O_2 AND CO_2 LEVELS WITH THE BLACK DIAMOND AVALUNG DURING HUMAN SNOW BURIALS LASTING UP TO ONE HOUR

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ABSTRACT: The patented AvaLung aims to permit an avalanche victim to breathe the air contained in snow. Hypotheses: (1) Human blood O_2 saturation will be about equal across four tests: open-atmosphere breathing through the mouthpiece only, open-atmosphere breathing through an AvaLung, breathing during head-out snow burials, and breathing during full burial. (2) Across those tests CO_2 concentrations will remain about equal. Methods: Three highly conditioned males, 30 - 40 years old, consented to testing at Mt. Hood, Oregon, (2225 m altitude). Snow density was 600-610 kg/m^3. Burials were 0.3 - 1 m deep at the chest. Testers measured pulse and respiratory rates, blood O_2 saturation, and CO_2 concentration of inhaled and exhaled air. Intercoms permitted tester-subject communication. Results: Two subjects' blood O_2 saturation remained over 90 % through full burials of 10 and 63 minutes, respectively, supporting Hypothesis 1. A third subject breathed without problem, although saturation fell to 81 % during 45 minutes of full burial; a valve apparently had malfunctioned in his prototype AvaLung. Regarding Hypothesis 2, CO_2 in inhaled air rose from 0% during mouthpiece-only breathing to 0.8 - 1.2 % with AvaLung breathing in open atmosphere, a minor deadspace effect. During burials inhaled CO_2 reached 4.9% in two subjects, and 6.6% in the subject with the malfunction. Pulse rates were elevated during burials, probably reflecting anxiety. Conclusions: The prototype AvaLung supported life through burials of usually-fatal duration. O_2 availability was excellent. Results suggested slow accumulation of CO_2 around buried subjects.

KEYWORDS: Avalanche accidents, Avalanche safety, Avalanche rescue, Snow permeability.
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1. INTRODUCTION

It is estimated that two-thirds of avalanche victims die of suffocation (Armstrong, 1992). The probability of survival is over 90 percent for victims dug out within 15 minutes, but after burials of 35 minutes, Falk et al. (1994) note that 70 percent will be dead. Those authors state that an "essential step would be to develop self-help techniques to facilitate creation of a life-saving air pocket, which would give the skier a relatively safe haven for about 90 minutes".

The patented AvaLung, intended to achieve that aim by allowing a buried person to breathe the air contained in snow for an extended period, may be built into a vest or parka.

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The user breathes through a mouthpiece at the collar, and tubing and valves direct air within the garment. One cloth panel on the garment filters fresh air for inhalation from the snow in front of the victim, and a similar panel deposits exhaled air into the snow behind the victim. The AvaLung's design, and its successful function during one 40-minute burial of a volunteer, have been described briefly in scientific (Crowley, 1996) and popular (Riordan, 1996; Soloman, 1996; Hicks, 1996) publications. However, no reports have examined respiratory physiology during test burials with the AvaLung.

The first goal of this study was to assess the ability of AvaLung prototypes to sustain adequate O_2 supplies for human burials of up to one hour. We hypothesized that human blood O_2 saturation would be about equal across four tests: open-atmosphere breathing through the mouthpiece only (OAMO), open-atmosphere breathing through an AvaLung (OAAL), breathing through the AvaLung during head-out snow burials (HOAL), and breathing through the AvaLung during full burials (FBAL). Our second goal was to assess the ability of AvaLung prototypes to minimize rebreathing of exhaled CO_2 during burials of up to one hour. We hypothesized that across those same four tests CO_2 concentration in *exhaled* air would remain about equal, and that similarly, for each subject, CO_2 concentration in *inhaled* air would remain about equal across those tests. We also aimed to record psychological and physical responses of buried volunteers, and to give the development team personal experience in AvaLung-supported burials.

2. METHODS

2.1 Setting and Subjects. Testing was in a snow-filled ravine of Mt. Hood, Oregon, on a south-facing slope above timberline and exposed to full sun at approximately 2225 m altitude. This late-August snow was composed of ovoid ice crystals, estimated 1-2 mm size, which had undergone natural, firm compaction. Density, in repeated measures (Winter Engineering field densitometer) in the wall of two snow pits was 60 % water, or 600 kg m^{-3}. When snow was removed and then packed back into pits, density still was 60 - 61% in multiple measures. Skills among the seven-member team included two design and production specialists, a quality-control engineer, a consulting design engineer, a research-development engineer for anesthesia equipment, a psychiatrist-inventor, and an internal medicine specialist. Three other observers also were present.

2.2 Test Subjects. Safety Arrangements. Three volunteers were selected, based on their involvement in the AvaLung's development and on their high level of athletic training and endurance. Subjects reviewed, modified, and then approved, test protocols. They also provided signed, informed consent to participate. A physician in each subject's home town assured that the subject was mentally and physically qualified for this testing. In the field another physician, not associated with the development of the product, examined each subject's heart and lungs just prior to full-burial tests. This physician monitored incoming data and was authorized to terminate testing at any time. Resuscitation equipment was available.

To minimize spread of communicable diseases, each subject used an AvaLung which had not been used by others. These AvaLungs were modified, so that a T-tube tapped into the AvaLung's tubing just below the mouthpiece, from whence it led to the snow's surface. This tube was sealed at its surface end. In an emergency the surface crew could remove that seal, permitting inhalation through the T-tube of surface air or of supplied, concentrated O_2.

2.3 Assessments.

2.31 Finger pulse oximetry. For the four tests each subject wore an oximetry sensor (Datex-Ohmeda, Denver, Colo.) on one finger under heavy mittens which kept the hands warm. An electrical lead about 2 m long ran to a hand-held, battery-powered Datex-Ohmeda Model 3770 pulse oximeter. It provided continuous digital readings of blood O_2 saturation (% of arterial hemoglobin bound to O_2) and of pulse rate (beats/min.).

2.32 CO2 concentration. One end of a small-bore sampling tube (about 3 mm OD, about 2 m long) was sealed into the AvaLung tubing between the mouthpiece and the first valve. It continuously sampled both inhaled and exhaled air passing through the AvaLung tubing. The other end of the sampling tube was attached to a capnometer (BCI International, Waukesha, Wisc., Model 8200), which gave digital readings of both end-of-exhalation (end-tidal) CO_2 in mm Hg, and of respiratory rate (a moving average of the last four breaths). The capnometer further showed the CO_2 concentration of inhaled air, with a resolution of about 5 mm Hg. The capnometer was calibrated at the test site, using a BCI gas standard (10 percent CO_2 = 61 mm Hg partial pressure of CO_2). The capnometer pump drew 140 ml of air per min from the AvaLung tubing, via the sampling tubing. Because of water condensation in the sampling tubing, in some experiments two sample tubes were placed in the AvaLung tubing. One was sealed until the other became water-clogged; then the first was sealed and the second was opened.

2.33 Verbal comments. During the FBAL tests intercom systems (Radio Shack) allowed continuous communication between subject and test team. The buried intercom was placed in a plastic bag in the snow about 5 cm from the subject's mouth. An identical back-up system was similarly placed. Also, in the first moments after

FBAL tests ended the team informally debriefed the subject, noting relevant comments. Finally, subjects provided written comments on their experience a few days after testing.

2.4 Test Procedures.

2.41 Open atmosphere breathing through mouthpiece only (OAMO). Subjects, wearing an obstructive noseclip, breathed outdoor air through an AvaLung mouthpiece (about 1.5 cm ID, about 3 cm long) for several minutes. Pulse oximetry and CO_2 measures were continuously obtained, except that Subject B's pulse and O_2 data for this test were lost. The CO_2 sampling tube was taped inside the mouthpiece. This test provided baseline information on pulse, respiratory rates, O_2 saturation, and inspired and expired CO_2 levels for these subjects at this altitude and site, as they concentrated on breathing through a mouthpiece.

2.42 Open atmosphere breathing through AvaLung (OAAL). The three subjects, each wearing an obstructive noseclip, breathed outdoor air through an AvaLung for several minutes. Pulse oximetry and capnometry were continuously obtained. Compared to the OAMO test, the OAAL test would show whether the dead space of the AvaLung (tubing containing just-exhaled air which would be inhaled at the next breath) increased the level of inhaled CO_2, and whether such increases of inhaled CO_2 would change the body's CO_2 level (as reflected in exhaled CO_2). The OAAL test also would show whether subjects experienced any problem, such as a need for forced breathing, with the prototype AvaLungs.

2.43 During Head-Out burial, breathing from the snow through the AvaLung (HOAL). Subjects, wearing an obstructive noseclip and multiple layers of very heavy clothing, were buried to the chin for 30 minutes in well-packed snow which fully covered the AvaLung. Breathing only through the AvaLung, they inhaled air only from the snow; all exhaled air went back into the snow. Pulse oximetry and CO_2 measures were continuously obtained. Compared to the OAAL, the HOAL test would show: (1) Whether the AvaLung extracts sufficient air from the snow to maintain adequate blood O_2 saturation. (2) Whether some CO_2 is rebreathed, due to migration of CO_2 from AvaLung's exhalation membrane to its inhalation membrane, via the snow or the user's garments. (3) Whether such an increase in inhaled CO_2 would change the body's CO_2 level (as reflected in exhaled CO_2).

2.44 AvaLung breathing in Full Burial (FBAL). These tests were done on the day following the first three tests. The subjects, heavily dressed and wearing skiers' goggles and facemasks, but without noseclips, were fully buried beneath well-packed snow, breathing only through the AvaLung. All subjects used the same pit, although its sides and bottom were scrapped back somewhat for successive tests. The FBAL test would show whether an unrecognized leak of air from the surface (e.g., around the neck and down to the AvaLung) had been responsible for any favorable outcomes in HOAL tests. It also would extend the physiological findings from the briefer HOAL tests: (1) During a longer test would the AvaLung extract sufficient air from the snow to maintain adequate blood O_2 saturation? (2) In longer tests would inhaled CO_2 rise due to inhalation of CO_2 which had migrated through the snow from AvaLung's exhalation membrane to the inhalation membrane? (3) In longer tests would such increases in inhaled CO_2 change the body's CO_2 level (as reflected in exhaled CO_2)? The FBAL test also could show whether the weight of this dense snow would restrict breathing by limiting chest movement. Finally, the test could provide initial information on psychological responses to full burial, information that might help in preparing directions for the use of the AvaLung.

3. RESULTS

3.1 Subject C (Figure 1). Subject C assumed a seated position for both the HOAL and the FBAL. The AvaLung was about 1 m beneath the surface in the FBAL.

3.11 Oxygen Saturation, Pulse and Respiration Rates. Subject C's O_2 saturation remained between 93 - 97 percent while breathing open atmosphere either through the mouthpiece (OAMO) alone or through the AvaLung (OAAL), as well as during both head-out (HOAL) and full burials (FBAL) while breathing through the snow. His FBAL test continued for 60 minutes, the maximum planned duration. This highly trained athlete reported that his resting pulse rate was 39 beats per min (bpm), and his rate ranged from 57 - 68 bpm during OAMO, OAAL, and HOAL. However, during FBAL it rose, ranging from 66 - 85 bpm. Similarly, in the first three tests his respiratory

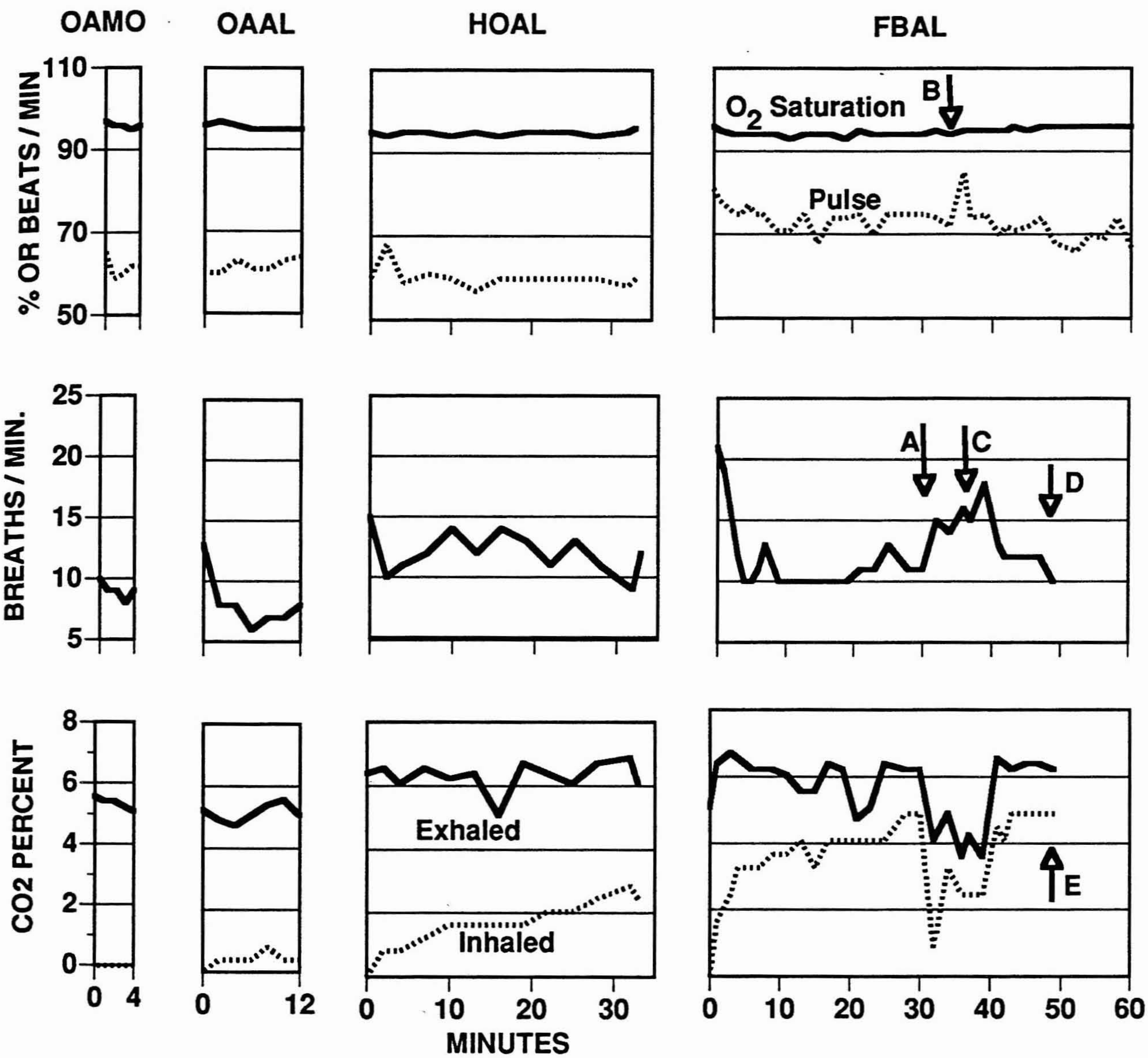

Figure 1. Subject C: Arterial blood oxygen saturation, pulse rate, respiration rate, end-tidal (end-of-exhalation) carbon dioxide concentration, and carbon dioxide concentration of inhaled air. Vertical axes do not all originate at zero. In each row (L to R): OAMO: Breathing in open atmosphere, nose blocked, through mouthpiece only. OAAL: Breathing in open atmosphere, nose blocked, through AvaLung. HOAL: Head-out burial, nose blocked, breathing entirely through buried AvaLung. FBAL: Full burial, breathing entirely through AvaLung . Arrows: A, instructed by surface team to take some deep breaths. B, 35 minutes, the time when 70 % of avalanche victims are expected to be dead (Falk, 1994). C, subject makes joke, laughs. D and E, data lost due to limitations of the monitoring equipment.

rate ranged from 6 - 15 breaths per minute, but it ranged from 10 - 21 breaths per minute during full burial.

3.12 Inhaled and Exhaled CO_2 Levels. During the baseline OAMO and OAAL, CO_2 comprised 4.8 - 5.6 percent of the exhaled (end-tidal) air. However, it ranged as high as 6.9 percent during HOAL. Levels above 6.0 percent generally continued during FBAL, but then dropped very sharply 30 - 40 minutes into that test when Subject C breathed more rapidly and laughed.

As expected, the CO_2 concentration of inhaled atmospheric air was measured at zero during the baseline OAMO, and it rose slightly (maximum 0.8 percent) during OAAL, probably due to the small dead space of the AvaLung tubing. However, the CO_2 concentration of inhaled air rose very steadily to 2.9 percent during HOAL, and it rose even more quickly to 4.9 percent during full burial. Interestingly, as the exhaled CO_2 concentration fell after about 30 minutes of full burial, the inhaled CO_2 concentration also fell.

3.13 Behavioral Responses and Verbal Comments. Subject C later said that the HOAL "Provided the first dramatic insight into the severity of being caught in an avalanche. A snow depth of just a few inches prevented any movement whatsoever. Small packing forces around the chest and neck collapsed lung expansion areas. Movements of a quarter inch were impossible". Regarding the FBAL, he later noted, "When I first got buried, I tried to keep good posture, but the weight of the snow and the packing literally compressed my spine, slumping me over. It was impossible to take a full, deep breath from this position". Subject C employed a meditation-like strategy; he later joked that he used "Zen and the Art of Elective Burial". He requested that the surface intercom communicator not bother him with too many questions because having to respond broke up his rhythmic breathing. His communications to the surface were calm and controlled, and at about 38 minutes into FBAL he made a very funny joking comment about Subject B. As the builder of the AvaLung, Subject C had recognized that during his full burial one inhalation valve had a high cracking pressure, but that the other still permitted almost effortless air flow. He also reported trying to breathe around the mouthpiece into the snow, as an unprepared avalanche victim would; he could barely move air then, and it made him feel "woozy". He later said, "Several times I had to really concentrate and relax. Any small doubt quickly escalated to total paranoia. The trick for me seemed to be to minimize these spells. I had the feeling several times of being outside my body, seeing myself in the seated position encased in cement through the snow from above. And it was not a good visual to have. The word claustrophobia was not allowed into my head". Despite his heavy clothing, his feet were cold toward the end of the FBAL.

3.14 Condensation, Ice-Mask Formation. There was moderate formation of droplets within the AvaLung tubing following the HOAL and FBAL. A small area of uniquely dense snow, estimated at 5 - 8 cm diameter, was found near the exhalation membrane after FBAL. It was not, however, icy hard.

3.2 Subject A (Figure 2). This subject was seated for the HOAL but prone for the FBAL. The AvaLung was about 0.3 m below the surface in the FBAL.

3.21 Oxygen Saturation, Pulse and Respiration Rates. Data on O_2 saturation and pulse rates were not available for OAMO, but saturation was 96 - 99 percent during OAAL and HOAL tests. It was 92 - 98 percent during FBAL. Pulse rates ranged from 66 - 82 bpm during OAAL and HOAL, but became extremely variable and much higher during FBAL, ranging then from 77 - 110. Respiration rates ranged from 10 - 17 breaths per minute during the first three tests. However, like pulse, respiration rates rose and varied considerably during FBAL, ranging from 15 - 24.

3.22 Inhaled and Exhaled CO_2 Levels. Subject A's concentration of exhaled CO_2 showed the expected inverse relationship with respiration rate. Across all four tests when he breathed more rapidly he "blew off" CO_2, and the level in exhaled air fell; when he breathed more slowly, CO_2 accumulated in the body and the level in exhaled air rose.

As with Subject C, CO_2 levels in the inhaled air of Subject A were near zero in the OAMO test and rose slightly during the OAAL test, probably due to dead space. Also like Subject C, Subject A's inhaled CO_2 level rose considerably during the two burial tests. Interestingly, that rise apparently was suppressed by rapid breathing in the first moments of the FBAL.

3.23 Behavioral Responses and Verbal Comments. Subject A complained of

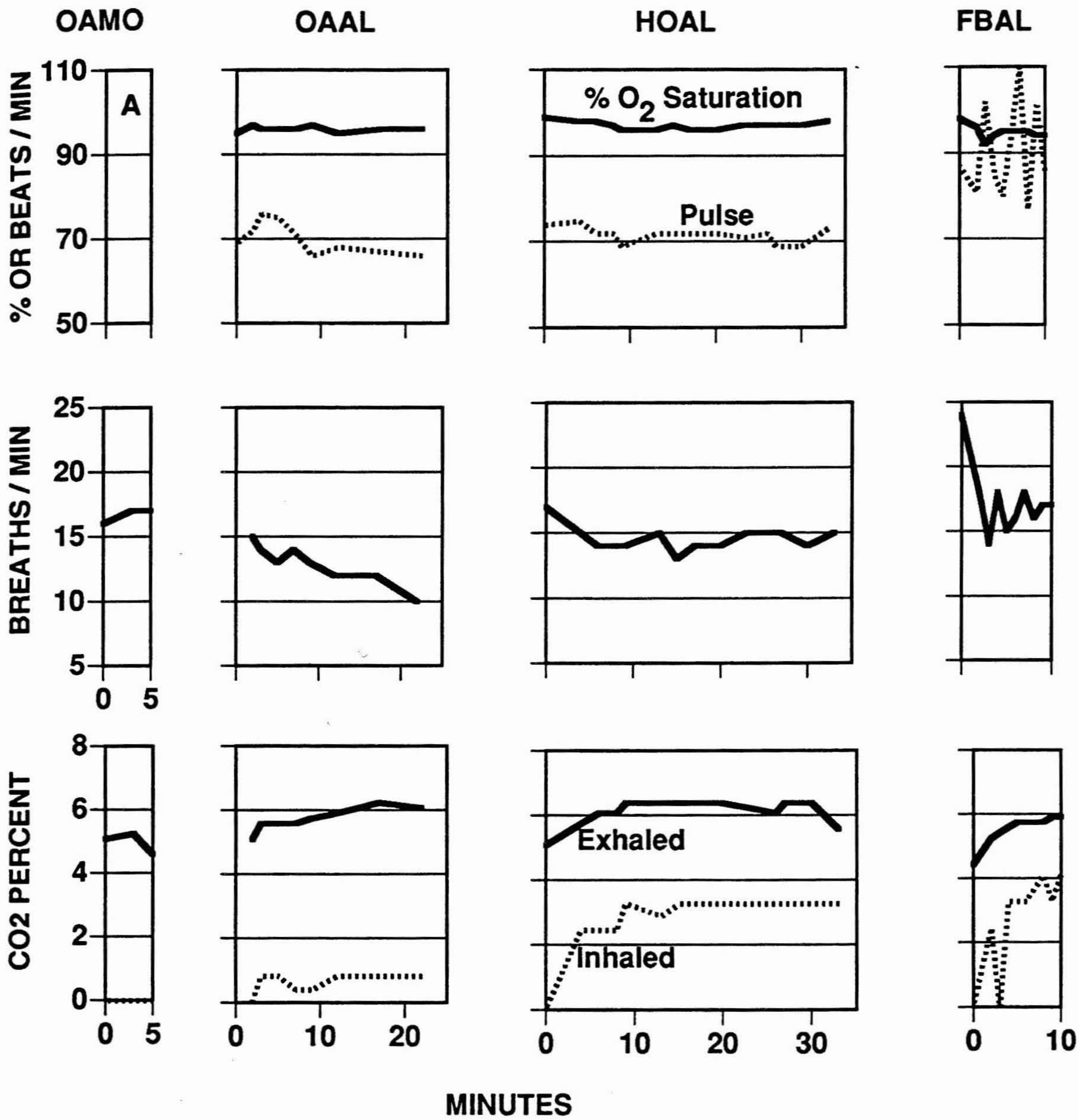

Figure 2. Subject A: Layout and data as in Figure 1. Note A, Pulse and O_2 saturation data not available for the mouthpiece-only test.

lightheadedness and tingling in the extremities after the OAAL test, strongly suggesting that he had hyperventilated and excessively reduced his blood CO_2 level. Subject A became quite anxious during FBAL. During debriefing he stated that, in a prone position, melting snow trickled into his nose. He said, "Having to swallow caused my breathing patterns to change, which is partly why I think my heart rate went up and down. The fact that I was scared as hell made my heart rate jump around too, I'm sure." In addition he experienced very unpleasant illusions of movement, with a sense that his feet slowly had risen above the level of his head, and that he had been slowly rolled onto one

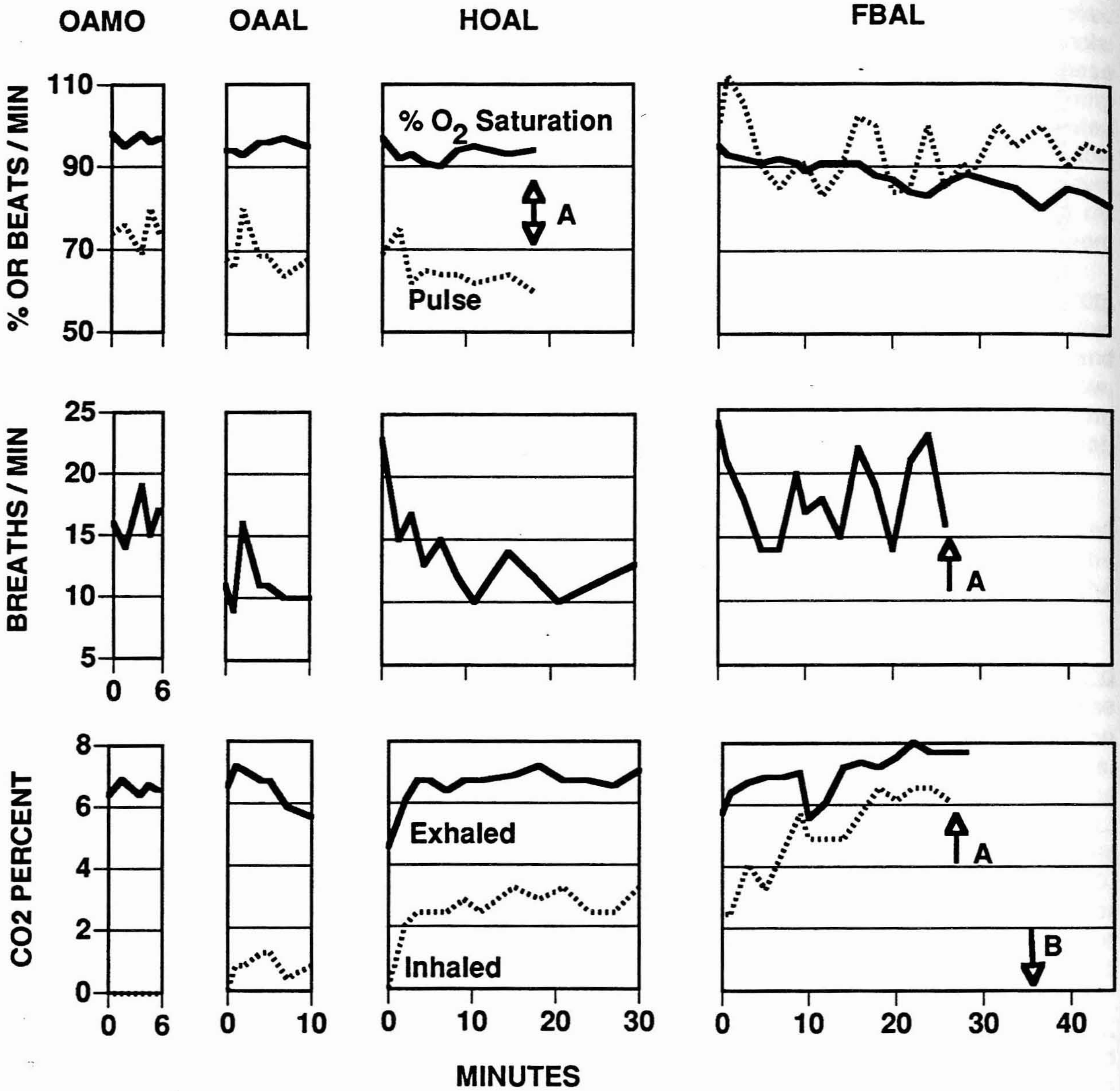

Figure 3. Subject B: Layout and data as in Figure 1. Notes: A, Data lost due to problem with monitoring equipment. B, 35 minutes, the time when 70 % of avalanche victims are expected to be dead (Falk, 1994).

side. He requested to be dug out after 10 minutes of FBAL. He later said that he had had "claustrophobia" in childhood.

3.24 Condensation, Ice-Mask Formation. A moderate amount of moisture droplets, but no icing, was found in the AvaLung tubing after Subject A's HOAL and FBAL tests. As with Subject C, a small area of increased firmness, but no true ice, was found in the snow adjacent to the exhalation membrane.

3.3 Subject B (Figure 3). Subject B was in a seated position for both the HOAL and FBAL. His AvaLung was about 1 m below the surface during the FBAL.

3.31 Oxygen Saturation, Pulse and Respiration Rates. Blood oxygen saturation ranged from 93 - 98 percent during OAMO and OAAL tests, and from 90 - 97 % during the HOAL test. However, during the FBAL test, O_2 saturation slowly declined from 95 to 81 percent, the latter value being considerably lower than any from Subjects C and A. Pulse rates ranged from 60 - 80 bpm during the first three tests, but rose dramatically and varied widely in the FBAL test, ranging then from 81 to 112 bpm. Like Subject B, but unlike Subject C, Subject A breathed relatively rapidly during the baseline OAMO test (range 14 - 19 breaths per minute), and like A, B's breathing slowed during the OAAL test (range 9 - 16 breaths per minute). Subject B breathed very rapidly at the beginning of the HOAL test (25 breaths per minute), but the rate then fell as low as 10 breaths per minute. However, rapid breathing at the beginning of the FBAL (24 breaths per min) was followed by several more peaks of rapid breathing through the rest of that test.

3.32 Inhaled and Exhaled CO_2 Levels. Of the three subjects, Subject B had the highest levels of exhaled CO_2 during the OAMO and OAAL baseline tests, ranging from 5.6 to 7.2 percent. The concentration of exhaled CO_2 was less at the beginning of the HOAL test when the respiration rate was elevated, but as respirations slowed the exhaled CO_2 rose to a high of 7.2 percent. During FBAL the exhaled CO_2 concentration rose even higher, peaking at 8.0 percent shortly before a frozen sample line ended the CO_2 data collection.

The inhaled CO_2 concentration showed the now-familiar pattern of zero readings during OAMO, small rises during OAAL, and increases to a maximum of 3.3 percent during HOAL. Subject B's increase in inhaled CO_2 during FBAL exceeded that of the other subjects, peaking at 6.6 percent before the data collection ended. An interesting pattern seen in the others also occurred in Subject B. About 10 minutes into FBAL his respirations increased in frequency, and both inhaled and exhaled CO_2 levels briefly declined. However, later peaking of the respiration rate during FBAL did not reduce CO_2 concentrations.

Careful inspection of Subject B's AvaLung after the FBAL test revealed one valve that was stuck in a partially-open position. This may have contributed to the decline in O_2 saturation and elevations of CO_2 during the FBAL, but it could not explain why Subject B already had CO_2 levels in the baseline OAMO test that were higher than those of the other subjects.

3.33 Behavioral Responses and Verbal Comments. Subject B felt "compressed" when packed into the snow in the HOAL test. He said of the snow piled above his head in the FBAL test, "When the snow was first put on my head, I could feel my spine compressing, and I thought, 'This is really heavy s--t'". It was clear that he was referring both to the weight of the snow and the seriousness of the FBAL test. During that test he asked the intercom communicator to speak to him frequently. Three times, while buried, he said "I'm really scared", but chose to continue the test. Then, after 45 minutes of FBAL, he asked to be dug free. At that time, because of the declining O_2 saturation and the elevated CO_2 levels, the surface team opened the safety tube, passing concentrated O_2 down it until the subject was uncovered. The O_2 saturation then rose within seconds to 100 percent (data not shown).

3.34 Condensation, Ice-Mask Formation. There was no ice-mask after the burial tests for Subject B. However, condensation may have amounted to 5 -10 ml (estimated), distributed in non-frozen droplets over the inner surface of the AvaLung's tubing.

4. DISCUSSION

4.1 Main Findings.

4.11 The AvaLung supported life during full burials of usually-fatal duration. Subjects C and B, respectively, were buried for 63 and 45 minutes. Neither showed any confusion, disorientation, lethargy, nor other signs of respiratory insufficiency. Subject C told a funny joke after 38 minutes of full burial. Subject C also tried to breathe through the snow around the AvaLung mouthpiece; he found this almost impossible. Others have shown that 70 percent of unprotected persons buried in snow are dead after 35 minutes (Falk, 1994).

4.12 Blood O_2 saturation remained in the normal range for two, and acceptable for one, subject in these burial tests. The saturation levels reported here may be compared to those of a healthy person acclimated to sea level (Guyton, 1996). That person will have an O_2 saturation of 97 percent at home. If the person ascends in an airplane without supplemental oxygen to about 3700 m (12,000 ft) the O_2 saturation will fall to 87 percent, and drowsiness, fatigue, headache, and nausea will appear. At about 5550 m (18,000 ft) the O_2 saturation will be 74 percent, and twitches and seizures may occur. At about 7100 m (23,000 ft), with an O_2 saturation of 50 percent, the person may lapse into coma.

Our subjects all maintained O_2 saturations of 90 percent or more during the HOAL test, in which all of their breathing was through the snow. O_2 saturation of two subjects remained above 90 percent during full burial tests of 10 and 63 minutes, respectively. The third subject's O_2 saturation fell to 81 percent during a full burial of 45 minutes duration. Although our subjects were acclimated to vigorous athletic activity at and above our test altitude of 2225 m, it appears nearly impossible that these O_2 saturation levels could have been maintained without the support of the AvaLung.

4.13 CO_2 concentrations rose more than expected, but remained in a range acceptable for relatively brief exposures. The body can "buffer" a considerable amount of inhaled CO_2. That is, the body can absorb much inhaled CO_2 before the level of exhaled CO_2 rises. But if exhaled CO_2 does rise significantly, the compound is quite toxic (Guyton, 1996). For example, CO_2 comprises only 0.04 percent of inhaled air, but it normally makes up about 5.3 percent of exhaled breath. If the CO_2 level of exhaled air rises to 9 percent, one experiences strong "air hunger" and rapid breathing. At 12 percent one becomes lethargic and semicomatose, and at 17 percent coma and death occur. We recorded exhaled CO_2 levels between 3.6 and 8.0 percent during six HOAL and FBAL tests. Without the AvaLung these burials almost certainly would have produced much higher CO_2 levels.

The rise of inhaled CO_2 concentrations during burials could have at least two causes. First, CO_2 may migrate (either by diffusion or active pumping) from the exhalation membrane to the inhalation membrane through the snow or the user's clothing. Second, a complete or partial valve failure could lead to rebreathing of exhaled air. We did find evidence of a partial valve failure in the AvaLung of Subject B.

We were surprised to see suggestions in data from all three subjects that more rapid breathing (presumably moving greater volumes of air) reduced the CO_2 concentration of inhaled, as well as exhaled, air. Again, at least two explanations are possible. First, CO_2 migrating from the exhalation chamber would establish some concentration in snow near the inhalation chamber. High-volume inhalation could temporarily empty that CO_2 reservoir. Second, certain valve malfunctions could increase the AvaLung's effective dead space. High-volume breathing would reduce that effect, since the ratio of dead space volume to tidal volume would partially determine CO_2 accumulation rates in the body.

CO_2 is not simply a respiratory waste product. It is extremely important for maintaining the body's acid-base balance. Special brain chemoreceptors respond to rising levels of carbonic acid (a CO_2 product), and they are believed to motivate people to leave environments with excessive atmospheric CO_2 (Krystal, 1996).

Indeed, inhalation of 5 - 7 percent CO_2 for 20 minutes may induce panic attacks in vulnerable individuals (Gorman, 1994). Two of our subjects reported considerable anxiety during their FBAL tests. However, their pulse and respiration rates were markedly elevated in the first moments of the test, suggesting that the burial experience, rather than CO_2, produced their anxiety. However, prolonged breathing of more than 5 percent CO_2 could induce panic attacks in vulnerable AvaLung users. Unfortunately, once buried, those users' only available alternative to the AvaLung might be fatal respiratory insufficiency. However, a challenge for Avalung's designers must be to minimize rising CO_2 levels in inhaled air.

4.14 Ice-mask formation was not problematic in these tests. True ice layers did not form, perhaps because moisture condensed in the AvaLung tubing before it could be deposited in the snow. Moreover, an ice mask may not interfere with exhalation. Presumably, an avalanche victim could expel "bubbles" of air between the facial skin and a tight-fitting ice mask. The problem would arise on inhalation; inhalation's negative pressure would only draw the skin more firmly against the ice, assuring no air entry. Since the AvaLung separates the site for inhalation from the site for exhalation, it may obviate the problem of ice masks.

4.15 No subject complained of a need for forced breathing. Back pressures and low flow rates were not problems with these prototype AvaLungs. Their gas exchange membranes were sufficiently large to easily draw from the snow, and place back into it, the approximately 500 ml of air moved during each resting breath.

4.2 Limitations of the AvaLung. Despite generally favorable results in these tests, the findings have important limitations. First, one-third of avalanche deaths are from trauma (Armstrong, 1992); this device will not help victims crushed against trees or rocks. Second, the AvaLung user must place the mouthpiece into the mouth; that may be difficult for a terrified person being swept down a mountainside. Third, in some circumstances the post-slide pressure of the snow may prevent any chest movement for breathing; the AvaLung cannot help then. However, even without AvaLungs some people do survive for many minutes or a few hours (Falk, 1994). Those survivors did breathe, and AvaLungs might help more people survive. Fourth, although the snow for these tests was very dense, the different crystal structure of avalanche debris suggests a need for further testing in avalanche conditions.

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