CHAPTER

20

Avalanche Accidents

Hermann Brugger, Giacomo Strapazzon, Ken Zafren

SUMMARY

- Most avalanches that affect winter recreationists are triggered by the recreationists themselves. Avalanche survival depends mainly on the immediate extrication of completely buried avalanche victims by bystanders before organised rescue can arrive, then on professional on-site treatment and on the optimal choice of destination hospital using established prognostic criteria. Survival probability during complete avalanche burial is a function of time and other factors that affect survival, including airway patency, the presence of an air pocket in front of the mouth or nose, and the depth of burial. Trauma pathophysiology is mainly related to types of injuries. The pathophysiology of avalanche burial is a unique case. Survival is determined by the severity of trauma, by the possibility of breathing in avalanche debris, which is primarily compacted snow, by the degree of hypoxia (decrease in arterial oxygen saturation [SpO_2]) and hypercapnia (increase in end-tidal carbon dioxide [$ETCO_2$] due to rebreathing expired air), and by the presence of accidental hypothermia.
- Most mountain areas of Europe and North America that are popular for winter recreation have pre-hospital emergency care available by organised rescue groups. Search and rescue of avalanche victims should be initiated as promptly as possible. Immediately after an avalanche burial, every minute may be crucial for survival. Organised rescue operations should be equipped to manage emergency conditions on scene, including normothermic cardiac arrest, accidental hypothermia, and multiple trauma. Pre-hospital triage should identify victims with a high risk of normothermic cardiac arrest due to asphyxia, a nonsurvivable condition, as opposed to victims in whom early hypercapnia may have increased the rate of core temperature cooling. Victims with hypercapnia are more likely to have had hypothermic, rather than normothermic, cardiac arrest. Hypothermic cardiac arrest may be survivable. Only victims who have sustained cardiac arrest due to hypothermia are likely to benefit from extracorporeal life support (ECLS). Although there are international recommendations for the management of avalanche victims, evidence regarding advanced life support (ALS) is scarce. Transfer of information from bystanders to organised rescue teams and from rescue teams at the accident site to the hospital is often suboptimal. An avalanche checklist is now available that may improve outcomes by promoting the transfer of critical information. There is still a need for protocols to optimise pre-hospital triage, initial on-site treatment, transport to suitable destination hospitals and in-hospital management of avalanche victims, including detailed criteria and protocols for ECLS and post-resuscitation care.

BACKGROUND

The discovery of the glacier mummy, Oetzi (the "Ice Man"), in 1991 at 3,200 m on the Tisen Pass in northern Italy revealed that migrants crossed the Alps from south to north and north to south >5,300 years ago. It is likely that avalanches have killed people in the European Alps since the late Copper Age (from the late fifth millennia BCE).

In ancient warfare, the greatest documented disaster was Hannibal's crossing of the Alps in 218 BCE during the Second Punic War. The Carthaginian general led his army of 38,000 foot soldiers, 8,000 horses, and 38 elephants over the Alps into Italy to take the war directly to Rome. Poet Silius Italicus recorded the loss of about half the soldiers and animals during this endeavour. [1] Although Hannibal's exact route has been the source of scholarly dispute ever since, the most influential modern theorists favour a march over the French Alps via the Col de Montgenèvre (1,788 m) or the Little St. Bernard Pass (2,188 m). In his

Hermann Brugger ✉ hermann.brugger@eurac.edu

narrative, Italicus stated that many lives were lost by "snow masses plummeting down the mountain slopes while Hannibal's troops descended from the pass into Italy."

One of the first detailed descriptions of a deadly avalanche dates to 1128 CE. The abbot of the monastery of St. Trond in Switzerland documented an avalanche that killed mountain guides who attempted to climb the Great St. Bernard Pass (2,469 m) above the monastery with a group of pilgrims. In the late nineteenth and early twentieth centuries hundreds of miners were killed by avalanches in Colorado.

Avalanches have claimed the greatest number of lives in twentieth century wars. During World War I, between 9,000 and 10,000 soldiers died in barracks destroyed by avalanches in the Dolomites in northern Italy. In these mountains, the death toll in World War I from avalanches was far higher than from acts of war.

The experience of deaths due to avalanches during World War I led to the foundation of the first Commission for Snow and Avalanche Research in Switzerland in 1931. In 1942, the Institute for Snow and Avalanche Research in Davos, Switzerland was established, with a snow laboratory on the Weissfluh Pass (2,693 m). After World War II, the institute took over the responsibility for avalanche warnings from the military and established the first civil avalanche warning service in the world.

In 1951, exceptionally high precipitation and the meeting of an Atlantic warm front with a polar cold front resulted in 3–5 m of snowfall in the European Alps over a period of a few days. This caused innumerable avalanches in Switzerland and Austria, destroying farmhouses, villages, and roads. By the end of this disastrous "Winter of Terror" 900 buildings had been levelled and about 500 cattle and 256 people had been killed, mostly in the Austrian Alps. Three years later, in January 1954, 388 devastating avalanches swept across the Austrian state of Vorarlberg, destroying hundreds of houses and farm buildings, and claiming 125 lives, most of them in the Grosswalser Valley and the village of Blons. These disaster years and growth of an emerging winter tourism industry prompted several political initiatives to protect Alpine residents and mountain travellers from avalanches. In all Alpine countries, public funds were invested to build defensive structures above roads and villages, to plant protective forests, and for avalanche forecasting. These measures resulted in an almost complete elimination of avalanche disasters in the Alps. Nevertheless, catastrophic avalanches in 1999 claimed the lives of 38 residents and tourists in the Austrian village of Galtür and an avalanche killed 29 people in a hotel in Farindola, Italy, in 2017 (Figure 20.1). [2, 3]

Figure 20.1 The catastrophic avalanche of Farindola, Italy. (Courtesy of Salvatore Diodato/CNSAS.)

In other parts of the world, even densely populated valleys and villages are still unprotected and threatened by deadly avalanches. In January 1962, in Peru, large masses of glacial ice and snow falling from high mountains wiped out the villages of Ranrahirca and Yungay, killing an estimated 4,000 people. It was the worst avalanche disaster in peacetime. In 1979, in India, a series of avalanches buried the Lahaul Valley, killing at least 200 people. In 1991, in Bingol, Turkey, an avalanche hit several villages, killing 255 people. In 2002, an avalanche from Mount Kazbek (5,047 m), one of the major mountains of the Caucasus located between Georgia and the Russian Republic of North Ossetia, killed 150 people. In March 2012, a series of avalanches struck the Badakhshan province of north-eastern Afghanistan and destroyed several villages, killing over 200 people. In February 2015, dozens of avalanches killed 310 people in Panjshir Province, Afghanistan.

One of the most devastating avalanches in the history of Nepal hit the Khumbu Icefall on the main climbing route of Mt. Everest in 2014, killing 16 people and injuring 9. A severe earthquake sent another ice avalanche into Everest Base Camp in 2015. The devastating wind blast killed 15 people and injured at least 70. [4, 5]

In Europe and North America over the last 5 decades, as the number of avalanches threatening roads and villages has declined, the number of avalanche accidents has increased significantly in areas in which avalanches are not actively controlled. It may be that with the decreasing threat of natural avalanche disasters, people in developed countries take greater risks during winter leisure activities by entering uncontrolled areas.

Keynotes

"Avalanches do not know that you are an expert." [6] Prevention can be life-saving. Winter recreationists in uncontrolled terrain should carry standard equipment: an avalanche transceiver, an avalanche probe, and a shovel. This equipment is used to find and extricate avalanche victims. Companion rescue increases the likelihood of survival for a victim who is completely buried. Organised rescue may increase the likelihood of survival for a victim with a patent airway and a long burial time, who is at risk of accidental hypothermia. The use of local protocols for hospital transport and management can maximise the likelihood of survival.

SNOW AND AVALANCHES

SNOW

Snowflakes (crystals) form when tiny water droplets in clouds solidify to form ice nuclei. Water vapour depos-

CASE REPORT 20.1

Solo ski touring without an avalanche transceiver

In March 2010, a 42-year-old male backcountry skier started a solo ascent of a peak in his "backyard" mountains in South Tyrol, Italy. The weather was stable, with low temperatures and no wind, but the avalanche hazard was grade 3 (avalanches can easily be triggered, particularly on steep slopes) on a scale of 5 due to strong wind earlier during the night, as evidenced by a cornice on the ridge above the ascent route. Despite the early hour (about 9:30 a.m.), the skier triggered an avalanche during the ascent at about 2,200 m, where there was an increase in slope angle to >35°. The skier was completely buried under medium to low density avalanche debris 180 cm deep. The accident was observed by bystanders, who immediately called the rescue service. Bystanders started immediate search operations using transceivers, without success. After only 12 min, the helicopter emergency medical services (HEMS) with an emergency physician, avalanche dog, and mountain rescue personnel arrived at the avalanche site. Once the scene was declared safe, a transceiver search was started. Unfortunately, the victim was not wearing a transceiver. The search strategy was extended to included probe lines and a RECCO® detector (a hand-held electronic location device for professional rescue teams). Additional mountain rescue personnel were brought to the site (about 5 avalanche dogs and 55 personnel). Scene safety was constantly reassessed throughout the operation due to increasing avalanche hazard from solar radiation and rising temperatures. The victim was located by probing and extricated after 2 h 7 min, including 20 min of digging. When extricated, the victim was prone with his head in the downhill position. He was not wearing gloves, hat, shell jacket or an insulating layer. He had an impaired level of consciousness with a Glasgow Coma Scale (GCS) score of 10. He had a patent airway, was breathing spontaneously, and had a palpable radial pulse. There was a clearly visible air space in front of the mouth and nose with evidence that the inner surface had been frozen. There was no sign of injury. After a primary assessment, oxygen was administrated by face mask at 5 L/min, the victim was protected with full-body insulation with an aluminium-foil blanket and rescue bag. The core temperature, measured with an epitympanic thermistor probe, was 25 °C. The victim was monitored and packaged on a vacuum mattress within 10–15 min. Meanwhile, the emergency physician discussed the choice of destination hospital with the dispatch centre based on hypothermia stage, absence of asphyxia, cardiac stability, availability of medical resources, and duration of transport. The victim was transported by helicopter to the General Hospital of Bolzano, Italy, a Level 1 trauma centre capable of active external and minimally invasive rewarming. The choice of hospital was influenced by the short flight time (3 min vs. 25 min to the nearest ECLS facility) and the absence of cardiac instability, although the core temperature was <28 °C).

The victim was admitted to the emergency department and immediately transferred to the intensive care unit (ICU), where peripheral intravenous access was obtained and a urinary bladder catheter was placed. Core temperature, again measured with an epitympanic thermistor probe, was about 25 °C, systolic blood pressure was >90 mmHg, and an electrocardiogram (ECG) showed a junctional rhythm of 44 bpm. The victim was treated with active external rewarming of the trunk with forced air. Normal saline at 40 °C was infused. After 75 min, when the core temperature was 31 °C, the victim suddenly developed respiratory failure with an SpO_2 by pulse oximeter of 73%. The victim was coughing pink frothy sputum. There were diffuse bilateral crackles on auscultation of the lungs. He was intubated and ventilated with continuous positive end-expiratory pressure (PEEP). The pulmonary oedema resolved without administration of drugs. The SpO_2 rose to 99%. Blood pressure was supported with inotropic drugs due to an episode of hypotension associated with increased urine output. After 5 h of rewarming, the core temperature reached 37 °C, for a mean rewarming rate of 2.2 °C/h. The victim made a complete recovery. After being discharged from hospital on day 3, the victim resumed his normal activities. [7]

its on the nuclei and freezes. Snowflakes have hexagonal symmetric structures. Shapes vary depending on ambient conditions. [8] Snowflakes accumulate on the ground and create an apparently homogeneous white mass. The flakes fuse, creating a complex multiphase structure that includes interstitial air, aerosol particles, ice-air interfaces, and ice crystals. [9] Snow undergoes metamorphosis as it is transformed by fusion of snowflakes. Snow temperature is always close to or below the melting point. Due to a high vapour pressure, snow is constantly vapourising by sublimation, that is without passing through the water phase. Water vapour recrystallises when it is deposited on a slightly colder surface. The rate of metamorphosis varies enormously, depending on environmental conditions. The higher the temperature gradient between ground and snow, the more rapidly the snow structure changes. The porous structure of snow allows air to circulate.

The likelihood of survival during burial in avalanche debris decreases as snow density increases. [10] Snow density is determined by the volume ratio of snowflakes (crystals) to air. In fresh (low density) snow air accounts for 90–95% of the volume. In older (medium or high density) snow, air still accounts for >60%. [10]

Snow accumulation on the ground creates the snowpack. The snowpack is usually formed by a series of layers. Temperature has a large influence on layer formation: the warmer the snow and the higher the temperature gradient between the snow surface and the ground, the more rapidly the snow layers and snowflakes transform. Wind also affects snowpack formation by shaping the surface, transporting and grinding the snowflakes, breaking them into much smaller pieces that pack very closely. Snowpack reflects not only the snowfall but also the succession of weather conditions. [8] Snow characteristics vary by geographical location and according to local topography and aspect.

AVALANCHES

Avalanches are masses of snow that fall down steep slopes. They are formed by a complex interaction among terrain, snow accumulation and weather conditions. When the forces that prevent sliding of snow on a slope are overwhelmed by gravity the snow slides. The forces that prevent sliding are adhesion to deeper layers of the snowpack or to the ground and friction.

Avalanches can contain rocks, soil, vegetation, and ice.

Avalanche Formation

Terrain, precipitation, especially new snow, wind, temperature, radiation effects, and snowpack stratigraphy affect avalanche formation. Suitable terrain is essential to produce avalanches and is the only constant factor over time. A slope angle >30° is usually required for slab avalanches of dry snow. [11, 12] Avalanches begin more frequently in starting zones with concave slope profiles and breaks in slope angle. Increased terrain roughness hinders the formation of continuous weak snowpack layers, although this effect may be modified by other factors, such as the thickness of the snowpack, the nature of the sliding surface and the existence of anchoring features. Sliding is less likely in rocky areas and more likely if the surface is grassy. Anchoring features such as large trees decrease the likelihood of an avalanche, especially in high density forest. Accumulation of more than 30–50 cm of new snow can cause naturally released avalanches. Smaller amounts can allow human-trigged avalanches. [11, 12] Wind may be a key factor in avalanche formation. Wind transports snow, causing wind loading. Even if a storm brings less than 30 cm of new snow to flat ground, wind transport can result in much larger accumulations in wind-loaded areas. Temperature is a decisive factor in avalanche formation, because the mechanical properties of snow (hardness, fracture propagation, strength) and metamorphism are highly temperature dependent. Finally, snowpack stratigraphy can be a key factor. The failure of a weak layer is the mechanism that causes a dry snow slab avalanche.

Types of Avalanches

Avalanches can be classified based on the mechanism of failure of the snowpack, the position of the sliding surface, humidity, type of track, and type of movement. [11] There are two types of avalanche based on type of failure. Loose snow avalanches (Figure 20.2) start from a single point on a surface layer of dry or wet snow. [11] Slab avalanches are caused by the release of a cohesive layer (slab) extending over a plane of weakness (Figure 20.3). The majority of avalanches triggered by skiers and snowboarders are dry slab avalanches. [13] Avalanches can slide in a channelled or open track on a layer of the snowpack or on the ground. Avalanches can run (slide) with laminar or turbulent flow.

Figure 20.2 An avalanche of loose snow. (Courtesy of LWD Tirol.)

Slab Avalanches

A slab avalanches is characterised by a sharp, linear fracture line and a crown faces. A slab avalanche is caused by a shear fracture that spreads along a weak layer below the slab, allowing the development of high tensile stress. Failure at the crown face produces a fracture across a slope. [11] A local rapid, near-surface loading, which could be caused by a skier or other winter recreationist can trigger the collapse of the weak layer. The collapse may be associated with a noise, sometimes described as a "whoomph". In a retrospective Swiss study of human-trigged avalanches, detached slabs had a median width of about 50 m, a median length of about 80 m, and had a median path length of about 150 m. The slope angle in the starting zone was typically 35–40°. The shear fracture depth was a median of 45 cm, mostly due to weak layers or interfaces in the snowpack. The weak layer was commonly soft, about 1-cm thick, and was found between harder layers above and below. The weak layer typically consisted of mostly large (2 mm) crystals with plane faces. [13]

Figure 20.3 A slab avalanche. (Courtesy of LWD Tirol.)

Loose Avalanches

Loose avalanches are point-release avalanches that move down the slope to form a characteristic inverted "V" shape. They are caused by progressive displacement of snow crystals on a slope. Loose avalanches can be small, usually with dry snow, or large, usually with wet snow.

Avalanche Dynamics

Avalanches usually run via the same paths each time conditions cause an avalanche. Avalanche paths may be channelled or open. Avalanche paths have 3 zones (Figure 20.4). The starting zone is the area in which an avalanche originates, gains the required force, and entrains the initial snow. In the track zone, where the avalanche runs, the snow content remains essentially constant and the avalanche picks up little or no additional snow. In the runout zone, avalanche movement ends and avalanche snow accumulates. [12]

The speed of an avalanche varies based on snow characteristics. A dry snow (low snow density) avalanche can have a speed of 50 to 350 km/h. A wet snow (high snow density) avalanche can have a speed of 40–100 km/h. [12] Increased speed increases impact pressure. Even small and medium-sized avalanches have impact pressures of 1–15 kPa, which are sufficient to cause serious injury. If an avalanche path is steep and long, impact pressures can increase by a factor of 10 or more, with the potential to destroy trees and concrete structures. [12] High speed avalanches usually follow the steepest route, but can deviate from the direct line if guided or channelled by terrain features. Slower-moving avalanches usually follow terrain features. Avalanches usually last a very short time, only large avalanches take a few minutes. Avalanche debris can fly through the air or flow along the ground, although avalanches move much more like sliding blocks than like flowing water. The presence of snow crystals can increase air density by a factor of 3 or more, creating a cloud of powder with an impact force as if the speed of the avalanche were about 300 km/h in an avalanche with a speed of 100 km/h.

Figure 20.4 Large avalanche path showing the starting zone, track, and runout zone where the avalanche slows and stops, depositing avalanche debris. (Courtesy of LWD Tirol.)

EPIDEMIOLOGY

AVALANCHE ACCIDENTS IN OPEN AREAS

Avalanches During Winter Outdoor Activities

Winter outdoor activities have become increasingly popular in recent decades due to higher mobility of recreationists, use of mechanised transportation such as helicopters, snowcats and snowmobiles, and significant improvements in equipment. Despite more effective means of preventing avalanche accidents, the number of avalanche accidents involving winter recreationists has markedly increased. One field survey of backcountry skiers and snowshoers in South Tyrol, Italy, a region of the European Alps, surveyed 5,576 individuals (78% skiers or snowboarders, 22% snowshoers) over a 1-week period in an area of ~7,400 km^2. [14] Frequency of skiers peaked during weekends. The sample contained more men than women (66% vs. 34%), most commonly in the 35–49-year-old range. However, recreational activity in avalanche terrain includes not only backcountry skiers and snowshoers but also snowmobilers and people pursuing other winter sports such as mountaineering and ice climbing. [15, 16] In winter activities in the European Alps, the risk of avalanche accidents is higher than for other events, such as falling from a height or developing hypothermia. [17, 18]

In most avalanche accidents in Europe or North America the avalanche was triggered by recreationists (85–94%). [13, 19] In Tyrol, Austria, two-thirds of avalanche accidents occurred on days with hazard grades 2 (triggering of an avalanche is possible with high additional loads) and 3 (triggering is possible even with low additional loads) on slope angles of between 35–40°. [19] Most avalanches were triggered in open areas without trees above 2,500 m, although >15% occurred below timberline. The highest incidence of avalanche accidents was between 10 a.m. and 3 p.m. [19]

The effects of avalanche training for recreationists is not well understood. Avalanche training may paradoxically decrease the perception of risk and increase risk-taking behaviours. [20]

Spontaneously triggered avalanches seldom involve recreationists. The low number of accidents due to spontaneous avalanches in the European Alps could be due to the low number of days with hazard grades 4 (triggering and avalanche is likely even with low additional loads, in some conditions natural avalanches are likely) and 5 (numerous large natural avalanches are likely, even on moderately steep terrain). More likely, the rarity of accidents due to spontaneous avalanches, is due to the low number of recreationists in avalanche terrain on those days. [19]

Avalanche Morbidity And Mortality

Backcountry skiers and snowboarders are the largest groups of recreationists involved in avalanche accidents in Europe, followed by off-piste skiers. Snowmobilers and backcountry skiers are the largest groups involved in avalanche accidents in North America. [15, 21] The total number of persons venturing into avalanche terrain is unknown. Mortality rates can only be rough estimates. The number of avalanche accidents involving winter recreationists has increased in recent decades due to the increasing popularity of winter outdoor activities. [13] The use of mechanised vehicles such as snowmobiles and increases in activities such as freeriding and snowshoeing, has led to epidemiologic changes and new types of injuries. [21, 22]

Between 1983 and 2015, avalanche fatalities claimed over 5,000 lives in Europe and in North America with an average annual number of about 130 in Europe and 36 in North America. [23]

Backcountry recreationists account for about 50% of annual fatalities in European Alpine countries [15, 24] and about 60% in North America, where snowmobilers accounted for approximately 20–25% of deaths. [15, 21] Avalanche fatalities are not systematically reported in developing countries and other mountain regions, such as the Andes, the Karakoram and the Himalayas. Historical reports suggest fatalities could be many times higher in the great ranges in both civilian and military populations.

Avalanche Survival

Survival analyses have shown that grade of burial (complete or partial) is the main determinant of survival, followed by duration of burial, airway patency, and the presence of injuries. [25] The overall mortality rate of avalanche victims has been estimated to be 23%. [26] Data from a Swiss study showed a mortality rate of 52% for completely buried victims (head and chest buried under snow) and ~4% for victims who were partially buried or not buried at all. [26] More recent data from Austria, Canada, and Switzerland confirm a similar fatality rate of completely buried victims (48–56%). [15, 27] Survival is inversely related to the duration of complete burial in Europe and Canada, as shown by the avalanche survival curves (Figure 20.5). [15, 26–28] The stepwise decrease of survival probability with increasing duration of burial was first recognised using avalanche data from Switzerland in 1994. [28] The most recent avalanche survival curves from Switzerland (2005–2013) were similar to those for 1980–2005 and to those using data from Austria (2005–2013). [15, 27] Swiss and Austrian data demonstrate a rapid initial drop in survival probability to 87–91% after a burial time of ~7–10 min, compared to ~18 min in the previous survival curve, followed by a second drop to a survival probability of 25–28% after ~35 min, where an inflection point exists. After ~35 min, the curve levels off until 180 min. [15, 27] Another survival curve, calculated in 2011 using data from Canada, showed a similarly rapid initial drop to a lower survival probability (77%), but after the second drop, the survival probability was calculated to be as low as 4%. [15] The incidence of traumatic injuries, the characteristics of the snowpack and winter climate were likely the major causes of the differences in survival rates between Europe and Canada in the early phase of burial. Maritime climates with high snow density due to mild temperatures were characterised by a considerably earlier drop in survival compared to continental climates, with low snow density due to cold temperatures. Longer rescue and transport times in Canada than in Europe may have accounted for lower survival in Canada after prolonged burial. In Canada, specific survival curves for avalanche survival of backcountry skiers, off-piste skiers, and snowmobilers did not differ significantly from each other. [15]

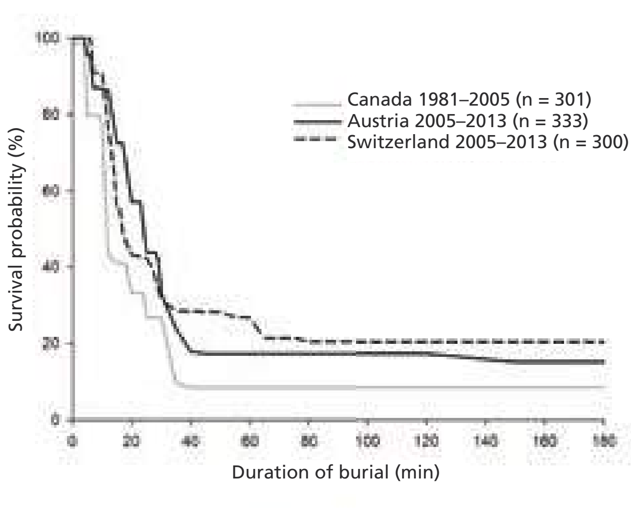


Figure 20.5 Survival curve for completely buried victims in Austria, Switzerland, and Canada. (Modified from [15] and [27].)

The longest survival in an avalanche in which the victim was not in a building was an uninjured backcountry skier, extricated with a core temperature <32 °C who survived despite 43 h 45 min of complete burial. [29]

Emergency Medical Services in Avalanche Accidents

For completely buried avalanche victims, survival depends largely on immediate extrication. In Austria and Switzerland, half of completely buried avalanche victims were extricated within the first 15 min of burial and up to 75% within 60 min. [27] Similar statistics were reported in Canada. [15] Although in most European countries rescue is immediately available by mountain rescue organisations, HEMS, and avalanche dogs, the survival rate of completely buried victims was ~80% when completely buried victims were rescued by bystanders before search and rescue (SAR) teams arrived compared to <20% when rescued by professional rescuers. [19, 30] The most likely explanation for this difference in survival probability is that the time to arrival at the scene for rescue teams, about 45 min on average, is too long to affect the rapid initial drop in survival probability. An American study showed that victims who were completely buried were most often found prone and with the head downhill, [31] making initial intervention and resuscitation challenging. A high incidence of complete burial with the victim prone and head downhill was also described in a case series from Norway. [32] One third of victims in the Norwegian study were found sitting, standing, or lying on their sides, making a probe search challenging, especially when no avalanche transceiver was available. About 50% of victims in Austria and Switzerland were buried at a depth ≥100 cm. [27]

During a season in Tyrol, Austria, most avalanche accidents and most HEMS SAR operations occurred on days with hazard grades 2 and 3. [19, 30] In missions to rescue partially or totally buried victims, HEMS and rescue teams were involved in search and probing on scene in 5.5–49% of operations; there were multiple victims in about one third of avalanche missions in the European Alps. [30, 33] On arrival at the scene in 11% of missions, HEMS teams managed medical emergencies, including normothermic cardiac arrest, accidental hypothermia, and multiple trauma. [30]

Summer Avalanches

Avalanches can occur during summer. In a Swiss study, summer avalanches accounted for 6% of avalanche fatalities. [34] Some of the summer avalanches are due to falling ice and are not really snow avalanches in the usual sense. Although the number of completely buried victims per avalanche was lower in summer than in winter, the average number of fatalities in a summer avalanche was higher mainly due to trauma (94% of fatalities). Avalanche SAR teams should expect to search for victims of summer avalanches using clues visible on the surface rather than performing a standard search with transceivers and probes.

AVALANCHE ACCIDENTS INVOLVING BUILDINGS AND ROADS

Avalanches can claim lives when victims are buried in buildings or vehicles, often by spontaneously occurring avalanches, such as catastrophic avalanches in Italy in 2017 and in Austria in 1999. These mainly happen on days with hazard grades 4 and 5. In developed countries, especially in central Europe, the effects and frequency of catastrophic avalanches have been mitigated by prevention strategies and infrastructure construction. Catastrophic avalanches also occur in less developed countries, especially in the highest mountain ranges of the world, the Himalayas and Karakoram, where few resources are employed in prevention strategies and infrastructure.

Avalanche survival curves for victims buried in buildings or vehicles are similar to other avalanche survival curves, showing a rapid initial drop in survival probability to 90–95% after burial of ~10 min and a second drop to 50% after ~35 min, where an inflection point exists and the curve levels off to survival probability >30% until 190 min. [26] Avalanche victims entrapped in buildings or vehicles may have larger air pockets or even a connection to the outside and thus a higher survival probability compared to completely buried victims in open areas. The longest survival time in a building following an avalanche was 13 days, by a miner trapped in a house that was partially destroyed by a catastrophic avalanche in Heiligenblut, Austria. He was never in direct contact with the snow. [29] In Tyrol, Austria, 6% of avalanche rescues by HEMS SAR involved people trapped in buildings. [30]

PATHOPHYSIOLOGY

The pathophysiology of avalanche burial is related to the interaction between the victim, avalanche dynamics, and snow properties. Pathophysiological mechanisms can be temporally related to the phases of avalanche survival curves. Trauma is the leading cause of death in the initial survival phase. Asphyxia is the main cause of death in the second (asphyxial) phase. The combination of severe hypothermia, hypoxia, and hypercapnia (triple H syndrome) is the usual cause of death when the curve levels off, in the latent and long-term survival phases (Figure 20.5 and Table 20.1). [35] Excluding fatal trauma during the avalanche, the pathophysiology of

Table 20.1 Causes of death from avalanches, diagnosed on autopsy or full external examination in Canada, USA and Austria

	External examination*				Autopsy**				Both methods			
	Trauma[§]	Asphyxia[+]	HT	Subtotal	Trauma[§]	Asphyxia[+]	HT	Subtotal	Trauma[§]	Asphyxia[+]	HT	Total
Tough 1993 [36]	1 (9.1%)	10 (90.9%)	0 (0%)	11 (100%) *(73.3%)*	0 (0%)	4 (100%)	0 (0%)	4 (100%) *(26.7%)*	1 (6.7%)	14 (93.3%)	0 (0%)	15 (100%) *(100%)*
McIntosh 2007 [18]	1 (3.6%)	27 (96.4%)	0 (0%)	28 (100%) *(50%)*	2 (7.1%)	26 (92.9%)	0 (0%)	28 (100%) *(50%)*	3 (5.4%)	53 (94.6%)	0 (0%)	56 (100%) *(100%)*
Hohlrieder 2007 [37]	0 (0%)	6 (100%)	0 (0%)	6 (100%) *(16.7%)*	2 (6.7%)	27 (90%)	1 (3.3%)	30 (100%) *(83.3%)*	2 (5.5%)	33 (91.7%)	1 (2.8%)	36 (100%) *(100%)*
Total	2 (4.4%)	43 (95.6%)	0 (0%)	45 (100%) *(42.1%)*	4 (6.5%)	57 (91.9%)	1 (1.6%)	62 (100%) *(57.9%)*	6 (5.6%)	100 (93.5%)	1 (0.9%)	107 (100%) *(100%)*

HT hypothermia.

*Full external examination with or without review of in-hospital medical records; **Full examination of external and internal organs; [§]Trauma as solely cause of death; [+]Including cases presenting traumatic injuries not considered the primary cause of death. (Reproduced from [35], with permission.)

avalanche burial is a unique situation related to the possibility of breathing under avalanche debris and to the duration of burial.

RESPIRATION UNDER THE SNOW

Several studies have shown that breathing under avalanche debris is possible in the presence of a patent (open) airway (Figure 20.6). [10, 38–42] If an air pocket (i.e. space in front of the mouth and nose) with even a limited volume, as small as 0.06 L, is available, the work of breathing decreases (Figure 20.6a). [38] The volume of the air pocket determines the rate of oxygen desaturation. This has been demonstrated by an experimental field study in which a 1-L air pocket led to an earlier onset of hypoxaemia, defined as an SpO_2 <75%, compared to a 2-L pocket. [41] Over 60% of subjects had to abort the test before 30 min (Figure 20.6b). Air pocket volume does not explain how ~40% of participants were able to breathe in such a small volume for up to 30 min. In contrast, subjects breathing into a 4-L flexible plastic bag were only able to maintain an SpO_2 >75% for <4 min. [10]

SpO_2 decreases during respiration in avalanche debris because the rate of oxygen consumption is greater than the rate of oxygen diffusion through the debris. Carbon dioxide increases during respiration in avalanche debris because the rate of CO_2 production is greater than the rate of adsorption into the avalanche debris. Using a device that separates CO_2-rich exhaled air from inhaled air, 75% of subjects were able to maintain SpO_2 >90% with adequate ventilation for up to 60 min whilst breathing under snow (Figure 20.6c). [42] Rebreathing expired gas leads to hypercapnia that displaces oxygen, worsening hypoxaemia, and also induc-

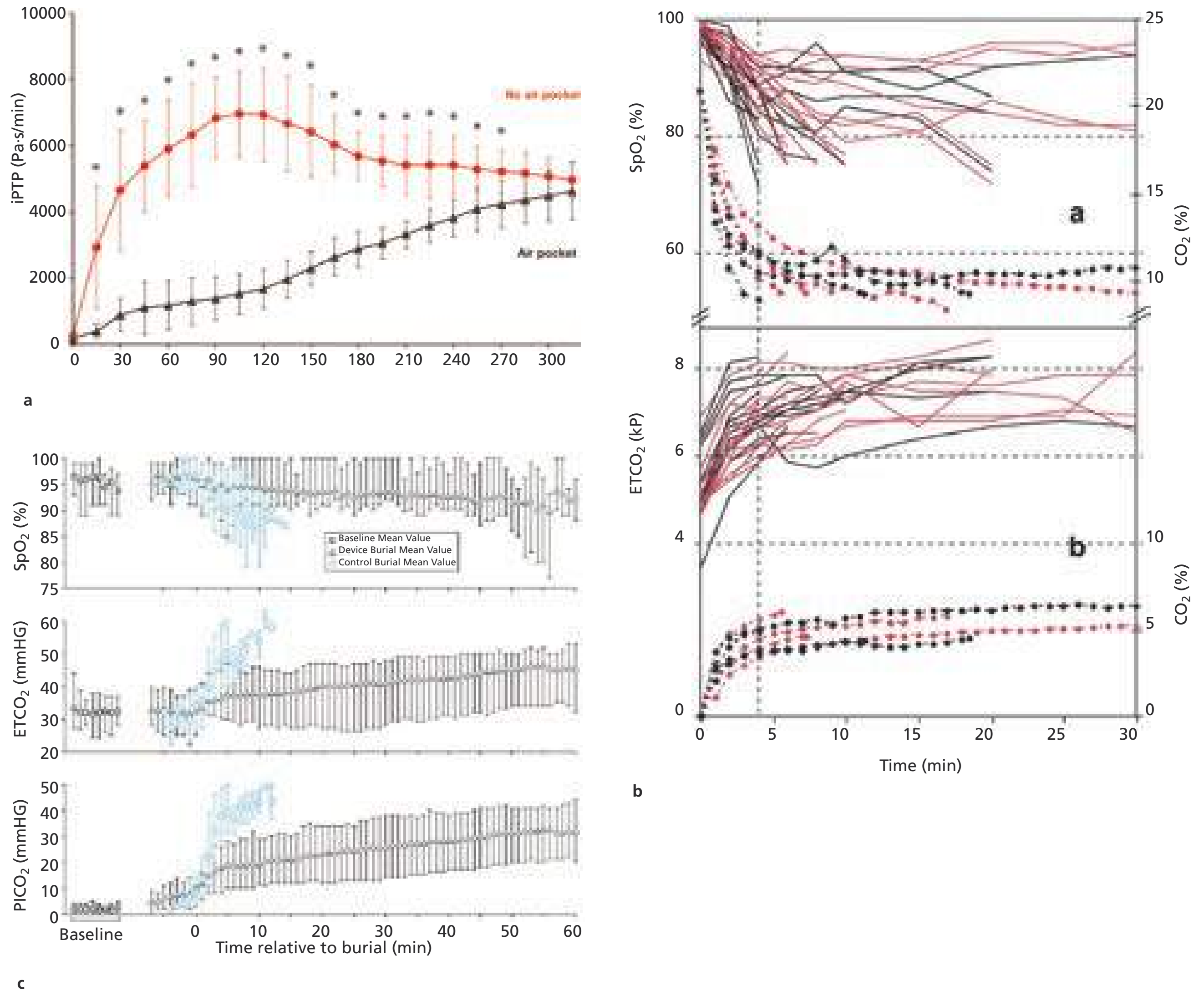


Figure 20.6 Pathophysiology of avalanche burial. **(a)** Difference in breathing effort expressed as imposed pressure-time product (iPTP) caused by snow flow resistance between no air pocket and 1-L air pocket(*) *p* ≤0.05. (Modified from [38], with permission.) **(b)** Curves of individual respiratory parameters in persons breathing into an artificial air pocket in relation to time [peripheral oxygen saturation (SpO_2), end-tidal carbon dioxide ($ETCO_2$), and percentage of air-pocket oxygen (O_2), and CO_2]. Colours indicate air-pocket volume: *black* 1 L, *red* 2 L. (Modified from [41], with permission.) **(c)** Mean values and ranges for SpO_2, $ETCO_2$, and $PICO_2$ at baseline and during trials of participants breathing through a device that diverts expired CO_2. (Modified from [42].)

es an increase in tidal volume and minute ventilation. This leads to a vicious cycle of increased CO_2 production and increased O_2 consumption. A strong compensatory ventilatory response was demonstrated, in simulated avalanche burials, by rapid increases in respiratory rate, tidal volume, minute ventilation, and $ETCO_2$. [10, 41, 42] Gas diffusion, may explain why some buried victims can breathe longer than expected for a give volume of air. Gas exchange while breathing in avalanche debris allows the use of large amount of interstitial air entrapped in the snow. At a density of 300 kg/m^3, air comprises almost 70% of the volume of avalanche debris. [10] The porosity of surrounding snow allows O_2 diffusion into an air pocket, where it is gradually consumed by the victim. Avalanche debris also seems to adsorb exhaled CO_2 by allowing diffusion in the opposite direction. A large, effective air space, in the surrounding snow enables prolonged breathing, due to diffusion of O_2 and CO_2 (Figure 20.7). [10] Other experimental studies showed that gas diffusivity is strongly correlated with snow density. [36, 41, 42] Epidemiological data from Canada suggest that there is lower survival in high density snow in maritime climates than in low density snow in continental climates. [15] Higher snow density is associated with an increased rate of decrease in SpO_2 and increase in $ETCO_2$. [10]

Asphyxia

Approximately 70% of completely buried avalanche victims die of asphyxia within 35 min. No victim with an obstructed airway has survived burial longer than 35 min. [27, 43] Asphyxia in a buried victim can result from obstruction of the upper airway due to inhaled avalanche debris or vomitus, airway obstruction due to anatomical causes, compression of the chest by avalanche debris, [32] ice-mask formation, or a combination of hypoxia and hypercapnia due to inadequate gas diffusion. Asphyxia from any cause results in hypoxic cardiac arrest. [10, 40–42] The initial effort of breathing in avalanche debris with a patent airway but no air pocket likely increases the likelihood of asphyxia due to significantly increased work of breathing that increases metabolic rate (O_2 consumption and CO_2 production). [38] Epidemiological data suggest an increased likelihood of asphyxia due to the lack of an air pocket. There was a lower survival of avalanche victims in Austria who had no air pocket compared to those with an air pocket. Of victims buried ≤15 min, 69% without an air pocket survived, compared to 95% with an air pocket ($p < 0.001$). Of victims buried >15 min, only 4% without an air pocket survived compared to 67% with an air pocket ($p < 0.001$). [27] Based on survival curves from Canada, asphyxia seems to occur earlier in avalanche burials in maritime climates, where snow density is higher, compared with avalanche burials in continental climates. [15] Avalanche victims buried in high density avalanche debris likely have a higher risk of normothermic hypoxic cardiac arrest due to a low concentration of O_2 in the air pocket and to hypoxia worsened by high CO_2.

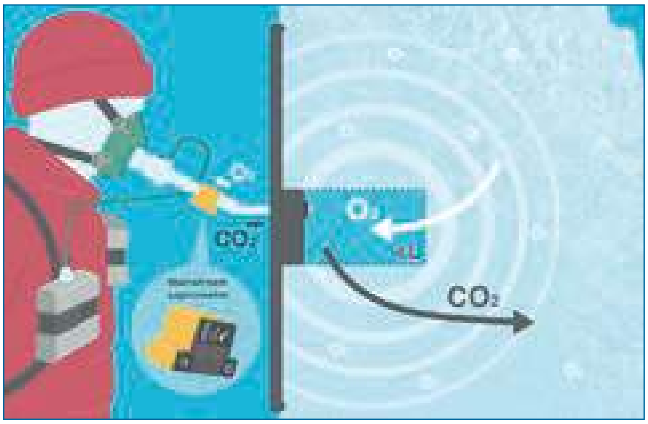


Figure 20.7 Breathing into artificial avalanche debris. Snow is a highly porous medium containing large amounts of interstitial air, ~70% air with a snow density of 300 kg/m^3. Porosity seems to favour oxygen (O_2) diffusion from snow debris into an air pocket and exhaled carbon dioxide (CO_2) absorption by surrounding snow. *$ETCO_2$* end-tidal CO_2, *L* litre, *O_2* oxygen. (Modified from [10].)

Triple H Syndrome: Hypothermia, Hypoxia, and Hypercapnia

Survival past 36 min has been reported in up to ~25% of completely buried avalanche victims who were able to breathe under the snow without sustaining critical levels of O_2 and CO_2, before hypothermia could exert a protective effect on the central nervous system. The term, “triple H syndrome,” signifying the combined effect of hypoxia, hypercapnia, and hypothermia was coined in 2003. [41] A porcine model was used to investigate the cardiovascular effects of breathing under avalanche debris with or without sufficient O_2 supply and CO_2 clearance. [44] Anaesthetised pigs were positioned so that they would breathe directly into simulated avalanche debris. With a closed air pocket of 1 or 2 L in high density snow (>400 kg/m^3), the pigs rapidly cooled to a mild or moderate level of hypothermia with progressive hypoxaemia and hypercapnia (Figure 20.8). [44] The rate of cooling then increased due to insufficient O_2 supply and CO_2 clearance. The initial response was a mixed respiratory (hypercapnia-induced) and metabolic (lactate-induced) acidosis with decreased cardiac output. Asystole occurred between 22 and 53 min with a core temperature between 31 and 34 °C. When the pigs were breathing into an open air pocket, the decrease in O_2 and increase in CO_2 did not reach critical levels and there was no acidosis. Cardiac output decreased gradually, which allowed rapid and progressive cooling to a moderate or severe level of hypothermia. Finally, hypothermic cardiac arrest occurred between 83 and 178 min, with core temperatures between 21 and 28 °C.

Clinical, epidemiological and experimental data suggest that avalanche victims breathing into an air pocket in low density avalanche debris or into a large or open air pocket under any conditions might still develop triple H syndrome. Under favourable conditions, prolonged time to onset of a critical level of hypoxia, may be preceded by early hypercapnia, [10] which might accelerate the cooling rate and lead to the development of hypothermia, due to hypercapnia-induced unconsciousness, vasodilation, and inhibition of shivering. [39, 40]

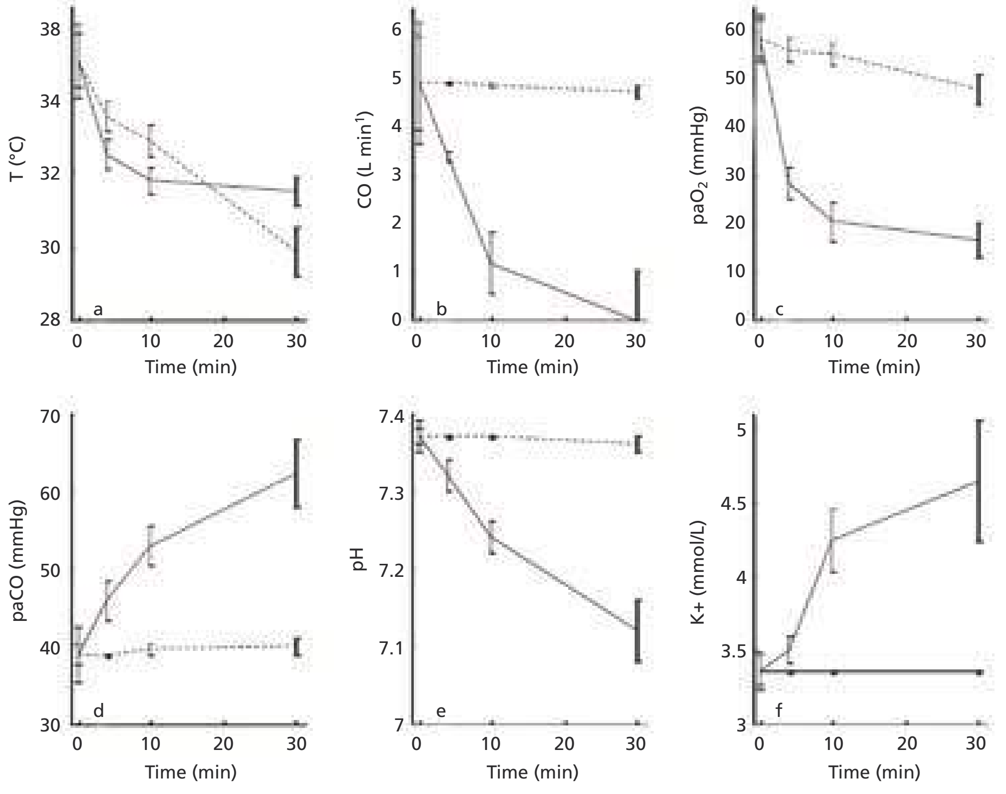


Figure 20.8 Mean and standard error of pulmonary artery temperature (T), cardiac output (CO), arterial oxygen partial pressure (paO$_2$), arterial carbon dioxide partial pressure (paCO$_2$), arterial pH, and serum potassium (K$^+$) for the air pocket group (solid line) and ambient air group (dashed line). (Modified from [44].)

Pulmonary Oedema in Avalanche Burial

Pulmonary oedema can be a complication of avalanche burial with various possible aetiologies. Since 1981, 4 cases have been reported in victims with both open and obstructed airways who were buried between 5 and 127 min. [6, 45–47] The true incidence and risk of pulmonary oedema after avalanche burial are unknown. Pulmonary oedema associated with avalanche burial is very likely under-reported.

Suspected aetiologies include negative-pressure pulmonary oedema, due to increased central venous return and transcapillary pressure gradient, pulmonary arterial hypertension, and pulmonary capillary leak. [48, 49] Pulmonary capillary leak may be caused by the significantly increased work of breathing under avalanche debris without an air pocket, especially in the initial phases, [38] combined with hypoxia-induced pulmonary arterial hypertension and left ventricular insufficiency. Hypothermia-induced pulmonary oedema may occur after burial. A forceful inspiration against a glottic obstruction can result in intrathoracic pressures as low as –13 kPa, which are sufficient to induce non-cardiogenic pulmonary oedema. [50]

Pulmonary oedema of avalanche burial is a diagnosis of exclusion. The differential diagnosis includes aspiration and pulmonary contusion, as well as a negative pressure pulmonary oedema which is a form of non-cardiogenic pulmonary oedema that results from a high negative intrathoracic pressure caused by upper airway obstruction. This is often associated with the presence of haemorrhage, as shown by Glisenti et al. in a report with computed tomography (CT) scans. [45] Prognosis can be excellent with timely diagnosis and treatment.

Non-Avalanche Snow Burial

Non-avalanche snow burial (NASB), also called non-avalanche-related snow immersion, is different from avalanche burial, but death is still caused by the impossibility of breathing under the snow. Since 2010, only one review article and one small burial simulation study have appeared in the published literature. [51, 52] NASB has been reported mainly in the Sierrra Nevada of California, in the Cascade Mountains of Oregon and Washington in the USA and in the Coast Range of British Columbia, in Canada. [51, 53]

NASB occurs when backcountry recreationists fall head first into snow-filled tree wells or deep powder snow. Victims who are unable to extricate themselves may die from asphyxia when snow compacts around the head. No evidence exists as to the exact mechanism of asphyxia. The risk of NASB asphyxiation is up to 10 times as high as avalanche death within the boundaries of ski resorts in the USA. Although the duration of burial necessary to cause death is not known, death can occur in a short period. [51] A simulated burial study found that struggling caused the victim to sink deeper into the snow. When the victim was upside down, sinking was accentuated when skis or snowboards were removed. [54]

ACCIDENTAL HYPOTHERMIA

Accidental hypothermia is the main cause of death in only about 1% of completely buried avalanche victims, but hypothermia should be suspected in victims who do not die of asphyxia within 35 min, especially in victims buried for >60 min. [43] With a core temperature drop of 1 °C, there is initial stimulation of cerebral metabolism. With further cooling, there is a decrease in oxygen consumption of ~6% for every 1 °C reduction in core temperature. [29] Level of consciousness, mental functioning, and cardiovascular and respiratory functions are often not determined by core temperature alone. Trauma as well as low O_2 and high CO_2 levels commonly complicate the pathophysiology of accidental hypothermia in avalanche victims (see Chapter 19, Accidental Hypothermia, and Chapter 43, In-Hospital Treatment of Accidental Hypothermia). Accidental hypothermia by alone causes hypokalaemia in the absence of trauma and asphyxiation. [55] However, serum potassium can rise due to severe acidosis and hypoxia in avalanche victims with triple H syndrome when gas exchange is inadequate after prolonged burial. Mixed respiratory and metabolic acidosis with serum potassium increases have been observed in animal studies with inadequate gas exchange. [44] If cooling precedes critical levels of hypoxia, hypothermia will delay the rise of potassium levels. [54] Avalanche victims in hypothermic cardiac arrest probably experience a final rise of serum potassium related to cell depolarisation and cell lysis. [56] High serum potassium was associated with signs of cerebral hypoxia on CT scans of victims with complete avalanche burial and cardiac arrest. [57] Serum potassium should be used for the triage of avalanche victims only if they were buried for longer time. [58]

A mean core cooling rate of 3 °C/h has been calculated for entire time between avalanche burial and hospital admission. [59] Calculated, individual cooling rates during snow burial varies widely, from 0.1 °C/h to 9 °C/h. [60] It generally takes at least 1 h after avalanche burial to reach a core temperature <30 °C. [61] Hypercapnia during burial increases the cooling rate through increased respiratory heat loss, rather than because of diminished shivering thermogenesis. In human experimental studies with exposure to moderate cold stress under avalanche debris, hypercapnia led to a >70% increase in the cooling rate. [39, 40]

There is an additional risk of post-extrication cooling when avalanche victims are exposed to low ambient temperatures during rescue operations. [58]

TRAUMA

Trauma can be the cause of death in avalanche victims. Trauma can also increase morbidity and mortality due to primary aetiologies, including asphyxia, hypothermia, and triple H syndrome. Avalanche victims can sustain any type of injury. [37, 62] Blunt trauma due to collisions with objects such as trees, rocks or ice, or due to churning or crushing effects of snow during the descent can cause severe injuries. [15, 62, 63] In a Canadian study collisions with trees caused 68% of trauma deaths. [63] Head, cervical spine, chest, and extremities are the most frequent sites of severe injuries. [18, 36, 37, 62–65] Closed head injuries were found in ~60% of avalanche burial victims in Utah, USA. [65] Although injuries may not be severe enough to cause death, a depressed level of consciousness due to injury may decrease survival probability by predisposing to asphyxiation. In a Canadian study, 42% of fatalities had isolated head injuries. [63] Cervical spine dislocations were the main cause of traumatic death in an Austrian study. [37] Chest trauma was the most common isolated injury in Canada (46%). As with head injury, chest trauma may decrease survival by causing asphyxiation. [63] Transection of the thoracic aorta and intra-abdominal bleeding have also been reported. Minor injuries and skin abrasions likely remain unreported. [23, 32]

Trauma as the primary cause of death in avalanche victims who were not buried in buildings or vehicles varies with location and time. Trauma accounts for 6–24% of avalanche deaths in Europe and North America. In Canada the proportion of avalanche deaths related to trauma has been reported to be 18%. [15] Median injury severity score (ISS) in trauma deaths was 30 [inter-quartile range (IQR) 22–75] in Canada but exceeded 15 in 13% of cases in which the cause of death was asphyxia. [63] This supports the hypothesis that trauma can contribute to death due to asphyxia. The mortality rate also increased with increasing depth of burial. Mortality rate was almost 5 times higher if a victim was buried >120 cm compared to ≤40 cm, independent of the duration of burial. [27]

CASE REPORT 20.2

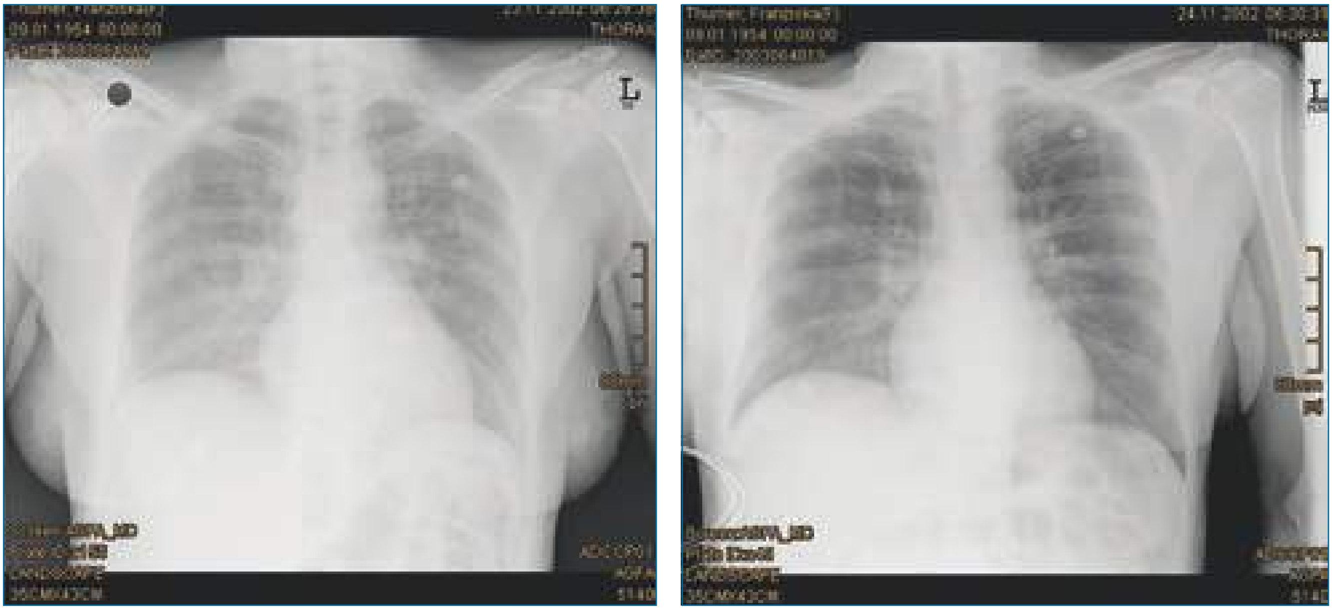
A rare but life-threatening complication

In 2012, a group of backcountry skiers triggered an avalanche. One 48-year-old woman was completely buried. The other members of the group were not injured. The group immediately called for help by mobile phone and activated HEMS. At the same time, all the other group members searched for the missing person using their transceivers and avalanche probes. After 20 min, they located the victim 50 cm below the surface and extricated her. She was fully responsive, spontaneously breathing, and did not complain of any serious injury. When the rescue helicopter arrived at the scene, the emergency physician documented a GCS of 14. ECG showed sinus tachycardia with a heart rate of 130 bpm. Blood pressure was normal. Core temperature was 32 °C by epitympanic thermometer. At first glance, the victim was uninjured and had fortunately survived without any sequelae. Shortly afterwards, however, on a second assessment, the physician noticed dyspnoea and detected crackles on auscultation of the lungs. SpO_2 was 86%, representing moderate hypoxaemia. The victim remained alert and breathing spontaneously. She received O_2 at 6 L/min oxygen by face mask, was loaded into the helicopter, and was transported to the closest hospital for observation. On arrival in the emergency department, the victim still had a GCS of 15, but with worsening respiratory status, with central cyanosis, tachypnoea, and increased cough, although supplementary oxygen increased the SpO_2 to 92%. She was tachycardic with a heart rate of 120 bpm. She had a normal blood pressure of 120/70 mmHg. The core temperature was 33.8 °C which is mildly hypothermic. A CT scan of the head was normal. A chest CT showed bilateral alveolar fluid accumulation consistent with pulmonary oedema, without any other abnormalities. During the investigations, the victim deteriorated further. After ~40 min, she showed clinical signs of pulmonary oedema with progressive dyspnoea, tachypnoea, severe cyanosis, and widely distributed crackles on auscultation. At this point, rapid sequence intubation was performed. The victim was ventilated with an FIO_2 of 1.0 and PEEP of 10 cm H^2O. However, she remained hypoxic and hypercapnic, with PaO_2 73.6 mmHg and $PaCO_2$ 56.2 mmHg. A chest x-ray showed diffuse bilateral pulmonary oedema (Figure 20.9a). The victim was transferred to the ICU and rewarmed using forced air. Within 3 h, normal core temperature was achieved and oxygenation improved markedly. FiO_2 was reduced to 0.35. After 8 h of artificial ventilation, the victim was breathing spontaneously with continuous positive airway pressure (CPAP). On day 2, she was extubated, regained consciousness, and did well with supplementary oxygen and intermittent CPAP. On day 3, respiratory and cardiovascular parameters and chest x-ray were normal (Figure 20.9b). The victim was discharged from hospital. She recovered quickly at home.

This victim had no known risk factors for pulmonary oedema, had no significant past medical history, and was athletic.

Keynotes

When caring for a victim after complete avalanche burial, the risk of pulmonary oedema should be considered, even if the victim presents without cardiopulmonary symptoms at extrication. Completely buried victims should be transferred to a hospital capable of treating pulmonary oedema with oxygen administration and positive-pressure ventilation.



a

b

Figure 20.9 **(a)** Chest x-ray of a completely buried avalanche victim showing bilateral pulmonary oedema. **(b)** On day 3, the chest x-ray was normal. (Modified from [45].)

Trauma is the main cause of death in summer avalanches and is associated with a higher likelihood of fatality in catastrophic avalanches. [26, 34]

ON-SITE MANAGEMENT

AID BY FIRST RESPONDERS

Survival from complete avalanche burial is very time-dependent, as discussed in the sections on Epidemiology and Pathophysiology. In the first 15 min the chance of extricating a victim alive is as high as ~90%. [26] Depending on snow characteristics, the onset of asphyxia occurs between 15 and 20 min after burial. This highlights the importance of immediate rescue by uninjured companions at the site of an avalanche. [30] Companion rescue can give up to a fourfold increase in the likelihood of survival.

Once at the scene, it takes at least 3–5 min to locate a completely buried person. Digging out a person from a depth of 1 m takes ~10 min. These times can be shorter if 2 or more persons are searching and digging simultaneously. All uninjured companions should remain at the scene for at least 20 min to help in rescuing the victim. Rescue should be accomplished as rapidly as possible after an avalanche, as every minute is crucial for survival in this early stage. An emergency call should be made as soon as possible if cell phone service is available. If there is no cell phone service, a member of the party should leave the site to make the call only after 20 min.

As soon as the victim's head is free, a rescuer should clear the airway. If there is no breathing or pulse and no movement, rescuers should start cardiopulmonary resuscitation (CPR) including rescue breathing. Although the Adult Basic Life Support guidelines of the European Resuscitation Council encourage chest compression only CPR by untrained lay rescuers for victims of sudden cardiac death, the guidelines strongly recommend chest compressions with rescue breathing for successful resuscitation from asphyxial cardiac arrest. [66]

The position of the victim's body under the snow significantly affects the duration of extrication and the possibility of providing immediate rescue breathing and chest compressions (see Epidemiology). In almost half of completely buried victims, administering rescue breaths is not possible before complete extrication. Attempts to administer rescue breathing may prolong the extrication process. [31] Ideally, first responders should be trained how best to approach a buried victim who is in a prone (face down) position. Rescuers should attempt to clear the airway as soon as possible. If the victim is supine (face up), chest compressions with rescue breathing can be initiated when the head and the chest are exposed, before exposure and extrication of the entire body.

After being extricated, the victim should be insulated from cold using available materials, such as parkas, wind shells, hats, gloves, bivouac sacks and aluminium blankets.

Keynotes

Uninjured companions have the best chance of extricating a victim alive if a search is initiated as promptly as possible after an avalanche. All companions should remain at the scene for at least for 20 min to help facilitate the rescue. An emergency call can be delayed if there is no cell coverage. A victim who is not breathing and who does not have a pulse or other signs of life, such as movement, should immediately receive CPR including rescue breathing as well as chest compressions.

ORGANISED AVALANCHE RESCUE

Helicopter Rescue

An avalanche accident can be a medical emergency and should prompt a helicopter rescue if available. Helicopters have significant advantages compared to ground rescue. HEMS operations decrease response times and risks to the rescue teams by transporting rescuers safely above potentially hazardous terrain. Helicopters can transport rescuers and equipment rapidly and can evacuate victims more rapidly than any other means of transport, except over very long distances. Helicopters can also be used to search from the air with avalanche transceivers and RECCO®. However, air rescue operations may be restricted by adverse weather conditions with low visibility and wind. Night flights are inherently risky and are allowed only in some countries.

In many countries, regional dispatch centres activate and coordinate ground and air rescue operations, activate Emergency Medical System (EMS) and check the capacity of destination hospitals. In some densely populated regions and ski areas with a high incidence of avalanches, 2 helicopters may be available for simultaneous activation to carry rescuers, dog handlers, and trained healthcare personnel to the avalanche site as rapidly as possible. With this strategy, at least in some populated reagions, it may be possible for organised rescue to located and extricate victims within 35 min of burial. [33]

Keynotes

For avalanche rescue, if conditions allow helicopter flight, helicopters should be given priority over ground rescue teams, as they are faster, safer, and more efficient.

Ground Rescue

When air rescue is not possible, ground rescue teams can be dispatched. Ground rescue teams may include healthcare personnel trained in basic life support (BLS) and advanced life support (ALS), such as emergency medical technicians, paramedics, emergency physicians, volunteer or professional rescuers, dog handlers, and, in some cases, backup teams such as mountain guides, ski patrollers, or firefighters. Organised rescue differs from companion rescue because the response time is typically longer, resources are more available, and group size is larger. Because organised rescue teams take longer than companions to reach avalanche victims, the likelihood of survival is greater with companion rescue than with organised rescue.

SAFETY, COMMAND, AND SCENE MANAGEMENT

"Safety first" should be the guiding principle for rescue operations. The risks incurred by rescue teams must be weighed against the potential benefits for the victim.

In 2001, 2 mountain rescuers were killed by an avalanche in the Tatra Mountains in Poland. In 2009, 4 Italian avalanche rescuers lost their lives in an avalanche during SAR operations. In 2010, a Swiss rescue physician died after being buried by a second avalanche during a rescue. These events emphasise that risk assessment should be of paramount importance for every avalanche rescue operation. Immediately after arrival at the site, at least one person should assess the scene for safety. The safety officer should be positioned at a vantage point that allows visualisation of the entire scene in order to constantly reassess safety throughout the rescue.

Although the risk to the rescuers should always be the first priority, it may be justified to take greater risks soon after the accident and less risk after longer burials, since the probability of survival decreases over time. Respectively, after long burial rescue teams may delay operations (Figure 20.10). [23]

Avalanche scene management is important if large groups of rescuers and multiple resources are involved. Cooperation between rescue teams, dog handlers, and medical personnel should be coordinated in order to min-

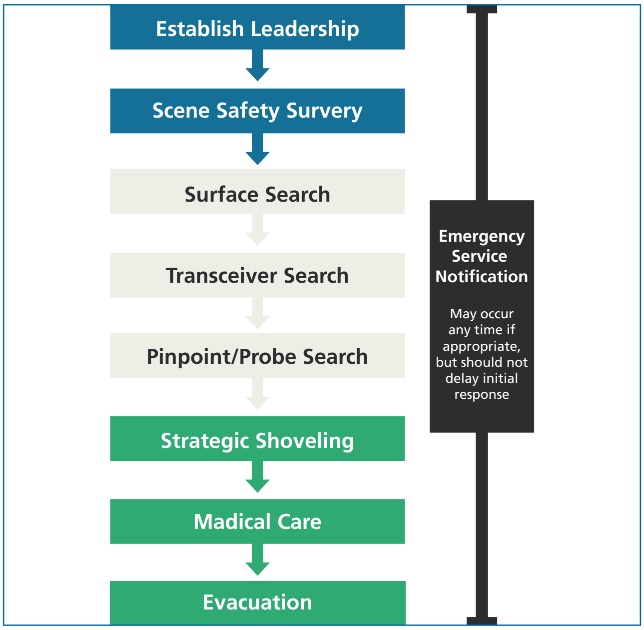


Figure 20.10 Avalanche rescue sequence. (Modified from [23].)

imise the number of rescuers and time spent in the danger zone. Avalanche path boundaries should be marked to keep unauthorised people from entering. All persons entering and leaving the operational area must be tracked.

> **Keynotes**
>
> Safety comes first! The risk of a second avalanche must be constantly assessed throughout a rescue. The safety plan should be continuously revised based on ongoing risk assessment.

EQUIPMENT

Every ground or air rescuer, who enters avalanche terrain must be properly equipped with an avalanche transceiver and, ideally, an avalanche airbag. An avalanche airbag offers protection on approach as well as on scene. Rescuers should be dressed warmly with full winter equipment, including suitable boots or snowshoes to walk safely on avalanche debris.

Medical equipment should be protected from the cold. Electronic instruments should have full batteries. Rescue equipment should include rescue bags, which are similar to sleeping bags, but modified for rescue use, or other insulating layers, aluminium blankets, chemical heat packs, a thermometer suitable for measuring core temperature, a cardiac monitor/defibrillator. [25]

SEARCH

Organised search for a completely buried avalanche victim can rely on visual and acoustic methods, avalanche dogs, avalanche transceivers, the RECCO® rescue system, and probing. Companions and rescuers should immediately search for clues on the surface and acoustic signs (calling out and listening for the victim to cry for help). Rescue dogs are trained to detect buried victims by scent. The initial dog search should be with the handler before the terrain is contaminated by helicopter fumes. The search continues with avalanche transceivers and the RECCO® system, if available. [67] If these attempts fail, rescuers should begin a probe line search. A probe line leader is necessary to ensure accuracy and effectiveness. Professional healthcare personnel should be at the scene to treat the victim during and after extrication.

GUIDELINES FOR ON-SITE MEDICAL TREATMENT

The first algorithm was published for on-site triage of avalanche victims with asystole in 1996. [68] Recommendations for on-site care of avalanche victims were adopted by the International Commission for Mountain Emergency Medicine (ICAR MedCom) in 2002. [69] In 2010, guidelines were approved by the International Liaison Committee for Resuscitation (ILCOR) and incorporated into the European Resuscitation Council (ERC) (Figure 20.11) and American Heart Association (AHA) guidelines. [70, 71] In 2015, the ERC dedicated a section of the resuscitation guidelines in special circumstances to mountain emergency

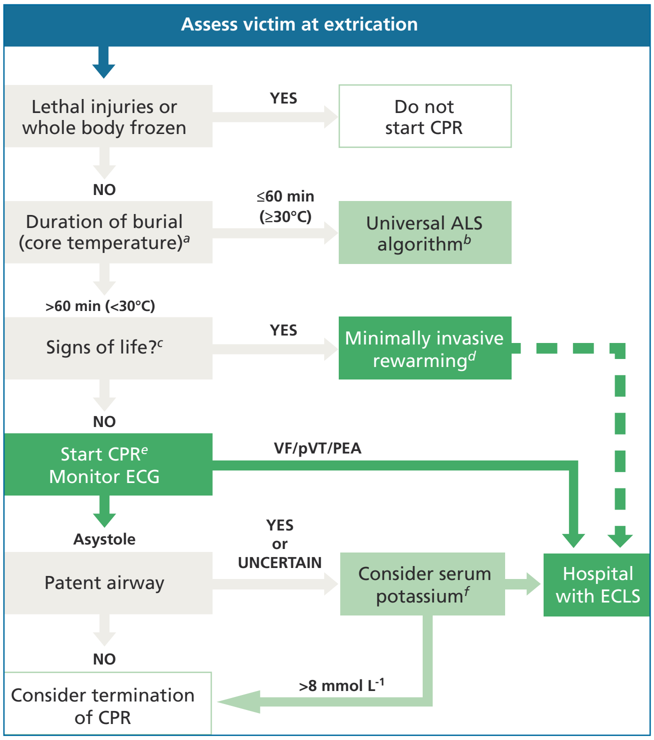


Figure 20.11 Avalanche accident algorithm. Management of completely buried victims. *ALS* advanced life support, *BLS* basic life support, *CPR* cardiopulmonary resuscitation, *ECLS* extracorporeal life support.
[a] Core temperature may substitute if duration of burial is unknown.
[b] Transport victims with injuries or potential complications (e.g. pulmonary oedema) to the most appropriate hospital.
[c] Check for spontaneous breathing and pulse for up to 1 min.
[d] Transport victims with cardiovascular instability or core temperature <28°C to a hospital with ECLS.
[e] Withold CPR if risk to the rescue team is unacceptably high.
[f] Crush injuries and depolarising neuromuscular blocking drugs may elevate serum potassium. (Modified from [61].).

medicine (MEM) and avalanche rescue. [66] The Wilderness Medical Society (WMS) published Practise Guidelines for Prevention and Management of Avalanche and NASB Accidents in 2017. [23]

EXTRICATION, INITIAL ASSESSMENT, AND MONITORING

In an organised avalanche SAR operation, the duration of victim burial usually exceeds 35 min. The victim can be expected to be mildly or moderately hypothermic. For this reason, extrication and the initial assessment should be carried out as carefully, rather than as rapidly, as possible. The rescuers should first assess the position of the victim and should dig a channel towards the victim's head (Figure 20.12). The rescuer who uncovers the face should check whether there is an air pocket in front of the mouth and nose and should note whether the airway is open or is blocked by snow or debris. Ideally, these observations should be made by a rescuer trained in ALS or by an emergency physician. Knowing whether there was an air pocket is crucial for decisions concerning resuscitation and rewarming. Digging around the victim's head should be carried out with great care and ideally from the side to avoid injuring the victim or destroying an air pocket. If the airway is blocked, it should be cleared of snow or other debris and kept open. If the victim is unconscious, the rescuers should check for vital signs (movements, breathing, and carotid pulse).

If the position of the victim allows, the first assessment can be made in the hole before complete extrication. An ECG should be obtained as soon as possible.

If possible, core temperature should be measured using an oesophageal probe or a low reading thermistor-based epitympanic thermometer (see Chapter 19, Accidental Hypothermia). Pulse oximetry is not mandatory, as it may be inaccurate with cold exposure due to peripheral vasoconstriction.

As soon as the victim is extricated, a first assessment should be made to look for vital signs and evident injuries. Cardiac activity and core temperature should be continuously monitored throughout the rescue for early detection of after-drop or circum-rescue collapse. If a defibrillator is available, defibrillator pads should be placed. The victim should be protected from cold and wind (Figure 20.13).

Figure 20.12 A rescuer reaching a victim by digging a channel into avalanche debris towards the victim's head. (Courtesy of Eurac Research/Ivo Corrà.)

Figure 20.13 Victim protected from cold and wind at the site of the avalanche. (Courtesy of Eurac Research/Ivo Corrà.)

Keynotes

Oesophageal temperature measurement correlates well with cardiac temperature. An oesophageal probe is placed with the distal end in the lower third of the oesophagus. Epitympanic measurement using a thermistor is a reliable alternative but may register a much lower temperature than actual core temperature if the environment is very cold. The probe must be well insulated and the external auditory canal must be free of snow or water. Epitympanic probes that are not manufactured for outdoor use, should not be used at the scene.

TRAUMA

Chest and head trauma are the most frequent injuries in avalanches. Spinal, abdominal, and limb injuries are less frequent (see Epidemiology). Current resuscitation guidelines emphasise stabilisation of injuries, advanced airway management, haemorrhage control, and prompt evacuation to definitive care (see Chapter 14, Multiple Trauma).

Rescuers and healthcare professionals should provide spinal motion restriction, splint limb fractures, and administer effective analgesia during on-site management and transport. In severe head trauma, early intubation and normocapnic ventilation improve outcomes. Tourniquets can be life-saving in exsanguinating limb injuries. Immediate chest decompression is mandatory for tension pneumothorax. For pneumo- or haemothorax, a thoracostomy tube should be considered, particularly before evacuation by helicopter if a climb in altitude is expected and the victim is intubated (see Chapter 14, Multiple Trauma).

The combination of trauma and hypothermia can be fatal. Immediately after extrication, avalanche victims with injuries should be protected from further cooling by using multi-layer, full-body insulation and active external rewarming with heat packs on the trunk (see Chapter 19, Accidental Hypothermia). For trauma victims, on-site management should be kept to a minimum to expedite direct transport to a dedicated trauma centre.

In victims of traumatic cardiac arrest, survival is low and prolonged CPR associated with poor neurological outcome. After 15 min of unsuccessful CPR, or in a multi-victim accident, termination of CPR at the scene is at the physician's discretion, especially if human resources are limited. [72, 73]

ADVANCED AIRWAY MANAGEMENT

For unconscious avalanche victims, advanced airway management provides effective oxygenation and reduces the likelihood of aspiration. Especially in pre-hospital settings with long transport times, endotracheal intubation with ventilation is associated with improved survival. Endotracheal intubation can, rarely, provoke ventricular fibrillation in victims with moderate or severe hypothermia, usually at a core temperature <30 °C. The small risk is far outweighed by the advantages of airway control.

Whether ventilation in unconscious avalanche victims should target normocapnia ($ETCO_2$ 35–45 mmHg) is controversial. Hypocapnia ($ETCO_2$ <35 mmHg) due to excessive ventilation or to decreased metabolic production of CO_2 decreases cerebral blood flow due to vasoconstriction and can induce arrhythmias as frequently as hypercapnia, especially in victims with traumatic brain injuries or hypothermia. Normoxia may protect against malignant arrhythmias. Normoxia improves myocardial stability in asphyxiated as well as in severely hypothermic victims. It seems likely that adequate oxygenation might help to reduce the risk of post-rescue collapse.

Endotracheal intubation requires training and practise and should be done only by qualified personnel (Figure 20.14). Placement of supraglottic devices is easier and safer than endotracheal intubation. [74] For rescuers who are not experienced in advanced airway management, ventilation is most effective with mouth-to-mask or bag valve mask techniques. For a survivor with an unsecured airway, hospital transport should be expedited for advanced airway management. [29]

Figure 20.14 Endotracheal intubation by healthcare personnel during an organised avalanche rescue. Advanced airway management enables effective oxygenation and reduces the likelihood of aspiration for unconscious victims. (Courtesy of Eurac Research/Ivo Corrà.)

Keynotes

Endotracheal intubation by direct laryngoscopy may be difficult on a snow surface due to bright light. Covering the intubator's head with a jacket or blanket can improve the view with the laryngoscope.

DRUGS FOR ADVANCED LIFE SUPPORT

For controlled volume resuscitation and administration of drugs, intravenous or intraosseous access should be obtained. Obtaining peripheral intravenous access can be difficult if the victim is hypothermic with peripheral vasoconstriction and centralised circulation. It is usually easier to obtain intraosseous access under these circumstances.

In a hypothermic victim, aggressive volume replacement is not indicated without central venous pressure monitoring, as cardiac output can be reduced, and circulating volume contracted due to peripheral vasoconstriction. In a cold environment, infused fluids should be warmed to ~42 °C. This can be difficult in the field. Fluid infusion should be delayed until the victim is loaded into a heated ambulance or helicopter.

In a hypothermic victim, particularly if core temperature is <30 °C, administration of ALS drugs is controversial. For a victim in cardiac arrest, vasopressors such as epinephrine are intended to augment myocardial blood flow and increase return of spontaneous circulation (ROSC). Effectiveness of vasopressors has never been demonstrated in a hypothermic victim with core temperature <30 °C. The impact of epinephrine on survival and neurological outcome is mixed. Larger doses of epinephrine may be associated with unfavourable neurological outcome. In a hypothermic victim, peripheral vasoconstriction may worsen coexisting frostbite. The ERC 2015 guidelines recommend withholding epinephrine if core temperature is <30 °C, whilst the AHA guidelines state that it may be reasonable in hypothermia to consider epinephrine administration during cardiac arrest according to the standard ALS algorithm. [66, 71]

The benefit of antiarrhythmic drugs in hypothermic victims is also unclear. Many arrhythmias, including bradycardia, atrioventricular blocks, atrial fibrillation, and nodal rhythms are benign, reversible with rewarming and require no further treatment if perfusion is adequate. Transcutaneous pacing is likely to be ineffective and is not recommended. [75]

Most intravenous drugs for induction of anaesthesia can cause cardiovascular depression. Ketamine is likely to be safe in a hypothermic victim, but the sympathomimetic effects could theoretically cause problems for an irritable heart. Neuromuscular transmission decreases in hypothermia, and sensitivity to non-depolarising muscle relaxants increases. Hypothermia also reduces the systemic clearance of cytochrome P450 which is involved in the metabolism of many drugs, such as propofol and ketamine. If depolarising muscle relaxants such as suxamethonium are used for paralysis to obtain favourable intubating conditions, the potential to increase serum potassium should be taken into account. This may affect subsequent resuscitation or advanced rewarming decisions.

To prevent unpredictable toxic and arrhythmogenic effects in a hypothermic victim, drugs should be used with great care. Epinephrine and antiarrhythmic drugs should not be used when core temperature is <30 °C. When core temperature is between 30 and 35 °C, one strategy is to administer smaller doses with long intervals between doses. Use of small doses is also desirable for induction of anaesthesia. [29]

Providers should institute continuous ECG monitoring, should place defibrillator pads during rescue and transport and should be prepared to start CPR.

Keynotes

In a hypothermic avalanche victim in the field, aggressive volume replacement is not indicated. Administration of vasopressors is controversial. Vasopressors should be withheld if the core temperature is <30 °C. Doses for induction of anaesthesia should be smaller than usual for a normothermic victim and should only be repeated at longer than usual intervals.

HYPOTHERMIA PREVENTION AND TREATMENT

Mild Hypothermia

If a victim is fully responsive and shivering, the core temperature is unlikely to be below 30 °C. Although exercising can rewarm a hypothermic victim more rapidly than shivering, providers should be cautious with avalanche victims who may have sustained trauma. Allowing a victim of accidental hypothermia who is not already standing or sitting to exercise before providing insulation can cause a clinically significant after-drop, resulting in a lower core temperature before exercise rewarming occurs. A responsive victim who may be hypothermic should be kept as warm as possible, given calorie replacement, and observed before exercising. After this time period of observation, the alert victim may be allowed to stand. If the victim can stand without difficulty, exercise intensity should start low and increase gradually as tolerated. The victim should be closely monitored and if the condition worsens, the victim should stop exercising and be treated accordingly (see Chapter 19, Accidental Hypothermia). An alert victim in hypothermia stage I without arrhythmias and with normal blood pressure may be transported to the nearest hospital for observation. [25]

Moderate to Severe Hypothermia

An avalanche victim who is not fully responsive or who is unable to walk should be extricated without unnecessary movement and immobilised on a stretcher in a horizontal position to avoid after-drop and circum-rescue collapse due to ventricular fibrillation. Gentle handling should be a priority over speed during extrication. Although it is not always possible to avoid rough handling, movements of the limbs and trunk should be carried out slowly and gently. If the victim is neither shivering nor moving, exposure to cold and wind after extrication can cause a rapid increase in the cooling rate, with an increased risk of ventricular arrhythmias and cardiac arrest, particularly if consciousness is impaired. Pre-hospital insulation and application of external heat immediately after extrication is mandatory for all immobile avalanche victims.

Keynotes

Multi-layer packaging of the victim should include an external heat source, such as chemical heat packs, applied to the chest but not directly to the skin because of the risk of burns. The victim should then be wrapped in the thickest available dry insulation, usually an insulated rescue bag or sleeping bag, with a vapour barrier outer layer, such as an aluminium blanket or bubble wrap. Removing wet clothes increases victim comfort but results in rapid cooling in a cold or windy environment and is not necessary if the victim can be properly insulated and a vapour barrier placed (Figure 20.13). [23]

If an avalanche victim is unconscious when extricated, core temperature should be measured early to distinguish between severe hypothermia and other causes of unconsciousness, such as asphyxia or traumatic brain injury. The lower third of the oesophagus is the most accurate location for core temperature monitoring if the victim is intubated. Otherwise a thermistor-based, insulated epitympanic thermometer that is designed for outdoor use is a reasonable alternative. The epitympanic temperature may be erroneously lower than the oesophageal temperature if the probe is poorly insulated, the external auditory canal is blocked, or if there is low carotid artery flow or cardiac arrest.

Severely hypothermic avalanche victims who present with a core temperature <28 °C, systolic blood pressure <80 mmHg, malignant ventricular arrhythmias, or cardiac instability should ideally be transported directly to a centre offering ECLS, not necessarily for extracorporeal rewarming but in case ECLS treatment becomes necessary. [76]

CARDIOPULMONARY RESUSCITATION

Detecting signs of life may be difficult in severely hypothermic avalanche victims, as respiration and pulse may be very slow, irregular, and faint. Vital signs should therefore be checked for up to 1 min rather than the 10 s recommended for normothermic victims. [66]

Due to the high death rate from asphyxia and trauma, the likelihood that an avalanche victim who is found in cardiac arrest and resuscitated by an organised rescue team is as low as 19%, and the likelihood of successful rewarming by ECLS is 11%. [77–79] These odds are significantly lower than those for a victim with hypothermia from causes other than avalanche burial. [76] Only one avalanche survivor with an unwitnessed asystolic arrest prior to extrication has been reported in the literature. [80] An avalanche victim with a witnessed cardiac arrest after extrication has a higher likelihood of successful resuscitation.

Various algorithms have been developed to select victims at the scene with potentially reversible cardiac arrest, in order to avoid futile transports with ongoing CPR that increase risk to the rescue teams. In mass casualty incidents these algorithms are designed to avoid delays in treating salvageable victims whilst withholding CPR for victims without signs of life. Stringent triage criteria to reduce the number of futile cases treated with ECLS are also important for economic reasons.

The most recent algorithm for the pre-hospital management of avalanche victims was published by the ERC in 2015. [66] The Hypothermia Outcome Prediction after ECLS (HOPE) score was developed for the in-hospital triage. [81] The ERC algorithm relies on parameters that should be assessed at extrication: duration of complete burial, core temperature, airway patency, vital signs, and ECG. At hospital admission, hyperkalaemia is an important negative prognostic marker suggesting that cardiac arrest from acute asphyxia occurred before cooling.

The cut-off values for on-site triage of avalanche victims in cardiac arrest, proposed by the ERC, are based on a systematic review published in 2010 [43] and a subsequent literature search. Based on the average cooling rate of 3 °C/h with a range from 0.6 °C/h to 9 °C/h, moderate to severe hypothermia may develop after 60 min of burial if the airway is patent. ECLS rewarming is not indicated if core temperature is ≥30 °C. The highest serum potassium in a completely buried avalanche victim who survived to hospital discharge was 6.4 mmol/L. [82]

Based on this analysis, expert consensus and statistical analysis, more stringent cut-off values have been proposed. ECLS with rewarming should not be attempted for an avalanche victim in cardiac arrest if the duration of complete burial was <60 min or core temperature at extrication was >30 °C. If duration of burial was ≤60 min and core temperature was ≥30 °C at extrication, cardiac arrest was likely due to trauma or asphyxia. The victim should receive standard CPR or ALS for at least 20–30 min. If this does not result in ROSC, the chance of survival is minimal. Further attempts at resuscitation should be withheld.

If burial duration is >60 min or core temperature <30 °C, ECG shows asystole, and the airway is blocked by snow or debris, the rescuer or physician should terminate resuscitation. If the airway was patent or if it is not known whether the airway was patent, cardiac arrest may have been due to hypothermia. In that case, it is warranted to attempt ECLS with rewarming. If the ECG shows any electrical activity, including pulseless electrical activity, pulseless ventricular tachycardia or ventricular fibrillation, the victim should be treated with prolonged CPR and transported to a centre for ECLS with rewarming. An avalanche victim who had a perfusing rhythm at extrication and who subsequently had a witnessed cardiac arrest has a particularly good chance of neurologically intact survival. The rate of chest compressions and ventilation should be the same as in standard BLS, with minimal interruptions.

The destination hospital should be contacted in advance to ensure the availability of ECLS. On hospital admission, the HOPE score (see Chapter 19, Accidental Hypothermia, and Chapter 43, In-Hospital Treatment of Accidental Hypothermia) or serum potassium level can be used as additional prognostic indicator. If serum potassium is >8 mmol/L, the chance of survival is miniscule, and CPR should be terminated. If serum potassium is <8 mmol/L, prolonged CPR and treatment with ECLS is indicated.

DEFIBRILLATION

Pulseless shockable rhythms (ventricular tachycardia and ventricular fibrillation) may not respond to defibrillation at a core temperature <30 °C. ERC guidelines recommend limiting defibrillation to 3 attempts until core temperature is 30 °C. By contrast, AHA guidelines suggest further defibrillation attempts during rewarming. [71] Although case reports have shown sustained ROSC after defibrillation at core temperatures <30 °C, most attempts are unsuccessful. If core temperature is <30 °C, a maximum of 3 defibrillations seems reasonable, as every shock may cause myocardial injury. If not successful, CPR should be continued and further defibrillation attempts delayed until ECLS has increased core temperature to 30 °C.

MECHANICAL CHEST COMPRESSIONS

Early CPR improves the survival of hypothermic victims who are in cardiac arrest, but performing continuous manual chest compressions with minimal hands-off time during ground transport or helicopter transport may be difficult or impossible. Mechanical chest compressions are higher quality than manual CPR in technically difficult settings. [83] Mechanical devices should be available in helicopters and rescue vehicles for long or difficult transports in regions with avalanches.

DELAYED AND INTERMITTENT RESUSCITATION

If continuous CPR is not possible for safety reasons, limitation in the number of rescuers, or difficulty performing CPR during extrication and transport, CPR can be delayed or intermittent (see Chapter 19, Accidental Hypothermia, and Chapter 39 Termination of Cardiopulmonary Resuscitation in Mountain Rescue). Successful use of delayed and intermittent CPR has been documented in avalanche victims. A hypothermic victim with a core temperature of 20–28 °C or an unknown core temperature should receive at least 5 min of CPR, alternating with periods of up to 5 min without CPR. If core temperature is <20 °C, pauses in CPR can be extended to up to 10 min. [84]

WITHHOLDING OR TERMINATING CPR

In mountain and other remote areas, rescuers and health care personnel may be confronted with decisions regarding termination of CPR. Because legal requirements for confirmation and certification of death, responsibilities, and authorisations differ among countries and regions, general recommendations cannot be made. Decisions regarding withholding or terminating CPR should be made in compliance with local statutes and regulations.

CPR may be withheld or terminated in a victim without vital signs when the risk is unacceptable to the rescuer, the rescuer is exhausted, or when CPR cannot be performed due to extreme environmental conditions. CPR should be withheld if the victim has sustained injuries incompatible with life, such as decapitation, truncal transection, or if the body is frozen solid. CPR should be terminated in an avalanche victim in asystole with obstructed airway and duration of burial >60 min or if ROSC cannot be achieved after 20–30 min of CPR and ALS (Figure 20.15). [72]

Figure 20.15 Avalanche victim with obstructed airway. (Courtesy of Eurac Research/Ivo Corrà.)

AVALANCHE RESUSCITATION CHECKLIST

The decision whether to use ECLS rewarming is usually made in the emergency department of the destination hospital, where pre-hospital data about the extent and duration of burial, core temperature at the scene, and patency of the airway may not be available. One study has shown that adherence to ERC avalanche resuscitation guidelines by rescue teams is suboptimal. [85] The use of an avalanche resuscitation checklist (Figure 20.16) is intended to improve adherence to the ERC guidelines and to enable data transfer from the avalanche site to the hospital. The checklist is designed to be completed at the accident site and remain with the victim until hospital admission. [86, 87]

CASE REPORT 20.3

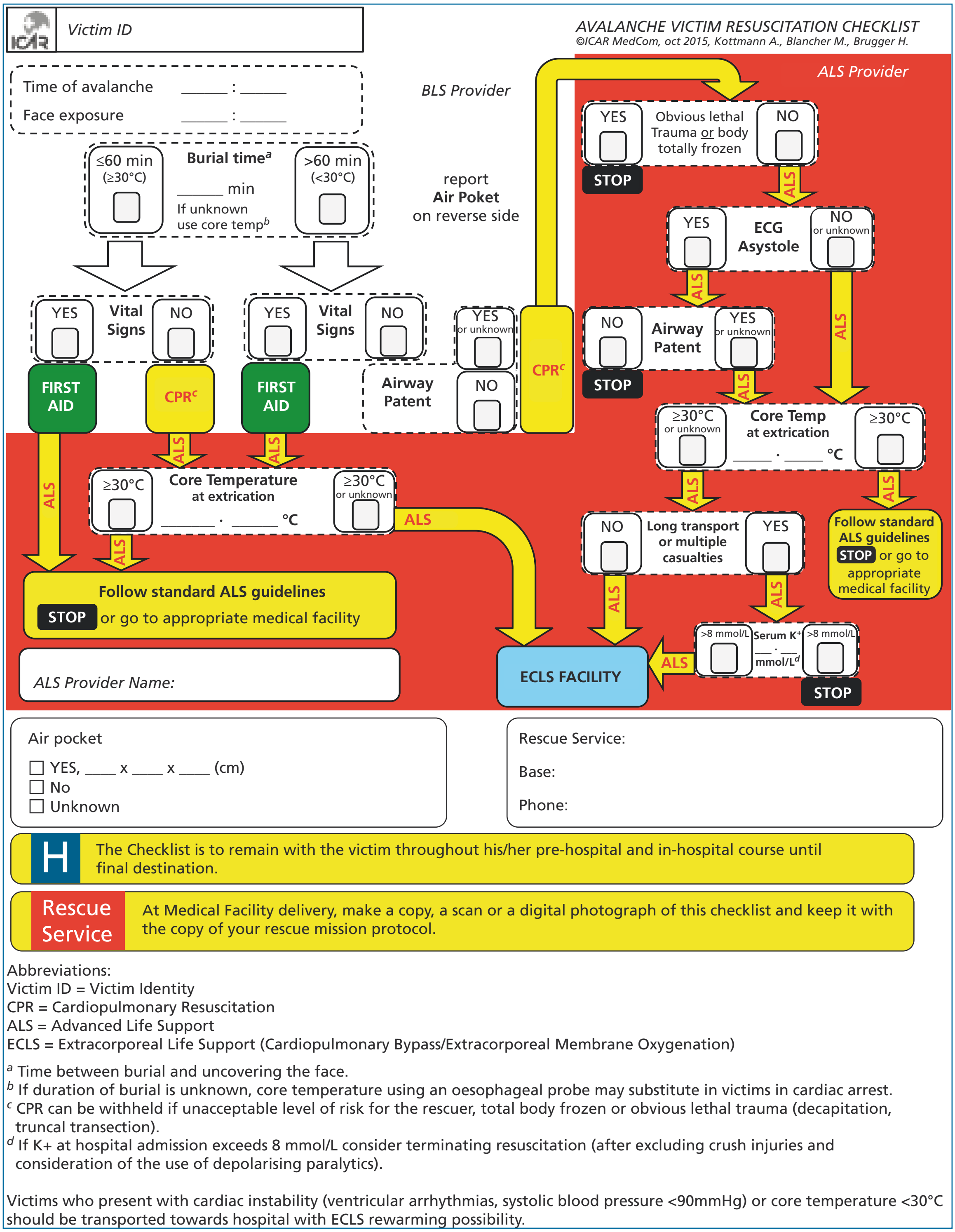
A difficult decision

On an evening in February, HEMS in Switzerland was called for a night flight to search for 2 missing mountaineers. These backcountry-skiing enthusiasts had left their homes at noon. Their car was found, but ground rescue teams did not see an avalanche in the surrounding mountains. HEMS was activated. Swiss rescue helicopters can perform SAR missions at night. They are equipped with special searchlights that provide infrared illumination for use with night-vision goggles, enhancing light detection by a factor of 30,000. After a 30 min flight, the helicopter crew identified ski tracks that ended in a slab avalanche and, surprisingly, saw a hand poking out of the snow. They immediately requested dog handlers and other rescue personnel from the dispatch centre and landed safely near the avalanche. The rescuer and physician carrying standard safety equipment, including avalanche transceivers, shovels, and probes, entered the avalanche debris. The estimated time from the avalanche was >9 h. When the rescuer and physician dug out the first victim, who was completely buried, they found a large air pocket around his face, a patent airway, and, almost unbelievably, spontaneous respiration. The victim was lying horizontally on his left side. The inner surface of the air pocket was frozen, but there was a clearly visible connection between the air pocket and the surface. The victim's pupils were fixed and dilated, GCS was 7, heart rate was 70 bpm, and systolic blood pressure was 100 mmHg. Fingertip pulse oximetry showed no signal. Epitympanic temperature was 23 °C. On first assessment, the victim seemed uninjured. Because of the very cold ambient temperature of −16 °C, the physician initiated rapid extrication and transport of this severely hypothermic victim. The victim was immediately extricated, stabilised supine on a stretcher, given supplementary oxygen via mask, and loaded into the helicopter. After a 10-min flight, the victim was admitted to the ICU of the closest hospital. During the flight, the victim was attended by a mountain rescuer trained in BLS, whilst the emergency physician remained at the avalanche site to search for the second victim. The second victim was found rapidly and had a clearly visible air pocket in front of the mouth and nose. There were no vital signs. The entire body was frozen and rigid. The victim was declared dead at the scene.

At hospital arrival, the first victim was surprisingly stable with spontaneous respirations, normal sinus rhythm at 70 bpm, blood pressure 120/60 mmHg, and SpO_2 80% with supplementary oxygen. Bladder temperature was 22.6 °C, which is severely hypothermic (Swiss stage III). The left forearm and hand, which had been poking out of the snow, were cold and pulseless due to severe frostbite. Serum potassium, glucose, and creatinine were normal. Chest x-ray showed left-sided pulmonary oedema. Because the victim had spontaneous respiration and stable circulation, the decision was made not to risk a night transfer to a centre with extracorporeal rewarming, but to use forced air to rewarm the victim externally. The victim was continuously monitored and a helicopter was on standby for transport to a centre for extracorporeal rewarming, should the victim have become unstable. No complications occurred during rewarming, except for a few short runs of ventricular tachycardia.

At a core temperature of 32 °C the victim regained consciousness. After 5 h, the core temperature reached 37 °C. The pulmonary oedema resolved completely in 3 days with administration of low dose diuretics. The frostbite did not resolve. After 3 months of conservative treatment, all fingers of the left hand were partially amputated. The victim recovered from hypothermia without any neurological damage and graduated from high school 2 years later. [88]

This case shows that long-term survival is possible, even after many hours, if there is an adequate air pocket. In this case there was a connection between the patent airway and the outside. A core temperature as low as 22 °C does not preclude survival with excellent neurological outcome. As long as circulation remains stable, active external rewarming may be an option, although a victim with a core temperature <28 °C should be transferred to a centre with extracorporeal rewarming capability, if feasible. It may not be necessary to use extracorporeal membrane oxygenation (ECMO) or cardiopulmonary bypass (CPB), although it may be desirable to have ECMO or CPB ready if needed.



Air pocket

☐ YES, ____ x ____ x ____ (cm)
☐ No
☐ Unknown

Rescue Service:

Base:

Phone:

H The Checklist is to remain with the victim throughout his/her pre-hospital and in-hospital course until final destination.

Rescue Service At Medical Facility delivery, make a copy, a scan or a digital photograph of this checklist and keep it with the copy of your rescue mission protocol.

Abbreviations:
Victim ID = Victim Identity
CPR = Cardiopulmonary Resuscitation
ALS = Advanced Life Support
ECLS = Extracorporeal Life Support (Cardiopulmonary Bypass/Extracorporeal Membrane Oxygenation)

[a] Time between burial and uncovering the face.
[b] If duration of burial is unknown, core temperature using an oesophageal probe may substitute in victims in cardiac arrest.
[c] CPR can be withheld if unacceptable level of risk for the rescuer, total body frozen or obvious lethal trauma (decapitation, truncal transection).
[d] If K+ at hospital admission exceeds 8 mmol/L consider terminating resuscitation (after excluding crush injuries and consideration of the use of depolarising paralytics).

Victims who present with cardiac instability (ventricular arrhythmias, systolic blood pressure <90mmHg) or core temperature <30°C should be transported towards hospital with ECLS rewarming possibility.

Figure 20.16 Avalanche Victim Resuscitation Checklist. The *white section* is meant for first responders trained in basic life support (BLS). The *red section* is meant for providers trained in advanced life support (ALS). (Modified from [86].)

TRANSPORT AND IN-HOSPITAL TRIAGE AND MANAGEMENT

The most likely medical problems in avalanche victims admitted to hospital are asphyxia, trauma, and hypothermia (see section Pathophysiology). Although it is possible for an avalanche victim to have only one of these conditions many will have two or all three conditions. Also, victims who were completely buried, even for a short time, can develop pulmonary oedema.

TRANSPORT

An avalanche victim should initially be triaged at the scene by an ALS provider. If the decision is made to transport the victim, transport should be by helicopter, if possible. Because of the complexity of potential conditions and therapeutic options, the ideal destination hospital is a Level 1 trauma centre with ECLS capability, either ECMO or CPB. However, avalanches occur in the mountains, where transport times may be long and hospitals may be sparser than in urban areas. This may make on-site triage and decisions regarding transport difficult. It is more likely that a critical victim will be transported to a community hospital with limited resources than in urban areas. Protocols should be established to dispatch victims to the most suitable hospital in each SAR region.

If a victim is responsive, has a core temperature >30 °C, and is haemodinamically stable with a systolic blood pressure >80 mmHg and no ventricular arrhythmias, admission to a community hospital is reasonable. Otherwise an avalanche victim should be transported or transferred to a Level 1 trauma centre with ECLS capability. If there are no vital signs, the victim should receive continuous CPR with mechanical chest compressions. If transport to a Level 1 trauma centre is not possible, treatment should be continued at the highest level of available care, in the nearest hospital.

Keynotes

Avalanche victims who are not severely injured, are normothermic or only mildly hypothermic, and are haemodinamically stable should be transported to a community hospital. All other victims should be transported to a Level 1 trauma centre with ECLS capability.

DIAGNOSIS AND TRIAGE

The goal of diagnostic investigations at hospital admission is to detect and differentiate among the 3 main critical conditions of avalanche victims: asphyxia, trauma, and hypothermia.

An avalanche victim should undergo standard diagnostic investigations that include core temperature measurement, focused assessment with sonography in trauma (FAST) to detect internal haemorrhage and to assess myocardial contractility in victims with pulseless electrical activity, and a CT scan of the head, if consciousness is impaired or head trauma suspected. Laboratory tests should include standard metabolic parameters, including serum potassium.

If a victim is admitted to hospital in asystole, the main challenge is to distinguish between asphyxia and hypothermia as the cause of cardiac arrest, using clinical information and laboratory findings. This distinction is needed for decisions regarding further treatment. If asphyxia is the cause of cardiac arrest, the prognosis is poor and the physician should terminate CPR. If hypothermia is likely the cause, the victim may benefit from attempted rewarming and should be resuscitated using ECLS. If ECLS is not available, the victim should be transferred with ongoing CPR to a centre with ECLS. [29]

Selection for ECLS rewarming is still suboptimal. Survival rates for avalanche victims who receive ECLS are ~11% compared with ~50% for victims with hypothermia from all causes. [76–79]

The mechanism of cooling after avalanche burial is clear for most victims admitted to hospital. In many cases, however, this is the only information available at hospital admission, whilst additional pre-hospital data are missing. If a victim is admitted in cardiac arrest, in order to determine whether the cause of cardiac arrest was asphyxia or hypothermia, it is crucial to know the duration of complete burial, whether vital signs were present on extrication, and whether an air pocket was seen when the victim was extricated. If these data are not known, the diagnosis must rely on in-hospital clinical findings and laboratory parameters, which are less reliable for diagnosis and prediction of outcome. Use of the Avalanche Resuscitation Checklist can facilitate reliable data transfer from the avalanche site to the hospital. [86, 87] Two strategies have been proposed to distinguish between asphyxia and hypothermia as the cause of cardiac arrest and to predict outcome. In 2015, the ERC published an algorithm for the on-site triage of avalanche victims in cardiac arrest to help emergency physicians distinguish between asphyxial and hypothermic cardiac arrest in order to make transport decisions and for in-hospital management (Figure 20.11). [66] The algorithm is based on a combination of pre-hospital clinical data and serum potassium level at hospital admission. Successful use of the algorithm requires close collaboration with flow of data from the rescue team to HEMS and then to the admitting hospital.

In 2018, the HOPE score was proposed for in-hospital prognosis and triage of hypothermic victims in cardiac arrest. The score uses variables of age, gender, core temperature and serum potassium level at admission, mechanism of cooling, and duration of CPR. [81] The HOPE score has been validated on 122 hypothermic arrested victims who underwent rewarming with ECLS, achieving a negative predictive value of 97%. [89]

The HOPE score can be used to calculate a survival probability score. The calculations can be done online through a Web application (https://www.urg-admin.ch/hope/). The only pre-hospital data included in the HOPE score are whether cooling was asphyxial or non-asphyxial with complete avalanche burial considered to be asphyxial and duration of CPR. The HOPE score does not include pre-hospital data, such as duration of burial, airway status, presence of electrical cardiac activity, or whether an air pocket was noted at the time of extrication.

A recent multi-centre study included 103 avalanche victims with OHCA admitted to 7 centres in Europe capable of ECLS aiming at reliable cut-off values for the identification of hypothermic avalanche victims with reversible OHCA at hospital admission. Of the 103 victims 61 (58%) were rewarmed by ECLS. Six (10%) of the rewarmed victims survived whilst 55 (90%) died. The authors calculated sensitivity and receiver operating curves and used bootstrapping and exact binomial distribution to determine optimal cut-off values. For in-hospital triage of avalanche victims admitted with OHCA they obtained the highest positive predictive value (19%), with a sensitivity of 100% for survivors, with the cut-off values of 7 mmol/L for serum potassium and 30 °C for core temperature. [90]

Keynotes

In an avalanche victim admitted to hospital, the diagnoses of asphyxia, trauma and hypothermia can be made using clinical signs and symptoms, cardiovascular and metabolic data, and standard imaging methods. The ERC algorithm for avalanche victims in cardiac arrest or the HOPE score for hypothermic victims can be used to help select victims for ECLS rewarming.

TREATMENT

In-hospital treatment of avalanche victims should focus on the consequences of asphyxia, trauma, or hypothermia.

Neurological outcome depends mainly on the severity of asphyxia and less on trauma and hypothermia. The severely asphyxiated avalanche victim has typically been extricated within 35 min of burial, does not present with hypothermia and may need continuous cardiopulmonary resuscitation. In many cases, hypoxic damage to heart and brain is irreversible. Since the rapid development of SAR operations has decreased the mean duration of burial, asphyxiated avalanche victims are more frequently being seen in the hospital, often with permanent brain damage.

A completely buried avalanche victim can develop pulmonary oedema several hours after extrication (see Pathophysiology). Pulmonary oedema may require advanced airway management with PEEP, assisted or artificial ventilation and intensive care. Victims sustaining severe trauma are increasingly being reported in Europe and North America (see Epidemiology and Pathophysiology). Trauma is likely to be associated with moderate or severe hypothermia, which can result in the lethal triad of acidosis, coagulopathy, and hypothermia. [91] This combination is strongly associated with multi-organ dysfunction syndrome and with high mortality rates. Victims with trauma should be treated early and aggressively with active rewarming or, if indicated, with ECLS. In hypothermic multi-trauma victims, completely heparinised ECMO systems may be used with minimal heparinisation. ECLS rewarming therefore can be suitable for victims in hypothermic cardiac arrest with trauma and a high risk of haemorrhage.

The in-hospital treatment of hypothermia depends on level of consciousness, core temperature, and cardiovascular stability and should, like trauma treatment, follow international guidelines. In a victim with haemodynamic instability or cardiac arrest, ECLS using veno-arterial ECMO or CPB is the rewarming method of choice. Alternative non-ECLS rewarming methods for hypothermic victims in cardiac arrest should only be used if ECLS is not available. Active internal rewarming by non-ECLS methods is slow. Until the heart is warm enough to restart, it is necessary to provide prolonged continuous CPR. There is little evidence to guide the non-ECLS rewarming of hypothermic avalanche victims (see Chapter 43, In-Hospital Treatment of Accidental Hypothermia).

CASE REPORT 20.4

Limited resources and time: a challenging avalanche accident

In 2016, a group of 52 backcounty skiers was doing military training in Valfrejus, Savoie, France. The group triggered an avalanche 400 m wide by 500 m long, with a 350 m vertical drop, at around 1 p.m. Companions who were not buried immediately called the rescue service. After 15 min, HEMS with an ALS healthcare provider, avalanche dog, and mountain rescue personnel arrived at the site. The HEMS crew was equipped with avalanche transceivers, airbag systems, and triage tools, including the Avalanche Victim Resuscitation Checklist. Once the scene was declared safe, the avalanche site was divided into 3 parts and an avalanche search was started immediately by the HEMS crew together with unburied companions. Meanwhile, immediate medical backup was requested.

Thirty-three of the 52 backcountry skiers were partially or completely buried. Nineteen victims extricated themselves from avalanche debris, 11 were extricated by companions and only 3 by mountain rescue personnel. Within one hour, 2 additional rescue teams reached the site of the avalanche accident by helicopter. The local dispatch centre, and the regional Level 1 trauma centre, were activated. A medical coordinator certified in mountain rescue and disaster medicine was designated to manage this multiple casualty avalanche accident. Suspecting that there were more than 12 potentially completely buried avalanche victims who might need to be transferred to the Level 1 trauma centre for ECLS the medical coordinator alerted the Level 1 trauma centre that there were multiple victims who might require ECLS and requested information about the current status of the victims updated every 15 min. Communications issues were a challenge during the rescue operation. There was no predesignated medical radio communication channel. The 3 ALS healthcare providers at the avalanche site were unable to communicate easily with the medical coordinator. Triage and identification tools were not uniformly used.

After about 2 h 30 min from the time of the avalanche, all victims had been found. There were 18 completely buried avalanche victims, 8 with complete burial and 7 with partial burial. There were 23 avalanche victims who were extricated within 15 min, 4 between 15 to 35 min and only 2 at >60 min. Based on accumulating information, the level of hospital activation was slowly reduced. Six avalanche victims were found in cardiac arrest at extrication, one of whom had ROSC with CPR. Six of the completely buried victims had blocked airways. The victim with ROSC received standard ALS care then received ECLS on hospital admission for persistent haemodynamic instability. The victim never regained consciousness and died on day 10. Six of the 33 avalanche victims died. Autopsies identified asphyxia as the sole cause of death for all of them. Five of the 6 were declared dead on scene.

Post-traumatic stress disorder was diagnosed in 23 out of 46 survivors within 6 months after the avalanche accident. [88]

MULTI-CASUALTY AVALANCHE ACCIDENTS

Like other mountain emergencies, avalanche accidents can have multiple victims (see Chapter 44, Mass Casualty Incidents in the Mountains). More than 4 victims were reportedly involved in >10% of avalanche HEMS operations in Austria [30] and 32% in Switzerland, whilst <50% had multiple complete burials. [33] The ICAR MedCom recently released recommendations for on-site management of multi-causality incidents. [92] Unless sufficient resources are available, extrication is the first priority. Medical care should focus on those with vital signs and burial times <35 min. No CPR should be started on victims in cardiac arrest with burial time between 35 and 60 min. CPR should only be started if the airway is patent and burial time is >60 min.

PREVENTION, RISK ASSESSMENT, AND SAFETY EQUIPMENT

Preventing natural catastrophic avalanches that threaten people on traffic routes and in villages is a matter of civil protection that requires technical, logistic, and organisational measures. In Europe and North America, large projects have been undertaken to minimise the risk of devastating avalanches. These projects include the assessment of hazard zones, binding development plans for villages and towns, avalanche warning systems, construction of avalanche barriers, and, in areas of high hazard, the use of explosives to trigger avalanches intentionally. Emergency response and evacuation plans have also been put into place to mitigate the hazards of catastrophic avalanches.

Workers who must operate in hazardous terrain not subject to avalanche control and mountain recreationists, such as downhill skiers outside marked ski runs, ski tourers, and snowshoers, who voluntarily expose themselves to the risk of avalanches, take advantage of preventive strategies and rescue devices. They should pay attention to the weather history and forecast as well as avalanche warning levels, which are regularly announced by avalanche warning agencies. On arrival in potential avalanche terrain, the party should make a detailed assessment of avalanche-prone slopes. Safe route selection is critical. Factors to be considered include slope angles and aspect, snow characteristics including potential sliding layers, prevailing and wind direction. Meticulous observation of the weather development is essential. [2]

General recommendations include avoiding slopes >30° and avoiding leeward slopes. The most important measure may be to avoid traveling in avalanche terrain during conditions when avalanches are likely, such as during heavy snowfall and for the first 2–3 days afterwards and when temperatures are rapidly warming.

Keynotes

Despite all the recommendations, guidelines, and checklists for evaluating the snowpack and reducing the avalanche hazard, no strategy can eliminate the risk completely. There will always be a risk when leaving areas, such as pistes, where avalanches are controlled.

In addition to preventive measures, devices have been developed to increase the survival chances of avalanche victims. These devices are designed for persons at risk of being buried by an avalanche, including SAR personnel. Table 20.2 shows the most important safety equipment. [23, 94–97]

Complete snow burial is associated with a fatality rate of ~50%, compared to 5% for those partially buried. [26] Any measures that reduce the chance of being completely buried will decrease mortality. If complete burial cannot be avoided, the duration of burial is the most important factor for survival. Every effort should be made to extricate a victim within the first 15 min of burial. At 35 min after burial, survival is possible only if the victim can breathe under the snow. This requires a patent airway and an air pocket.

There are several recommendations regarding actions to be taken if caught by an avalanche. A skier threatened by an avalanche can try to escape by skiing quickly outside its path. If buried, the victim should try to keep both hands as close as possible to the mouth and nose before the avalanche stops in order to keep the airway free and to create an air pocket in which to breathe.

Table 20.2 Avalanche safety and rescue equipment

Equipment	Function	Use	Effect	Mortality reduction	Evidence level[a]
Avalanche airbag	Inverse segregation, cervical spine protection?	Activation of air-filled balloons	Risk reduction of complete burial	From 22% to 11% (all avalanche victims)	1B
Avalanche transceiver	Transmission of a long-wave signal from the buried victim to the rescuer	Active search for the buried victim by the rescuer	Reduction of burial duration	From ~70% to ~55% (completely buried victims only)	1B
Artificial air-pocket device	Keeping airway patent, enabling the victim to breath, discharge of carbon dioxide	Breathing through a tube	Prolonging survival under snow	Unknown	1C
Avalanche shovel		Digging manually	Reduction of burial duration	Unknown	1C
Avalanche probe	Probing	Locating the victim's body through direct contact	Reduction of burial duration	Unknown	1C
RECCO® rescue system	Transmission, reflection, and reception of a radar signal	Locating the victim's refractor	Reduction of burial duration	Unknown	1C

[a]American College of Chest Physicians grading system. [93] (Reproduced from [23], with permission.)

Keynotes

Essentially, there exist 3 types of safety and rescue equipment: devices with a buoyant effect to keep the victim's head and chest on the surface of the avalanche, devices to shorten the duration of burial by allowing location and extrication of the victim, and devices that keep the airway free and allow a completely buried victim to breathe (Figure 20.17). All methods are likely to reduce mortality. Combined use of multiple types of devices may increase effectiveness.

Figure 20.17 **(a)** Winter recreationists locating an avalanche victim using transceiver and probe about to dig into debris with a shovel. **(b)** Winter recreationist wearing a backpack with an airbag deployed and inflated, combined with an artificial air-pocket device. (Courtesy of Alfredo Croce/Pillow Lab.)

AVALANCHE AIRBAG

The first inflatable avalanche airbag was placed on the market in 1985. It consisted of 2 balloons that filled with ~150 L of mixed gas from a cylinder and ambient air. Multiple avalanche airbags are now commercially available. There are single use compressed gas units, and multiple use battery operated airbags that are filled almost instantly using a fan. Airbags are integrated into a backpack or vest. An airbag must be deployed manually by pulling a handle, although some airbags can be activated by a person nearby using a wireless system. The buoyant effect works by a process called inverse grading. In a flowing collection of various sized particles, larger particles are sorted towards the surface whilst smaller particles are sorted downwards. Inverse grading, with an avalanche airbag effectively making the victim into a very large particle, reduces the chance of becoming completely buried (Figure 20.17), but only whilst the victim is flowing freely in an avalanche.

Some airbags deflate automatically shortly after deployment, potentially creating an air pocket. Some airbag systems combine an airbag with a device that creates an artificial air pocket. Some models are shaped to surround the head and neck once deployed, which may help to protect the head and to prevent spinal injuries.

The notion that avalanche airbags can be effective is supported by simulations using crash-test dummies with and without airbags in intentionally triggered avalanches and also by epidemiologic studies. Haegeli et al. retrospectively analysed 245 avalanche accidents involving at least one airbag user in 6 European countries and the United States between 1994 and 2012. An inflated airbag reduced the risk of complete burial from 47% to 20%. The absolute mortality rate was reduced from 22% to 11%. In 20% of cases, the system was not activated. About 60% of missed activations were due to failure by the user to deploy the airbag. [94]

To ensure that an airbag will work properly, the user should be familiar with the deployment procedure and should properly maintain the device. Users should be aware that if they are buried in a terrain trap or if a second avalanche completely buries the balloon when they are stationary in avalanche debris, it is unlikely that an airbag will prevent a complete burial.

Keynotes

An avalanche airbag is the only safety device that prevents complete burial, but success depends on deployment by the user. Failure to deploy is the main limiting factor preventing effectiveness of an airbag.

ARTIFICIAL AIR-POCKET DEVICES

A patent airway is critical for surviving a complete avalanche burial. If the victim is not severely injured and has even a small air space in front of the mouth and nose, survival is likely for at least 1.5 to 2 h.

An artificial air pocket device is designed to separate exhaled air from inhaled air, diverting exhaled CO_2 away from the airway, delaying asphyxiation by preventing CO_2 toxicity. The device consists of a mouthpiece and breathing tubes, one of which is connected to a one-way inspiratory valve and the other to a one-way expiratory valve. The inspired air comes directly from air contained in the avalanche debris. Expired air is diverted behind the user. Artificial air pocket devices are either integrated into a backpack or are incorporated into a harness. At least one model is combined with an avalanche airbag. Two studies suggest that artificial air pocket devices can prolong survival if properly used. In one study, sufficient oxygenation was maintained for up to 60 min in buried subjects using an artificial air pocket (Figure 20.17). [42] Several reports support the notion that artificial air pocket device can reduce mortality, although it is unclear to what extent. It is unknown what percentage of users can position the mouthpiece before being caught and keep it in place during the avalanche.

Keynotes

The combination of an artificial air pocket device with an avalanche airbag may be advantageous. The mechanisms of action are complementary.

AVALANCHE TRANSCEIVER, PROBE, AND SHOVEL

If a victim is completely buried by an avalanche, the likelihood of survival depends heavily on the duration of burial. This was first demonstrated in 1994. [28] Any measure that can shorten the duration of burial, ideally to less than 15 min should theoretically save lives, based on the steep decline in survival from 15 to 35 min of burial. Short burial times (<35 min) can only be achieved if rescue is started by uninjured companions immediately after an avalanche. A person who is completely buried, with no visible or audible sign at the surface, can only be rescued successfully by using the standard equipment: transceiver, shovel, and probe (Figure 20.17). A study reported that in South Tyrol in the European Alps, 80% of backcountry skiers, but only 14% of snowshoers, carried all 3 items of standard equipment. [95]

The transceiver system for locating completely buried avalanche victims was developed in 1968 in the USA. It detected the radio signal from the victim's transceiver, set to transmit, and emitted an audible tone on the searchers' transceivers, set to receive. When a searcher moved towards a buried transceiver, the signal intensity increased and the tone became louder. When a searcher moved farther away a buried transceiver, signal intensity decreased and the tone became softer. By finding the maximum intensity, a searcher was able to determine the victim's location. The original transmission frequency was 2,275 kHz. In 1986, based on tests that identified the frequency with the greatest range when transmitting from under snow, the standard frequency of 347 kHz was adopted by ICAR. Since then, there have been many improvements including digital rather than analogue signal detectors, multiple antennae, displays indicating the direction and distances to multiple victims, and detection of vital signs of the buried victim using motion sensors. These changes have simplified use and enhanced the effectiveness of avalanche transceivers. However, in order to reliably find victims successfully in an actual avalanche, people carrying transceivers must practise searches, and anyone venturing into avalanche terrain, who could be either a rescuer or a victim, depending on who is caught by an avalanche, must be equipped with the devices (Figure 20.17).

Retrospective studies demonstrate a significant impact of avalanche transceivers on the duration of burial and on survival. In 2005, a study presented a series of 278 complete burials in the Austrian Alps. There was a significant reduction in median burial time from 102 to 20 min and in mortality rate from 68% to 53.8% ($p = 0.011$) for victims with avalanche transceivers. [96] In 2007, a retrospective analysis of 317 completely buried victims resulted in a significant reduction in burial duration from 125 to 25 min and an increase in survival from 55.2% to 70.6% [$p < 0.001$; odds ratio 0.26], corresponding to a relative reduction in mortality rate of 74%, with a 95% confidence interval ranging from 52% to 86%]. [97]

From these analyses, it is evident that the avalanche transceivers are effective and can reduce the duration of burial and therefore decrease mortality. The time it takes for searchers to reach a buried victim, especially if the searchers have to climb upwards on a slope, and the time necessary to extricate a victim, especially a victim who is deeply buried, can be much longer than the length of a search using a transceiver. Extrication within the target time of 15 min depends not only on a transceiver search but on topography, depth of burial, and the fitness of the rescuers, especially if there are multiple victims.

After a victim is located using a transceiver, a probe is used to determine burial depth and a shovel is used to extricate the victim. Anyone entering avalanche terrain should carry a collapsible probe for the pinpoint search and a metal shovel designed to extricate victims from avalanche debris. Efficient shovelling techniques are essential to minimise extrication time and increase survival (Figure 20.12).

Keynotes

Avalanche transceivers are effective at reducing mortality. Extrication of a victim can take much more time than an electronic search. In addition to a transceiver, a heavy duty, preferably metal, shovel and a 3-m long avalanche probe for pinpoint searching are essential. Training and practise are necessary to take full advantage of this equipment.

RECCO® RESCUE SYSTEM

The RECCO® system, like an avalanche transceiver, is used to locate completely buried avalanche victims. In contrast to an avalanche transceiver, RECCO® works unidirectionally. The RECCO® system consists of 2 parts, a lightweight, portable detector (actually a transmitter-detector) and a tiny, flat reflector. The reflector is worn by the recreationist, who may be unaware of this fact. RECCO® reflectors are integrated into outerwear, helmet, protection gear, and boots of many outdoor clothing brands. The detector transmits a highly directional radar signal at a frequency of 800 MHz that is received by the reflector, which doubles the frequency of the received signal (to distinguish the reflector from reflecting objects such as rocks) and reflects it to the detector. The detector is much larger than traditional transceivers. RECCO® requires frequent practise for rescuers to remain proficient. The RECCO® detector is intended only for professional rescue. It can be carried to an avalanche site by a rescue team or used by rescuers from a helicopter. RECCO® can also detect reflections from electronic devices, such as mobile phones, watches, cameras, radios, and avalanche transceivers.

Many avalanches are triggered close to controlled ski areas by off-piste skiers, many of whom are not familiar with avalanche safety and do not carry avalanche transceivers. RECCO® potentially offers a second option to locate avalanche victims. The combination of a transceiver and the RECCO® system provides a better chance of locating a victim than one device alone. There are case reports of avalanche victims who were rescued alive after being located by RECCO®. The impact on mortality is not known. [67]

MEDICAL TRAINING OF AVALANCHE RESCUE TEAMS

Rescue teams, healthcare professionals, and dispatchers should be familiar with the management of avalanche victims and with triage algorithms to identify victims who potentially would benefit from ECLS rewarming. The Avalanche Resuscitation Checklist should help BLS and ALS providers adhere to recommended medical management of avalanche victims and should facilitate reliable data transfer from the avalanche site to the hospital. In European studies, healthcare providers and laypersons were found to have poor knowledge of and adherence to ILCOR and ICAR MedCom recommendations. [85, 98] About 75% of BLS and ALS providers and members of mountain rescue services working in areas in which they were likely to manage avalanche victims, at the scene or in hospital, had never participated in avalanche-specific rescue training. [98] Basic knowledge of avalanche management was poor. Fewer than 40% of those surveyed chose the correct temporal sequence of reportable information in the BLS section of the Avalanche Resuscitation Checklist. A standardised lecture proposed by ICAR MedCom may be able to improve knowledge and awareness of avalanche-specific rescue considerations. Avalanche SAR teams and healthcare providers should periodically receive training in specific skills, such as pre-hospital core temperature measurement, insulation, and rewarming techniques. Protocols for the transport of avalanche victims to the most suitable hospital should be available to dispatchers. Ideally, a coordinator, who is an accidental hypothermia specialist, should be on call to assist with management of critical hypothermia victims. [99]

PROGNOSIS OF AVALANCHE VICTIMS

The lowest recorded core temperature from which an avalanche victim has been successfully resuscitated is 19 °C. [80] A few case reports of survivors with full neurologic recovery after hours of complete burial have provided reason to treat hypothermic avalanche victims without giving up hope. Most cardiac arrest victims who survived neurologically intact had vital signs at extrication and had a witnessed cardiac arrest during the rescue. Survival chances of buried avalanche victims with asystole at extrication are dismal. However, if a victim is extricated without vital signs but with an open airway, the guiding principle is “no hypothermic avalanche victim with a patent airway is dead until warm and dead.” [79]

TAKE-HOME MESSAGES

- Survival of completely buried avalanche victims depends largely on immediate extrication by bystanders before HEMS crew arrival, professional on-site treatment and optimal choice of destination hospital using established prognostic markers.
- It is crucial to know the duration of complete burial and core temperature and to assess vital signs, airway status, and the presence of an air pocket at extrication.
- It is important to understand that hypothermic avalanche victims in cardiac arrest have a good prognosis if arrest occurs after extrication.
- Without robust knowledge and training, poor choices in pre-hospital management can be made with potentially fatal consequences for avalanche victims.
- Tools such as the Avalanche Victim Resuscitation Checklist, combined with training, can be used to improve knowledge and clinical practice, and to improve the likelihood of survival of avalanche victims.
- Education and training specific to each emergency medical system should be required of all providers in the avalanche rescue chain.
- Protocols should be implemented, tailored to each emergency medical system, for transport to hospitals capable of extracorporeal cardiac life support.

REFERENCES

1. Stocks C. In: The Roman Hannibal: Remembering the Enemy in Silius Italicus' Punica. 1st ed. Liverpool, UK: Liverpool University Press; 2014.
2. Bernhard GKL. Lawinenhandbuch. 7th ed: Tyrolia, Innsbruck, Austria; 2000.
3. Pivot S. Gli incidenti da valanga. Neve e Valanghe. 2017;90:70-77.
4. Zafren K, Brants A, Tabner K, et al. Wilderness Mass Casualty Incident (MCI): Rescue Chain After Avalanche at Everest Base Camp (EBC) In 2015. Wilderness Environ Med. 2018;29(3):401-410.
5. Stokes S, Koirala P, Wallace S, Bhandari S. Tragedy on Everest: the Khumbu icefall. Emerg Med J. 2015;32(5):418-420.
6. Braham T. In Memoriam Andre Roch (1906-2002). The Himalayan Journal. 2003;59.
7. Strapazzon G, Nardin M, Zanon P, Kaufmann M, et al. Respiratory failure and spontaneous hypoglycemia during noninvasive rewarming from 24.7 degrees C (76.5 degrees F) core body temperature after prolonged avalanche burial. Ann Emerg Med. 2011;60(2):193-196.
8. Seligman G. "The nature of snow". Nature. 1937;139(3530):1090-1094.
9. Domine F, Albert M, Huthwelker T, et al. Snow physics as relevant to snow photochemistry. Atmos Chem Phys. 2008;8(2):171-208.
10. Strapazzon G, Paal P, Schweizer J, et al. Effects of snow properties on humans breathing into an artificial air pocket - an experimental field study. Sci Rep. 2017;7(1):17675.
11. Schweizer J, Bruce Jamieson J, Schneebeli M. Snow avalanche formation. Reviews of Geophysics. 2003;41(4).
12. Schweizer J, Bartelt P, van Herwijnen A. Chapter 12 - Snow Avalanches. In: Shroder JF, Haeberli W, Whiteman C, eds. Snow and Ice-Related Hazards, Risks and Disasters. Boston: Academic Press; 2015. pp 395-436.
13. Schweizer J, Lütschg M. Characteristics of human-triggered avalanches. Cold Regions Science and Technology. 2001;33(2):147-162.
14. Procter E, Strapazzon G, Dal Cappello T, et al. Adherence of backcountry winter recreationists to avalanche prevention and safety practises in northern Italy. Scand J Med Sci Sports. 2013.
15. Haegeli P, Falk M, Brugger H, et al. Comparison of avalanche survival patterns in Canada and Switzerland. CMAJ. 2011;183(7):789-795.
16. Stethem C JB, Schaerer P, Liverman D, et al. Snow avalanche hazard in Canada - A review. Nat Hazards. 2003;28:487-515.
17. Silverton NA, McIntosh SE, Kim HS. Risk assessment in winter backcountry travel. Wilderness Environ Med. 2009;20(3):269-274.
18. McIntosh SE, Grissom CK, Olivares CR, et al. Cause of death in avalanche fatalities. Wilderness Environ Med. 2007;18(4):293-297.
19. Rainer B, Frimmel C, Sumann G, et al. Correlation between avalanche emergencies and avalanche danger forecast in the alpine region of Tyrol. Eur J Emerg Med. 2008;15(1):43-47.
20. Burtscher M, Nachbauer W. Effects of training on the risk of avalanche fatality. In: Johnson RJ (ed). Skiing trauma and safety vol. 12, West Conshohocken, PA: American Society for Testing and Materials; 1999. pp 45–49
21. Jekich BM, Drake BD, Nacht JY, et al. Avalanche Fatalities in the United States: A Change in Demographics. Wilderness Environ Med. 2016;27(1):46-52.
22. Zweifel B TF, Björk C. Who is involved in avalanche accidents? Proceedings, 2012 International Snow Science Workshop, Anchorage, Alaska. 2012.
23. Van Tilburg C, Grissom CK, Zafren K, et al. Wilderness Medical Society Practise Guidelines for Prevention and Management of Avalanche and Nonavalanche Snow Burial Accidents. Wilderness Environ Med. 2017;28(1):23-42.
24. Etter HJ. Report of the avalanche subcommission presented at: general meeting of the International Commission for Alpine Rescue; October 20–21, 2011; Åre, Sweden. 2011.
25. Brugger H, Durrer B, Elsensohn F, et al. Resuscitation of avalanche victims: Evidence-based guidelines of the international commission for mountain emergency medicine (ICAR MEDCOM). Resuscitation. 2013;84(5):539-546.
26. Brugger H, Durrer B, Adler-Kastner L, Falk M, Tschirky F. Field management of avalanche victims. Resuscitation. 2001;51(1):7-15.
27. Procter E, Strapazzon G, Dal Cappello T, et al. Burial duration, depth and air pocket explain avalanche survival patterns in Austria and Switzerland. Resuscitation. 2016;105:173-176.
28. Falk M, Brugger H, Adler-Kastner L. Avalanche survival chances. Nature. 1994;368(6466):21.
29. Paal P, Gordon L, Strapazzon G, et al. Accidental hypothermia- an update : The content of this review is endorsed by the International Commission for Mountain Emergency Medicine

(ICAR MEDCOM). Scand J Trauma Resusc Emerg Med. 2016;24(1):111.
30. Mair P, Frimmel C, Vergeiner G, et al. Emergency medical helicopter operations for avalanche accidents. Resuscitation. 2013;84(4):492-495.
31. Kornhall DK, Logan S, Dolven T. Body Positioning of Buried Avalanche Victims. Wilderness Environ Med. 2016;27(2):321-325.
32. Stalsberg H, Albretsen C, Gilbert M, et al. Mechanism of death in avalanche victims. Virchows Arch A Pathol Anat Histopathol. 1989;414(5):415-422.
33. Kottmann A, Carron PN, Theiler L, et al. Identification of the technical and medical requirements for HEMS avalanche rescue missions through a 15-year retrospective analysis in a HEMS in Switzerland: a necessary step for quality improvement. Scand J Trauma Resusc Emerg Med. 2018;26(1):54.
34. Pasquier M, Hugli O, Kottmann A, Techel F. Avalanche Accidents Causing Fatalities: Are They Any Different in the Summer? High Alt Med Biol. 2017;18(1):67-72.
35. Brugger H, Etter HJ, Boyd J, Falk M. Causes of death from avalanche. Wilderness Environ Med. 2009;20(1):93-96.
36. Tough SC, Butt JC. A review of 19 fatal injuries associated with backcountry skiing. Am J Forensic Med Pathol. 1993;14(1):17-21.
37. Hohlrieder M, Brugger H, Schubert HM, et al. Pattern and severity of injury in avalanche victims. High Alt Med Biol. 2007;8(1):56-61.
38. Roubik K, Sieger L, Sykora K. Work of Breathing into Snow in the Presence versus Absence of an Artificial Air Pocket Affects Hypoxia and Hypercapnia of a Victim Covered with Avalanche Snow: A Randomized Double Blind Crossover Study. PloS one. 2015;10(12):e0144332.
39. Grissom CK, McAlpine JC, Harmston CH, et al. Hypercapnia effect on core cooling and shivering threshold during snow burial. Aviat Space Environ Med. 2008;79(8):735-742.
40. Grissom CK, Radwin MI, Scholand MB, et al. Hypercapnia increases core temperature cooling rate during snow burial. J Appl Phisiol 2004;96(4):1365-1370.
41. Brugger H, Sumann G, Meister R, et al. Hypoxia and hypercapnia during respiration into an artificial air pocket in snow: implications for avalanche survival. Resuscitation. 2003;58(1):81-88.
42. Grissom CK, Radwin MI, Harmston CH, et al. Respiration during snow burial using an artificial air pocket. JAMA. 2000;283(17):2266-2271.
43. Boyd J, Brugger H, Shuster M. Prognostic factors in avalanche resuscitation: a systematic review. Resuscitation. 2010;81(6):645-652.
44. Paal P, Strapazzon G, Braun P, et al. Factors affecting survival from avalanche burial--a randomised prospective porcine pilot study. Resuscitation. 2013;84(2):239-243.
45. Glisenti P, Rakusa J, Albrecht R, Luedi MM. Negative pressure pulmonary oedema with haemorrhage after 5-minute avalanche burial. Lancet. 2016;388(10057):2321-2322.
46. Sumann G, Putzer G, Brugger H, Paal P. Pulmonary edema after complete avalanche burial. High Alt Med Biol. 2012;13(4):295-296.
47. Schmid F. [The pathogenesis of pulmonary edema after being buried by an avalanche]. Schweiz Med Wochenschr. 1981;111(39):1441-1445.
48. Bhattacharya M, Kallet RH, Ware LB, Matthay MA. Negative-Pressure Pulmonary Edema. Chest. 2016;150(4):927-933.
49. Fremont RD, Kallet RH, Matthay MA, Ware LB. Postobstructive pulmonary edema: a case for hydrostatic mechanisms. Chest. 2007;131(6):1742-1746.
50. Udeshi A, Cantie SM, Pierre E. Postobstructive pulmonary edema. J Crit Care. 2010;25(3):508.e501-505.
51. Van Tilburg C. Non-avalanche-related snow immersion deaths: tree well and deep snow immersion asphyxiation. Wilderness Environ Med. 2010;21(3):257-261.
52. Kosinski S, Jasinski J, Krzeptowski-Sabala S, et al. Deep snow immersion suffocation--the deadly threat. Anaesthesiol Intensive Ther. 2013;45(1):33-34.
53. Cadman R. Eight nonavalanche snow-immersion deaths a 6-year series from british columbia ski areas. Phys Sportsmed. 1999;27(13):31-43.
54. Cadman R. How to stay alive in deep powder snow: avoiding tree-well accidents. Phys Sportsmed. 1999;27(13):44.
55. Sprung J, Cheng EY, Bosnjak ZJ. Hypothermia and serum potassium concentration. Anesthesiology. 1991;75(1):164.
56. Buse S, Blancher M, Viglino D, et al. The impact of hypothermia on serum potassium concentration: A systematic review. Resuscitation. 2017;118:35-42.
57. Cohen JG, Boue Y, Boussat B, et al. Serum potassium concentration predicts brain hypoxia on CT after avalanche-induced cardiac arrest. Am J Emerg Med. 2016;34(5):856-860.
58. Strapazzon G, Falk M, Paal P, Brugger H. The challenge of establishing a correct serum potassium cutoff for inhospital triage after avalanche-induced cardiac arrest. Am J Emerg Med. 2016;34(7):1317.
59. Locher T, Walpoth BH. Differential diagnosis of circulatory failure in hypothermic avalanche victims: retrospective analysis of 32 avalanche accidents. Praxis. 1996;85(41):1275-1282.
60. Oberhammer R, Beikircher W, Hormann C, et al. Full recovery of an avalanche victim with profound hypothermia and prolonged cardiac arrest treated by extracorporeal re-warming. Resuscitation. 2008;76(3):474-480.
61. Truhlar A, Deakin CD, Soar J, et al. European Resuscitation Council Guidelines for Resuscitation 2015: Section 4. Cardiac arrest in special circumstances. Resuscitation. 2015;95:148-201.
62. Grossman MD, Saffle JR, Thomas F, Tremper B. Avalanche trauma. J Trauma. 1989;29(12):1705-1709.
63. Boyd J, Haegeli P, Abu-Laban RB, et al. Patterns of death among avalanche fatalities: a 21-year review. CMAJ. 2009;180(5):507-512.
64. Wick MC, Weiss RJ, Hohlrieder M,t al. Radiological aspects of injuries of avalanche victims. Injury. 2008;40(1):93-98.
65. Johnson SM, Johnson AC, Barton RG. Avalanche trauma and closed head injury: adding insult to injury. Wilderness Environ Med. 2001;12(4):244-247.
66. Monsieurs KG, Nolan JP, Bossaert LL, et al. European Resuscitation Council Guidelines for Resuscitation 2015: Section 1. Executive summary. Resuscitation. 2015;95:1-80.
67. Grasegger K, Strapazzon G, Procter E, et al.Avalanche Survival After Rescue With the RECCO Rescue System: A Case Report. Wilderness Environ Med. 2016;27(2):282-286.
68. Brugger H, Durrer B, Adler-Kastner L. On-site triage of avalanche victims with asystole by the emergency doctor. Resuscitation. 1996;31(1):11-16.
69. Brugger H, Durrer B. On-site treatment of avalanche victims ICAR-MEDCOM-recommendation. High Alt Med Biol. 2002;3(4):421-425.
70. Soar J, Perkins GD, Abbas G, et al. European Resuscitation Council Guidelines for Resuscitation 2010 Section 8. Cardiac arrest in special circumstances: Electrolyte abnormalities, poisoning, drowning, accidental hypothermia, hyperthermia, asthma, anaphylaxis, cardiac surgery, trauma, pregnancy, electrocution. Resuscitation. 2010;81(10):1400-1433.
71. Vanden Hoek TL, Morrison LJ, Shuster M, et al. Part 12: cardiac arrest in special situations: 2010 American Heart

Association Guidelines for Cardiopulmonary Resuscitation and Emergency Cardiovascular Care. Circulation. 2010;122(18 Suppl 3):S829-861.

72. Paal P, Milani M, Brown D, et al. Termination of cardiopulmonary resuscitation in mountain rescue. High Alt Med Biol. 2012;13(3):200-208.
73. Hopson LR, Hirsh E, Delgado J, et al. Guidelines for withholding or termination of resuscitation in prehospital traumatic cardiopulmonary arrest. J Am Coll Surg. 2003;196(3):475-481.
74. Gruber E, Oberhammer R, Balkenhol K, et al. Basic life support trained nurses ventilate more efficiently with laryngeal mask supreme than with facemask or laryngeal tube suction-disposable--a prospective, randomized clinical trial. Resuscitation. 2014;85(4):499-502.
75. Danzl DF. Accidental Hypothermia. In: Auerbach PS, ed. Wilderness Medicine. Vol 6th. Philadelphia: Mosby; 2012. pp 116-142.
76. Brown DJ, Brugger H, Boyd J, Paal P. Accidental hypothermia. N Engl J Med. 2012;367(20):1930-1938.
77. Mair P, Brugger H, Mair B, et al. Is extracorporeal rewarming indicated in avalanche victims with unwitnessed hypothermic cardiorespiratory arrest? High Alt Med Biol. 2014;15(4):500-503.
78. Boue Y, Payen JF, Brun J, et al. Survival after avalanche-induced cardiac arrest. Resuscitation. 2014;85(9):1192-1196.
79. Hilmo J, Naesheim T, Gilbert M. “Nobody is dead until warm and dead”: Prolonged resuscitation is warranted in arrested hypothermic victims also in remote areas - A retrospective study from northern Norway. Resuscitation. 2014;85(9):1204-1211.
80. Althaus U, Aeberhard P, Schupbach P, et al. Management of profound accidental hypothermia with cardiorespiratory arrest. Ann Surg. 1982;195(4):492-495.
81. Pasquier M, Hugli O, Paal P, et al. Hypothermia outcome prediction after extracorporeal life support for hypothermic cardiac arrest victims: The HOPE score. Resuscitation. 2018;126:58-64.
82. Locher T. Walpoth B. [Differential diagnosis of circulatory failure in hypothermic avalanche victims: retrospective analysis of 32 avalanche accidents]. Schweiz Rundsch Med Prax. 1996;85:1275-1282.
83. Putzer G, Braun P, Zimmermann A, et al. LUCAS compared to manual cardiopulmonary resuscitation is more effective during helicopter rescue-a prospective, randomized, cross-over manikin study. Am J Emerg Med. 2012;31(2):384-389.
84. Gordon L, Paal P, Ellerton JA, et al. Delayed and intermittent CPR for severe accidental hypothermia. Resuscitation. 2015;90:46-49.
85. Strapazzon G, Plankensteiner J, Mair P, et al. Prehospital management and outcome of avalanche victims with out-of-hospital cardiac arrest: a retrospective study in Tyrol, Austria. Eur J Emerg Med. 2017;24(6):398-403.
86. Kottmann A, Blancher M, Spichiger T, et al. The Avalanche Victim Resuscitation Checklist, a new concept for the management of avalanche victims. Resuscitation. 2015;91:e7-e8.
87. Kottmann A, Blancher M, Pasquier M, Brugger H. Avalanche Victim Resuscitation Checklist adaption to the 2015 ERC Resuscitation guidelines. Resuscitation. 2017;113:e3-e4.
88. Blancher M, Bauvent Y, Bare S, et al. Multiple casualty incident in the mountain: Experience from the Valfrejus avalanche. Resuscitation. 2017;111:e7-e8.
89. Pasquier M, Rousson V, Darocha T, et al. Hypothermia outcome prediction after extracorporeal life support for hypothermic cardiac arrest victims: An external validation of the HOPE score. Resuscitation. 2019;139:321-328.
90. Brugger H, Bouzat P, Pasquier M, et al. Cut-off values of serum potassium and core temperature at hospital admission for extracorporeal rewarming of avalanche victims in cardiac arrest: A retrospective multi-centre study. Resuscitation. 2019;139:222-229.
91. Rauch S, Dal Cappello T, Strapazzon G, et al. Pre-hospital times and clinical characteristics of severe trauma victims: A comparison between mountain and urban/suburban areas. Am J Emerg Med. 2018.
92. Blancher M, Albasini F, Elsensohn F, et al. Management of Multi-Casualty Incidents in Mountain Rescue: Evidence-Based Guidelines of the International Commission for Mountain Emergency Medicine (ICAR MEDCOM). High Alt Med Biol. 2018;19(2):131-140.
93. Guyatt G, Gutterman D, Baumann MH, et al. Grading strength of recommendations and quality of evidence in clinical guidelines: report from an american college of chest physicians task force. Chest. 2006;129(1):174-181.
94. Haegeli P, Falk M, Procter E, et al. The effectiveness of avalanche airbags. Resuscitation. 2014;85(9):1197-1203.
95. Procter E, Strapazzon G, Dal Cappello T, et al. Adherence of backcountry winter recreationists to avalanche prevention and safety practises in northern Italy. Scand J Med Sci Sports. 2014;24(5):823-829.
96. Hohlrieder M, Mair P, Wuertl W, Brugger H. The impact of avalanche transceivers on mortality from avalanche accidents. High Alt Med Biol. 2005;6(1):72-77.
97. Brugger H, Etter HJ, Zweifel B, et al. The impact of avalanche rescue devices on survival. Resuscitation. 2007;75(3):476-483.
98. Strapazzon G, Migliaccio D, Fontana D, et al. Knowledge of the Avalanche Victim Resuscitation Checklist and Utility of a Standardized Lecture in Italy. Wilderness Environ Med. 2018;29(1):56-60.
99. Darocha T, Kosinski S, Moskwa M, et al. The Role of Hypothermia Coordinator: A Case of Hypothermic Cardiac Arrest Treated with ECMO. High Alt Med Biol. 2015;16(4):352-355.