentrations of an inert gas in an enclosed space is its ability to displace oxygen from the inspired air. The term "displacement asphyxia" characterizes this mechanism (Baum 1993) and involves the progressive crowding of the partial pressure of oxygen by the addition of a simple asphyxiant such as carbon dioxide. Our previous data (Grissom 2000) suggests that this is the predominant effect of carbon dioxide after burial, gaseous displacement, effectively diluting the oxygen concentration in the adjacent burial environment.

Interestingly, the matched controls quickly became hypercapnic and hypoxic despite a small air pocket, whereas during the normocapnic experimental burials, they remained normoxic without an air space. Therefore, it appears that the life-saving air space does not play a role in the ability to extract oxygen from the snow, but rather may be more involved in removing carbon dioxide 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 demonstrated 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. However, the obvious limitations due to safety concerns mandate an extrapolation of our findings as the best nearest approximation from which we can work.

The importance of slowing the rate of hypercapnia was previously confirmed during physiologic trials with the artificial air pocket vest (AvaLung™, Black Diamond Equipment, Ltd., Salt Lake City, Utah) which diverts carbon dioxide away from the inhalation circuit thereby delaying hypoxia up to an hour. The present data suggests that complete removal of carbon dioxide from the burial environment, such as can be accomplished by a scrubbing agent in the exhalation circuitry of the artificial air pocket vest, would greatly prolong the ability to oxygenate using this device.

5. CONCLUSIONS

There is sufficient oxygen in a densified snowpack comparable to avalanche debris to sustain normal oxygenation and ventilation for at least 90 minutes during snow burial if exhaled CO_2 is removed. Remarkably, as no air pocket was necessary for the prolonged oxygenation observed during CO_2 removal, the function of the air pocket in extending survival after avalanche burial is likely in its ability to accommodate increased levels of exhaled CO_2 or by enhancing egress into the snowpack by diffusion.

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