CLINICAL UPDATES IN WILDERNESS MEDICINE

Technological Advances in Avalanche Survival

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Over the last decade, a proliferation of interest has emerged in the area of avalanche survival, yielding both an improved understanding of the pathophysiology of death after avalanche burial and technological advances in the development of survival equipment. The dismal survival statistics born out of the modern era of winter recreation unmistakably reveal that elapsed time and depth of burial are the most critical variables of survival and the focus of newer survival devices on the market. Although blunt trauma may kill up to one third of avalanche victims, early asphyxiation is the predominant mechanism of death, and hypothermia is rare. A survival plateau or delay in asphyxiation may be seen in those buried in respiratory communication with an air pocket until a critical accumulation of CO₂ or an ice lens develops. The newest survival devices available for adjunctive protection, along with a transceiver and shovel, are the artificial air pocket device (AvaLung), the avalanche air bag system (ABS), and the Avalanche Ball. The artificial air pocket prolongs adequate respiration during snow burial and may improve survival by delaying asphyxiation. The ABS, which forces the wearer to the surface of the avalanche debris by inverse segregation to help prevent burial, has been in use in Europe for the last 10 years with an impressive track record. Finally, the Avalanche Ball is a visual locator device in the form of a spring-loaded ball attached to a tether, which is released from a fanny pack by a rip cord. Despite the excitement surrounding these novel technologies, avalanche avoidance through knowledge and conservative judgment will always be the mainstay of avalanche survival, never to be replaced by any device.

Key words: avalanche, avalanche burial, avalanche survival, displacement asphyxia, carbon dioxide, artificial air pocket device, avalanche air bag system, Avalanche Ball

Fatal avalanche encounters in the United States entered a new era during the postwar period of the 1940s amid an emerging popularity of mountaineering and winter recreation. Since that time, the 5-year moving average of avalanche fatalities has steadily increased in parallel with backcountry usage. Page and colleagues¹ recently reviewed the changing demographics surrounding avalanche deaths in the United States during the last 45 years. The retrospective review of 440 victims revealed an increasing number of deaths among out-of-bounds skiers, backcountry skiers, and snowmobilers, while a marked decrease was noted among groups benefiting from avalanche mitigation such as highway workers, motorists, and in-bound skiers. Similarly, accident data from Switzerland analyzing a period covering 1985–99

confirm a 22% increase in the number of victims due to off-piste or backcountry activities.²

The rapid demise of burial victims confirmed by survival statistics worldwide demonstrates the unmistakable lesson that companion rescue is the only chance for survival after full burial in an avalanche. The introduction of devices such as lightweight shovels, collapsible probes, and avalanche transceivers was aimed at enhancing the probability of a speedy companion recovery; such devices are mandatory safety equipment during backcountry travel in avalanche terrain. More recently, in the United States and Europe, newer, potentially life-saving devices have been introduced into the marketplace, including the artificial air pocket device (AvaLung, Black Diamond Equipment Ltd, Salt Lake City, UT), the avalanche air bag system (ABS; Peter Aschauer, Gräfelting, Germany), and the Avalanche Ball (K2; Vashon Island, WA).

This clinical update examines current concepts re-

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Figure 1. Survival probability curve for completely buried avalanche victims in Switzerland 1981–98. $n = 638$ (solid line) compared with previously published Swiss survival curve, 1981–91, $n = 422$ (dotted line), calculated by Falk et al.⁴

garding the modern challenge of avalanche survival, the pathophysiology of avalanche death, and the newer technologies presently available that may improve survival.

Avalanche survival

Survival data from the United States and Europe indicate that asphyxia occurs rapidly after burial and accounts for up to 80% of all avalanche deaths.^{3,4} Falk et al.^{4,5} performed a computer-enhanced analysis of the Swiss survival experience from 1981 to 1991 involving 421 complete burials.^{4,5} Their landmark findings showed that if recovery is accomplished within 15 minutes of complete burial, 92% will be found alive. However, if 35 minutes elapse before recovery, the survival drops to a dismal 30%. Recently, Falk and Brugger⁶ confirmed identical findings upon a review of the data through 1998 involving 638 complete burials (Figure 1). An alternative analysis of all completely buried individuals over the last 20 years in Switzerland reveals that those who survived were buried for a mean of 11 minutes compared with a mean of 120 minutes for those found dead.⁷ Consequently, the time to extrication is the most critical determinant of survival currently recognized and the paramount consideration facing rescuers. The “golden” 15 minutes after burial leave no time for hesitancy, uncertainty, or panic. Rescue by individuals at the scene of the accident is the only reliable chance for survival, but unfortunately, in unpracticed hands, companion rescue is often inefficient and disorganized.

A retrospective review examining the differences in time to recovery and outcome between professional and recreational companion rescues was recently reported by Atkins.⁸ The study included 60 companion rescues utilizing transceivers in the United States from 1977 to

1998. Organized team rescues were excluded, focusing mainly on companion rescues by patrollers, guides, and rangers compared to backcountry skiers, snowboarders, snowmobilers, and climbers. As expected, the more practiced professionals are 77% faster than recreationalists in the use of transceivers and burial recovery techniques, finding the victim alive 60% of the time compared to only 32% in the recreational group. The mean burial time for professionals was 18 minutes in contrast to 32 minutes for recreationalists. Although limited by the retrospective nature of this analysis, the data provide evidence that recovery time and outcome are inextricably linked and suggest that avalanche rescue training and practice do impart a benefit to survival.

Depth of burial is another critical factor to consider regarding survival. In general, the deeper the victim, the less probability of a live recovery. Although this variable is probably related to the longer time required to uncover a deep burial, an adverse effect on respiratory mechanics may be present because of the massive weight of deep debris. Since initiating the official recording of US survival statistics in 1950, no victim has survived a burial greater than 7 feet.⁹

Dramatic reports of survival after prolonged burial are consistently related to the presence of a large air space or channel. One such case occurred near Invermore, BC, Canada, in January 1960 and involved a 59-year-old highway employee who was buried while acting as an avalanche lookout for a work crew. He was found alive after 25.5 hours with a “washtub”-sized air space around his head.³ More recently, on January 24, 2000, at the resort of Schoppernaut in Austria, a 25-year-old German snowboarder was buried for 20 hours, spending the night before being found by avalanche dogs. Although hypothermic, he too survived because of a large air space between his face and knees. The idea of an air pocket allowing for prolonged survival after burial has been appreciated for many years, although the exact mechanism has not previously been studied. Persons exposed to avalanche risk, if caught, have been emphatically instructed to create an air space in front of their face with one hand as the snow slows to a halt before setting up firmly. Diffusion of oxygen (O_2) and carbon dioxide (CO_2) at the air-snow interface appears to be a critical feature of a life-saving air pocket. The freezing of this interface from moisture in exhaled humidified air forms an ice lens that prevents diffusion of CO_2 and O_2 , thereby precipitating rapid asphyxiation.

A preliminary study¹⁰ investigating the effect of restricting gaseous exchange between the air space and snowpack suggested that such communication is essential for a prolongation of adequate respiration during snow burial, confirming the catastrophic nature of icing

of this interface. Falk et al⁴ have explained that the plateau in survival from 35 to 90 minutes in the Swiss data (Figure 1) is caused by the presence of an air space, allowing adequate respiration until late asphyxia develops after 90 minutes, which is accelerated by the icing of the diffusion interface.

The pathophysiology of avalanche death

The sequence of physiologic events concluding in the death of an avalanche victim has been intuitively drawn from survival data and field observations during recovery procedures. Aside from an earlier autopsy series examining the victims of a large avalanche accident in Norway,¹¹ scientific research seeking to understand the pathophysiology of these events has been deficient in the literature. However, more recent work on human physiology during experimental snow burial has initiated a renewed focus on uncovering specific factors related to the cause of death in avalanche victims.^{10,12–14} The currently acknowledged series of premortal events involves trauma, acute airway obstruction, displacement asphyxiation, and hypothermia. The contribution of chest restriction generated by the compressive forces of snow has been considered.¹¹

TRAUMA

Blunt trauma is incurred during forceful travel within the maelstrom of snow as it carries over rock bands and strains through trees. A retrospective review of avalanche trauma reported by the Utah Avalanche Forecast Center was compared with data from Europe and Canada.¹⁵ During a period from 1982 to 1987, 16% of 91 cases died of multiple trauma in Utah. By comparison, a 10-year European experience in France, Switzerland, Italy, and Austria involving 1447 persons found that 25% died of trauma.¹⁶ Similarly, the Canadian Avalanche Association reported a 26% trauma mortality from 1979 to 1985.¹⁷ In the Utah series, nonsurvivors with multiple trauma typically suffered from craniofacial injuries, multiple rib fractures with pneumothorax or pulmonary contusion, and intraabdominal hemorrhage. One died from a disrupted thoracic aorta discovered at autopsy. Open long bone fractures were common in both survivors and nonsurvivors.

The incidence of closed head injuries (CHI) was recently investigated in a retrospective analysis of medical examiner and hospital records on all avalanche fatalities in Utah from 1992 to 1999.¹⁸ In this review, 28 avalanche-related deaths were identified, 18 of which (61%) had evidence of some degree of CHI on postmortem exam, and 6 of which (21%) had evidence of severe CHI

to a degree that was felt to be either the primary cause of death or a strong contributor. Severe CHI included large scalp lacerations, skull fractures, cerebral contusion, and intracranial hemorrhage. This study makes a strong argument for the use of helmets in backcountry enthusiasts who may be subjected to avalanche trauma.

AIRWAY OBSTRUCTION

The overwhelming majority of avalanche victims succumb to rapid asphyxiation after burial. Throughout the desperate struggle within the churning debris, the inhalation of snow is unavoidable, often resulting in an acute airway obstruction. Snow can fill the oropharynx quickly and completely, occluding the airway as a “snow-plug.” If coughing cannot forcefully expel the plug, rapid asphyxia will ensue. This group of victims probably corresponds to the immediate drop in survival observed in the first 15 minutes of burial.

DISPLACEMENT ASPHYXIA AND CO₂

If breathing mechanics can be established after the snow settles, survival will depend on the size of the air space created either serendipitously or purposely as recommended. In some instances, dense debris may restrict chest movement and contribute to asphyxiation. An insufficient or absent air pocket and the subsequent failure of adequate air exchange with the snow also result in rapid asphyxiation. These factors probably correspond to the precipitous drop in survival observed during the first 30 minutes of burial. Ultimately, even the well-functioning air pocket fails because of the overwhelming contamination of inspired air with CO₂ and ice lens formation at the air-snow interface.

Serious deleterious effects on oxygenation are encountered when a high concentration of an inert gas is introduced into an enclosed space because of its ability to displace O₂ from the inspired air. The term “displacement asphyxia” characterizes this mechanism¹⁹ and involves the progressive crowding of the partial pressure of O₂ by the addition of another gas—in this case, CO₂. After burial, as the air space and surrounding snow become saturated with exhaled CO₂, progressively less O₂ is available because of gaseous displacement, and asphyxia quickly ensues. Any impedance to the diffusion of CO₂ away from the air space, such as with ice lensing or high-density/low-porosity snow,²⁰ will accelerate this process. The diffusion of O₂ and CO₂ proceeds across their respective concentration gradients until the snow becomes saturated with CO₂ as production exceeds diffusion. Finally, the icing of the snow interface complete-

Figure 2. Schematic drawing of the artificial air pocket vest as it is worn over all other clothing. Air from the snow enters the mesh air pocket, **E**, on inspiration flowing through 1-way valves, **D**, to the mouthpiece, **A**, via respiratory tubing. Expired air passes through the tubing to the 1-way expiratory valve, **F**, and then exits out the back of the device, **G**. The capnometer sampling tubing, **B**, and the emergency oxygen (O_2) tubing, **C**, are shown inserted in-line with the respiratory tubing just below the mouthpiece. These attachments were part of the experimental setup used to test the device but are not part of the commercially available product.

ly disrupts gaseous exchange between the air space and snowpack, thereby accelerating asphyxiation.

Additional effects of hypercapnia involve direct actions on the central nervous system. Mild increases in inspired CO_2 may be associated with headache and anxiety, while modest levels can result in visual changes, vertigo, confusion, or somnolence. The hypercapnic stimulation of the respiratory center in the brain increases minute ventilation and causes a profound sensation of breathlessness and tachypnea. Seizures and even coma have been reported at high levels. The term “ CO_2 narcosis” is used to describe the progressive degree of lethargy and central nervous system depression that occurs

with increasing hypercapnia, which, if untreated, results in coma, anesthesia, and death.²¹ However, it appears that in a closed space, asphyxiation due to lethal hypoxemia from displacement precedes CO_2 levels high enough to produce CO_2 narcosis.¹²

Studies from our group show that normal oxygenation and ventilation during experimental snow burial are possible for up to 90 minutes if all expired CO_2 is diverted out of the snowpack, confirming that the accumulation of CO_2 in the snow is the principal cause of nonmechanical asphyxiation during avalanche burial.¹³ We concluded that there is sufficient O_2 in the dense snow associated with avalanche debris to sustain normal oxygenation during burial if CO_2 is removed. The prolonged oxygenation observed during CO_2 exclusion was accomplished directly from the snow, breathing through a mouthpiece without the presence of an air pocket. These findings suggest that the life-saving air space does not enhance O_2 extraction from the snow but rather, promotes removal of CO_2 from the immediate respiratory environment.

CHEST RESTRICTION

An autopsy study by Stalsberg and colleagues,¹¹ which investigated multiple deaths in 2 large avalanches in North-Norway in the mid-1980s involving very dense maritime snowpacks, concluded that the common mechanism of death was generalized body compression from the force of the snow. Although the proposed mechanism was highly speculative, the phenomenon of external chest compression from settling debris compromising respiratory motion is a possible contributor to asphyxia in many cases, especially when the snow is exceptionally dense.

The newer survival devices

THE ARTIFICIAL AIR POCKET DEVICE (AvaLung)

Background

Born out of the ingenuity and dedication of Denver physician and inventor Dr Thomas Crowley, including the bravery of his own experimental burial,²² the artificial air pocket (AvaLung) has evolved.

The original device was designed as an externally worn vest, with the artificial air pocket built into the left front panel and accessed by the user through a mouthpiece in the lapel (Figure 2). This simple respiratory device functions by enabling the extraction of air from the surrounding snowpack during inspiration while diverting exhaled CO_2 away from the air pocket to delay hyper-

capnia. A series of 1-way valves accomplishes these actions via a circuit of respiratory tubing from the plastic air pocket to the mouthpiece during inspiration and out to the back of the vest during exhalation. The mouthpiece may be stowed or held in place between the lips or teeth while working in high-risk areas or may be alternatively positioned for ready use at the side of the mouth.

Another significant benefit observed during the separation of exhaled from inhaled air is the prevention of ice lens formation around the air pocket by the shunting of warmer, humidified exhaled air away from the air-snow interface.

Several concerns regarding the breathing device were repeatedly expressed after its introduction into the marketplace and will require further field experience for adequate answers. First, the ability to place and maintain the mouthpiece during an avalanche was seriously questioned. Second, skeptics felt that such a piece of equipment in the wrong hands would be a license for foolish risk taking. Finally, some critics stress that the primary goal of any avalanche rescue device should be the avoidance of burial and not the prolongation of survival time, which accepts complete burial with all of its risks.

A newer version of the device recently released to the marketplace incorporates a smaller air pocket box and valve system into a compact, externally worn harness for easier wear and use (Figure 3). The more compact version will be similar to wearing a transceiver harness, which will allow more acceptable usage among avalanche professionals and backcountry enthusiasts.

Physiologic trials

Preliminary experience with the artificial air pocket vest during the experimental burial of 3 subjects was acquired in August 1998 at Mount Hood.²³ The winter of 1998–99 offered an opportunity for our group to conduct rigorous physiologic testing of the vest in differing densities of dry intermountain snow.¹² Densification of the snow by compaction into a large mound, trenched out for the burial pit, enabled the examination of densities

Figure 3. AvaLung 2. **A**, The new version of the artificial air pocket device is worn as a harness over all other clothing. **B**, Schematic drawing of the artificial air pocket harness. Air from the snow enters the air pocket box, **D**, on inspiration passing through a 1-way valve into the respiratory tubing to the mouthpiece. Expired air travels back to the box, passes through the 1-way expiratory valve, and exits out the back of the device, **E**. The capnometer sampling tubing, **B**, **C**, and

emergency oxygen (O_2) tubing, **A**, are shown inserted in-line with the respiratory tubing just below the mouthpiece. These attachments were part of the experimental setup used to test the device but are not part of the commercially available product.

in the range of 300 to 600 kg/m.³ The oxygenation and ventilation of 8 subjects, fully buried in a sitting position, were examined while they breathed on the artificial air pocket device for up to 60 minutes. Measurements included O₂ saturation by pulse oximetry (SpO₂), heart rate, respiratory rate, inspired CO₂ (PiCO₂), and end-tidal CO₂ (E_TCO₂), both during a preburial baseline and throughout burial with the device. As controls, 7 of the same subjects were studied under identical burial conditions while breathing into a similarly sized air space (500 mL) but without the vest. The burials were terminated at the subject's request, at 60 minutes, or if the SpO₂ dropped below 85%.

Mean burial time was 58 minutes (45–60) with the breathing device and 10 minutes (5–14) in the control group ($P = .001$). The mean baseline SpO₂ of 96% (90–99) decreased to 90% (77–96) with the device ($P = .012$) and to 84% (79–92) in the control burials ($P = .018$). Mean baseline E_TCO₂ of 32 mm Hg (27–38) increased to 45 mm Hg (32–53) in the artificial air pocket burials ($P = .018$) and to 54 mm Hg (44–63) in the controls ($P = .018$). Respiratory rate and heart rate did not change while using the breathing vest, but both significantly increased in the controls.

We concluded that breathing with the artificial air pocket vest during snow burial maintains adequate oxygenation for up to 60 minutes compared to breathing with a similarly sized air space, which results in hypoxemia within 5 to 14 minutes. In addition, compared to the control group, breathing with the device markedly increased the time required to reach a clinically significant degree of hypercapnia. As previously discussed, any slowing of the development of hypercapnia will necessarily delay the onset of hypoxia and asphyxia.

Since that preliminary report, we have conducted additional tests with the artificial air pocket on a total of 14 subjects and 11 controls; these tests have revealed identical findings and conclusions.²⁴

Case reports

Two well-substantiated reports exist regarding the actual use of the emergency breathing device in avalanches.²⁵ In April 2000, a helicopter ski guide in Alaska ventured onto a slab that broke free shortly after dropoff. He was wearing the vest with the mouthpiece stowed in the collar but was able to access the mouthpiece and maintain it in his mouth during the slide and subsequent burial at 100-cm depth. Luckily, the avalanche was completely observed by his companions, and rescue was accomplished within 15 minutes. When extricated, he was found breathing on the device, which he claims allowed him to relax and concentrate on his breathing. Although

it is unknown if the artificial air pocket saved this guide's life, the incident served as an example that the mouthpiece could be placed and retained in the mouth during the chaos of an avalanche burial.

On March 24, 2001, a mountain guide near Aasta, Italy, was caught in an avalanche along with 3 clients while descending a small couloir. He was wearing an artificial air pocket vest, but his immediate reflex, which he feels was a mistake in retrospect, was to escape to the side of the slab and not to place the mouthpiece. After traveling 50 m in the flow, he was fully buried and could not move his arms. However, the mouthpiece was near his mouth, and he was able to grasp it between his lips. Breathing easily on the device, his spirits were renewed. Meanwhile, all but 1 of his clients had extricated themselves and discovered the guide's pole sticking out of the snow, uncovering him within 15 minutes. He was breathing on the vest for the entire time and feels that without it, he would have passed out because of the tightness of the space. He was then able to find the remaining client who was unconscious but survived.

AVALANCHE ABS

Background

Ruth Eigenmann proposed the concept of an inflatable ski jacket as early as 1970,²⁶ and around the same time, Joseph Hohenester, a German forester, presented the first avalanche balloon. He had observed that larger trees stayed on the surface of avalanches while smaller trees were buried, so he conceived that a balloon would enlarge the size of a person caught in an avalanche and force him to the surface. The balloon was further developed in the late 1980s, and within the next 10 years, several thousand ABS backpacks were sold. The present avalanche air bag, developed and marketed as a self-contained single- or dual-balloon system, is housed within various styles of backpacks weighing between 5 and 9 pounds, depending on the model style (Figure 4).

If caught in an avalanche, the skier deploys the balloon by activating a rip cord-like handle on the left shoulder strap, the trigger unit, which actively initiates the release of highly pressurized nitrogen gas from a cartridge in the backpack. The gas passes rapidly through jets drawing in outside air by a Venturi effect, which augments inflation of the balloon from inside the backpack in 2 to 3 seconds to a total volume of 150 L.

The device presumably prevents burial by increasing the victim's volume and size, which then follows the dynamic process of "inverse segregation" in a flowing granular medium.²⁷ Initially misunderstood as buoyancy in a fluid medium, the operative mechanism of inverse

Figure 4. Avalanche air bag system (ABS). The dual-balloon ABS is worn by a test dummy during field testing. Photo courtesy of the Swiss Federal Institute for Snow and Avalanche Research, Davos, Switzerland.

segregation governs the movement of particle size and volume in a granular flow such as an avalanche. In this process of size divergence, larger particles rise within the flow to the surface layer, where higher velocities carry it to the front, while smaller particles settle to the base of the flow (Figure 5). Ideally, the inflated balloons increase the volume and size of the wearer sufficiently to force the victim into the superficial flow of the avalanche, a region that may have less turbulence but higher velocity. Therefore, debris in the superficial layer travels farther along the avalanche path with uncertain consequences, depending on the terrain. Theoretically, the visible balloon on the snow surface should also hasten companion localization during rescue from partial or full burials and therefore enhance survival.

Despite considerable popularity and experience in Europe, the avalanche air bag has not been available in the United States because of shipping restrictions related to the pressurized cartridge, considered a hazardous material. Recently, however, a variation of the German air bag device became available in the United States involving a single balloon system (Avagear Inc, San Francisco, CA). The device incorporates a 90-L semicircular neckline balloon that, when deployed from the shoulder harness, surrounds the sides and back of the head and neck (Figure 6). The designers envisioned that this location of the balloon would offer some protection against head trauma during the avalanche, in addition to increasing the likelihood that the airway would be exposed to the surface of the debris when the avalanche settled. On the other hand, the location of the balloon may also impair vision and agility, which, if the device is deployed immediately after avalanche release, could

Figure 5. Inverse segregation. The physical unmixing of flowing particles based on size, which distributes the larger particles in the upper layers and is the basis for the successful functioning of the air bag system (ABS).

preclude any effective attempt to escape off the slab. Therefore, these are performance assumptions that will require field experience before any recommendations regarding efficacy. However, a recent preliminary field

Figure 6. Avagear air bag system (ABS). The single semicircular balloon is deployed from the shoulder harness of a test dummy during field testing. Photo courtesy of the Swiss Federal Institute for Snow and Avalanche Research, Davos, Switzerland.

study demonstrated encouraging results when compared to the German product.²⁸

Field studies

Initial testing was performed in the winter of 1994–95 by the Swiss Federal Institute for Snow and Avalanche Research, examining the Aschauer ABS device on dummies in an actual slab avalanche.²⁹ A total of 14 dummies ranging from 65 to 85 kg were used, 7 of which contained radio-activated balloons, and 7 of which lacked any device. All were placed by helicopter onto an avalanche test slope that was then triggered by explosives. In 6 of 7 balloons, inflation occurred properly by the remote mechanism, and none of these were deeply buried; hence, all or part of the balloon was revealed in all instances. Additionally, in the balloon group, 1 dummy was partially buried and would not have required extrication, and another remained on the surface of the debris. However, 4 were partial burials that included the head and thorax in a prone position, requiring potentially life-saving extrication. In addition, all of the dummies with inflated balloons were carried farther than the control dummies. Remarkably, 4 of the 8 dummies without inflated balloons were completely buried. The researchers concluded that the ABS device successfully prevents the frequency and extent of burial in avalanches and facilitates localization by companions, since part of the balloon is almost always visible on the surface. Potential limitations recognized were the strong likelihood of a prone burial requiring a companion rescue, terrain traps, wet snow conditions, large avalanches, trauma, and, in many cases, the possibility of being carried farther with uncertain consequences. However, on the whole, the avalanche air bag was highly lauded in Europe and embraced by all of the major rescue and mountaineering organizations.

During the winter of 2000–01, Swiss researchers conducted a direct comparison of the single- and double-balloon ABS with the Avagear balloon, again utilizing the test dummies on an artificially released avalanche slope. Burial depths for each device were recorded and evaluated for the necessity of airway extrication. Of the 13 dummies involved in the avalanches, 3 wore the Avagear product, 4 were equipped with either the single or double German air bag, and 6 functioned as controls (2 with K2 Avalanche Balls). Strikingly, 5 of the 6 control dummies were fully buried, requiring transceiver localization. Of the 7 air bag dummies, 3 were only partially buried requiring no extrication, 1 remained on the surface, and 3 were fully buried involving the head and thorax, with all or part of the balloon visible and thus allowing for rapid rescue. Interestingly, although the

numbers are small, all 3 full burials in which the airways were completely covered by snow were with the German ABS, whereas the 3 Avagear test dummies were only partially buried at the surface without airway involvement. In addition, the Avagear dummies tended to be oriented upright on the debris compared with lying flat in the ABS group, suggesting a causal role of the balloon position and its ability to force the head and upper body toward the surface. The data from these field experiments again strongly supported the efficacy of the balloon systems at minimizing the frequency and extent of burial in addition to aiding in rapid localization. A statement regarding the function of the Avagear's cephalad-oriented balloon would be notably premature at this time.

Documented cases

Field experience with the air bag has been accruing throughout Europe since February 1991 and has been expertly collected and analyzed by the Swiss Federal Institute in Davos (M. Kern, unpublished data, 2001). As of the end of the 2000–01 winter season, 29 known accidents with the ABS involving 44 persons have been well documented. Of these, 35 were able to successfully deploy the balloon (3 technical failures, and 6 did not pull the rip cord for unknown reasons). Remarkably, 16 remained on the snow surface, and 14 were only partially buried, which did not include the head or airway. Despite 5 burials including the head and airway, the balloon was visible on the surface in 4 cases, and only 1 was completely buried with no evidence of the balloon. In this instance, a second avalanche overcame the victim's final position in a terrain trap at the base of the path, and he died after being buried 170 cm deep. Overall, 34 persons with the ABS deployed survived, and only 1 died. Although minor questions about efficacy in specific situations remain, these statistics are remarkably compelling and warrant close attention in the United States, where this device has not yet achieved a market.

AVALANCHE BALL

The newest survival device introduced into the marketplace last year is the Avalanche Ball by K2, which is essentially a high-tech resurrection of the antiquated avalanche cord (Figure 7). A 20-L (60-cm diameter) spring-loaded ball is compressed into a small pack weighing less than 1 kg, which is attached to the user by a harness belt and deployed by a release cord. The ball is lofted on the end of a 6-m line and ideally comes to rest on the surface of the debris to indicate the burial location. Companions would then need to follow the

Figure 7. Avalanche Ball. **a**, The fanny pack contains the compressed spring-loaded ball, which is deployed by pulling the rip cord seen to the left of the pack. **b**, The Chinese lantern-like ball, which is attached to the pack by a 6-m line, is lofted after release and functions as a surface marker.

cord into the snow and dig along that axis to the buried victim. Although not designed to affect the likelihood of burial, this device takes advantage of the inverse segregation principle, since the tethered ball remains on the surface of the avalanche debris to function as a visual locator, presumably saving time over a transceiver search and hence increase survival.

The Avalanche Ball was field tested by the Swiss during the air bag trials last winter, at which time the 2

dummies equipped with the device were both fully buried as expected. In each instance, the ball was easily located on the surface of the debris, allowing for acceptable extrication times of 10 to 12 minutes. Although this technology allows rapid localization visually, it does not prevent or lessen burial and is therefore inferior to the air bag devices, which accomplish both tasks impressively.

Conclusion

Considering the multitude of variables involved in surviving an avalanche encounter, it comes as no surprise that no single device can be effective in all instances. Research will continue on the physiology of avalanche burial until it is clear that we can rely on a single type of apparatus. Trauma remains a problem not fully addressed by the present armamentarium of devices and, although the Avagear concept of protection is encouraging, the evolution of this product is especially early and speculative.

The artificial air pocket breathing device, the avalanche ABS balloon, and the Avalanche Ball may all increase the chances of survival during an avalanche accident, and these technologies may even complement one another if combined. However, they do not replace knowledge, conservative judgment, and appropriate safety precautions when recreating or working in avalanche terrain. In fact, they remain the last members of the self-rescue equipment team behind a transceiver, shovel, probe, and common sense. Avalanche avoidance will always be the mainstay of avalanche survival, never to be replaced by any device.

Author's note

Subsequent to this clinical update going to press, a landmark incident involving the artificial air pocket device occurred in the Canadian backcountry outside of Revelstoke, British Columbia. On February 10, 2002, a 44-year-old heli-skier wearing the survival device was buried along with 2 others after being hit from above by an avalanche. All 3 were buried instantly only a few feet from each other under almost 6 feet of debris for about 40 minutes. The individual wearing the artificial air pocket was able to place and maintain the mouthpiece during the struggle and breathe easily despite a complete inability to move after avalanche settlement. Snow packed his ears and nose but remained clear of his airway because of the mouthpiece. Shortly before rescue he became unconscious, but was quickly revived when uncovered, without any resuscitation required. In contrast, the 2 companions not wearing the device were

found dead from asphyxiation despite simultaneous recovery times and burial conditions. The event represents the first survival incident that is convincingly attributable to the air pocket device and will be reported more extensively in a future publication.

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