JOURNAL of TRAVEL MEDICINE
International Society of Travel Medicine
Promoting healthy travel worldwide
Established 1991

Journal of Travel Medicine, 2023, 1–6
https://doi.org/10.1093/jtm/taac133
Review

Review

Effectiveness and use of avalanche airbags in mortality reduction among winter-recreationists

Lucia Laura Di Stefano, MD[1,*], Bianca Della Libera, MS[2] and Paolo Rodi, MD[3]

[1]Internal Medicine department, Clinica Santa Chiara, via Stefano Franscini 4, 6600 Locarno, Switzerland, [2]Faculty of Medicine and Surgery, Università degli studi di Messina, Piazza Pugliatti 1, 98122 Messina, Italy and [3]Department of Surgery, Campus Virchow-Klinikum and Campus Charité Mitte, Charité - Universitätsmedizin Berlin, Augustenburger Platz 1, Berlin 13353, Germany

*To whom correspondence should be addressed. Email: lucialauradistefano@gmail.com

Submitted 19 August 2022; Revised 4 October 2022; Accepted 20 October 2022

Abstract

Background/objective: The number of backcountry skiers and snowboarder surged in the last years, especially during the COVID-19 pandemic, as ski resorts shut down. Inevitably, this led to an increase in avalanche-related injuries and death. As avalanche rescue device, avalanche airbags are increasingly becoming part of the standard winter mountaineering equipment. This study provides a review of the available data and an updated perspective on avalanche airbags, discussing their function and efficacy to reduce mortality and their limitations.
Results: Causes of death in individuals caught by avalanches are multiple. Airbags seem to reduce mortality by decreasing the chances of critical burial, the most determining risk factor. However, there is a scarcity of reliable scientific research on the topic, and the way in which airbags reduce mortality and to what extent is still debated. Several elements seem to influence airbags efficacy, and their use still yields several limitations linked to manufacturing, proper use, users education and risk compensation.
Conclusions: Avalanche airbags seem to be an important tool in reducing mortality in the backcountry expeditions. However, more research and standardized data collection are needed to fill the knowledge gap, and mountain communities should promote adequate education of winter-recreationists on how to prevent and react to an avalanche and on the correct use of airbags in combination with already available tools such as transceivers, probes and shovels; and manufacturing companies should ensure higher efficacy of the survival avalanche equipment for better prevention of burial, asphyxia and trauma.

Key words: Avalanche airbags, mountain medicine, avalanche airbags effectiveness in mortality reduction, avalanche survival

Introduction

Avalanches are major hazards of predominantly anthropogenic origin[1] and avalanche accidents are common events in the mountain areas, threatening people and infrastructures.[2] Avalanches pose a relevant risk of injury and mortality, especially in the backcountry and off-piste environment, namely unpatrolled areas far from ski resorts with no marked trails, where skiers and snowboarders adventure on uncontrolled terrains.[3] During the COVID-19 pandemic, as ski resort were forced to shut down slopes and lifts,[4] the number of backcountry skiers and snowboarders surged.[5] Inevitably, as >90% of avalanches that involve injuries are triggered by winter-recreationists,[6] this led to an increase in fatalities across the alps, with up to 130 avalanche-related deaths during the winter season 2020–21 with an all-time high rate of 15 fatalities per week.[7,8]

Given the high mortality rate of individuals caught in avalanches (13–23%),[9] several methods are being continuously developed to foster the prevention and rescue in the case of avalanche incidents. Examples include the promotion of avalanche education through alpine guides, alpine association or even academic institutions,[10] publicly and free available forecasts[11] as well as the improvement and cost reduction of avalanche rescue equipment.[12–15] Among the latter, avalanche airbags are particularly noteworthy and are becoming of common use in the mountaineering community.[16] They are sold as rucksacks equipped with inflatable balloon, and the aim is to keep the skier on the surface of an avalanche, thereby preventing his burial.[16,17]

This up-to-date review aims to survey literature to present available information on avalanche airbags in relation to avalanche-related mechanisms of injuries and mortality and to present updated and summarized data on the topic.

Mechanisms of deaths and avalanche survival

One historical study shows that general mortality rate for people caught in avalanches is 13%.[18] Causes of deaths in individuals caught by avalanches are multiple. Asphyxia represents the first death-trigger (85.7%), together with trauma (5.4%), or a combination of them (8.9%).[3,19,20] Instead, contrary to common belief, hypothermia is a very rare cause of death (1%), as it represents a slow process and victims tend to succumb from asphyxia before hypothermia develops.[3,19,21]

Among risk factors for mortality, the most decisive is critical burial, which is defined as burial of the head and impaired breathing, with mortality rates reaching 52 vs 3% for non-critically buried individuals.[6] Time to rescue plays a relevant role, too. Of the critically buried individuals rescued in 18 minutes, 9% die, compared with 34% of those rescued after 18–35 minutes, thereby showing a steep increase. A plateau in mortality is seen for those rescued after 35–90 minutes, and after 90 minutes of critical burial, survival is virtually impossible.[22–24]

The rapid decrease in survival rate for those buried for up to 35 minutes can be attributed to several precipitating factors. Indeed, it can be attributed to traumatic injuries, or to asphyxia because of obstructed airways, chest compression and movement restriction from the weight of the snow, or because of the absence of a so-called 'air pocket'—air-filled space around the airways—to allow the diffusion of carbon dioxide and of oxygen through the snow surface.

On the contrary, the mortality plateau recorded for burial times between 35 and 90 minutes can be attributed to the absence of injuries—which spare from haemorrhages, head trauma, compartment syndromes and the presence of unobstructed airways, adequate chest movements and an adequate air pocket. These factors avoid the insurgence of asphyxia and guarantee a longer survival.

Having an air pocket seems to be conducive to a prolonged survival, and the bigger the air pocket, the bigger are survival chances. However, after a certain period of time, usually not >90 minutes, the air pocket may fail. This is due to two phenomena termed 'displacement asphyxia' and 'ice lens'. Displacement asphyxia occurs when the exhaled CO_2 accumulates in the air pocket and displaces O_2, thereby decreasing its partial pressure in the breathable air. Although snow porosity influences diffusion velocity, both gases can freely move across the snow crust from the environment to the air pocket and vice versa. After burial, CO_2 and O_2 diffusions through the snow crust are initially balanced. However, when the amount of CO_2 accumulated exceeds that of O_2 extracted from the environment, the O_2 partial pressure in the air pocket drops to a level incompatible with adequate gas exchange, thereby leading to hypoxia and asphyxia. This process may be accelerated by the ice lens effect. An ice lens forms when the warm humidified exhaled air melts the snow layering the air pocket, which rapidly refreezes, thus creating an ice barrier on the walls of the air pocket and impeding the O_2 and CO_2 exchange.[20,24,25]

Another determining factor is the depth of burial. Since the time of extraction from an avalanche depends on the capacity of companions to dig their way to the victim, a deep burial is inevitably linked to a longer burial time. Moreover, the greater the weight of the debris above the victim's body, the higher the chances of critical chest compression, impaired breathing mechanic and of an inadequate air pocket. According to historical statistics, no victim has survived a burial >2 m [20,26]

Overview on devices

Given the mechanisms of injury and death, different devices that act on these mechanisms have been developed and introduced in the market. The current standard safety sets include a transceiver, a probe and a shovel, which are mandatory in some countries.[27] They allow a rapid assessment of the victim's geographical location under the snow, depth of burial and extraction, thus impacting on the time to rescue. Similarly, the avalanche ball decreases the time spent to search. This is an air-filled balloon that inflates after pulling a trigger. Thanks to its high volume/weight ratio, it floats on the surface of the snow, thus signalling the position of the victim.

Ice lens formation and CO_2 accumulation can be prevented with a device called the artificial air pocket. It consists of a mouthpiece and a tubing system that diverts the warm and CO_2-filled exhaled air towards the back of the victim. In turns, this slows down the insurgence of asphyxia and allows for longer survival.[20,24]

However, while these tools either reduce time to rescue (transceiver and ball) or delay time to asphyxia (artificial air pocket), they do not act on the most decisive and causative factor, critical burial. Indeed, there is only one technology that directly acts to preventing critical burial, i.e. the avalanche airbag.[28]

The avalanche airbag

The avalanche airbag consists of a rucksack equipped with a packable bag that rapidly inflates upon pulling a trigger handle. Notwithstanding its invention in Europe in the 1970s and its introduction to the market as a commercial product in 1991, its use has become popular only in the last 15 years.[17] In fact, airbags have long not been suggested by guidelines, given the lack of clear scientific evidence in the literature. Moreover, the mountaineering community was sceptic to the use of airbags because of cost and of the extra weight to be carried on already loaded rucksacks—the lightest airbags, nowadays, on the market weigh on average 2 Kg[28]—and because of impaired vision and agility to move once inflated, which could undermine efforts of the skier to escape the avalanche.[20] Despite being commonly used in Europe, in the USA, only some types of airbags (single-balloon system) are available because of shipping restrictions since the pressure cartridge of airbags is categorized as a hazardous material in the USA.[20] Recently, more affordable pricing (between 300 and 1200€) and production of lighter devices allowed a widespread use of airbags among the public. In a 2020 survey, ~60% of backcountry skiers declared to owning an airbag backpack.[29]

Despite its increase in popularity,[29] strong recommendation by the scientific community and an adequate research in literature are still lacking. Moreover, due to the lack of complete and adequate datasets on avalanche accidents and due to different inclusion criteria and materials and methods used, the results of existing studies, especially in terms of impact on survival, vary across the literature and are prone to biases and inaccuracies.[30]

By rapidly increasing in size, avalanche airbags exploit the mechanism of granular convection, also known as Brazil nut effect, according to which, in a moving mixture of varying sized particles, e.g. an avalanche, the relatively larger particles are propelled upwards.[31–33] As for airbags, the increase in volume of ∼150 l holds the victim at the surface, thus preventing critical burial.[28]

There are other airbags available on the market, which are designed to deflate after 3 minutes from deployment. In case of burial, deflation is supposed to leave an air pocket of ∼200 l around the head of the victim. An experimental study demonstrated that having this kind of airbag-created air pocket increases the tolerance time for survival.[24] In the study, 12 volunteers equipped with artificial air pocket (described above) were buried under snow for an hour during which oxygen saturation, end-tidal CO_2, heart rate and respiratory rate were measured. Participants were buried with the airbag inflated, which then deflated after 3 minutes, leaving an air pocket around the subject. Data were compared with historical controls which used only artificial air pocket devices. The experimental group held for more time the aforementioned parameters within the normal range compared with the historical controls, thereby prolonging survival.[24]

Some manufacturing companies envisioned the idea that the C-shaped airbags (surrounding the sides of back and head) could also offer some protection against head trauma. Some field experiments, where test dummies were caught by avalanches and where forces on the cervical vertebrae, were measured to support this hypothesis.[20]

Methods

The methodology of this study was based on the standards of narrative reviews. Primarily, a thorough literature research has been conducted on PubMed, ResearchGate, and Google Scholar to access information on avalanche mortality, mechanism of injury, and available devices. This formed the base knowledge of our background section. Secondly, to collect relevant literature on the effectiveness of avalanche airbags and their effect on mortality reduction, literature searches were conducted with following strings: (“avalanche airbag”), (“avalanche” AND “airbag”), (“avalanche airbags effectiveness”), (“avalanche airbag” AND “mortality reduction”), (“avalanche” AND “rescue device∗”). To expand research, we traced the references of the retrieved articles and used the “similar articles” tool on PubMed, which allows to automatically retrieve studies whose PubMed keywords do not precisely correspond to the ones included in the search strings, but that nevertheless may contain useful information. Finally, a direct Google search of the topic in English, Italian, and German (three commonly used languages around the alpine arch) was performed with the aim of accessing any non-peer-reviewed information. Similarly, the websites of the Italian, Swiss, Austrian, German, and American alpine club were accessed. We included surveys, questionnaires, observational studies on real-life accidents as well as articles that provided a quantitative assessment of mortality reduction. We excluded studies not based on humans or that did not report quantitative data. Retrieved articles were summarized and compared to provide an overall review of the topic.

Results

Impact on survival

Some on-field experimental studies, with crash dummies exposed to artificially triggered avalanches, show that wearing an avalanche airbag could decrease burial depth. In a 2001 test, the mean burial depth for dummies wearing an airbag was of 22 vs 59 cm of those not wearing an airbag. Moreover, the dummies wearing airbags were visible above the surface of the snow in 100% of the cases. On the contrary, all but one of the six tested dummies without airbag were completely buried.[34–37]

After filtering for our inclusion and exclusion criteria, we were able to retrieve six articles reporting the quantitative data on mortality reduction, of which one was survey and five were retrospective experimental studies on real life accidents. These are summarized in Table 1.

The 2000 study assessed 26 documented incidents globally involving 40 individuals with avalanche airbag from 1991 to 2000. In those cases where the airbag did not fail to deploy (32/40), only one individual died (3.2%), compared with the 13% mortality rate of individuals caught in avalanches.[18] The 2003 study assessed 47 accidents from 1991 to 2003 which were reported worldwide for a total of 60 people equipped with airbag systems. Data were collected and documented by the Federal Institute for Snow and Avalanche Studies in Davos using questionnaires. In the assessed group, 7 of the 60 people failed to inflate the airbag (11.6%). For the remaining 53 individuals, the overall burial rate was 15.1% and mortality rate was 1.9%. Historical data of all known cases of people swept away by an avalanche in an open terrain in Switzerland between 1981 and 2001 were used as the control group. Regardless of the safety devices used, a total burial rate of 37.0% and an overall mortality rate of 21.8% was recorded. Historical data did not report the rate of individuals using airbags.[38]

In other studies from 2002[9] and 2007,[17] conducted with similar methods, individuals equipped with an avalanche airbag had lower chances of dying compared with historical data of the general backcountry population: 2.5 vs 23%,[9] and 2.9 vs 18.9%.[17]

In a 2012 survey, out of 214 avalanche airbag users, 13 declared to have had deployed their airbags in an avalanche, of whom only 1 participant declared to have been completely buried, whereas 2 have been partially buried with their head above the surface and 10 have stopped at the surface. All of them survived.[37]

A bigger study published in 2014 included 245 avalanche accidents between 1994 and 2012 from different countries (Canada, France, Slovakia, Norway, Switzerland and USA) where data on airbag use were available. Collected data included accurate information about accidents victims, about the location

Table 1. Summary of the retrospective experimental studies on avalanche airbags retrieved by our search and the corresponding calculated absolute mortality reduction of individuals caught in avalanche who were wearing a functional airbag

Title	Authors	Year of publication	Absolute mortality reduction
Avalanche rescue systems in Switzerland: experience and limitations	Tschirky, Brabec, Kern	2000	9.8%
Analysis of avalanche safety equipment for backcountry skiers	Brugger, Falk	2002	20.5%
Effizienz am Lawinenkegel: Notfallausruestung fuer Tourengeher und Variantenfahrer. Eine kritische Analyse (Efficiency at the avalanche cone: emergency equipment for tourers and off-piste skiers. A critical analysis)	Brugger, Kern, Mair, *et al.*	2003	20%
The impact of avalanche rescue devices on survival	Brugger, Falk, *et al.*	2007	16%
Avalanche airbag survey: a US perspective	Christie	2012	N/A
The effectiveness of avalanche airbags	Haegeli, Falk, Brugger et.al	2014	8%

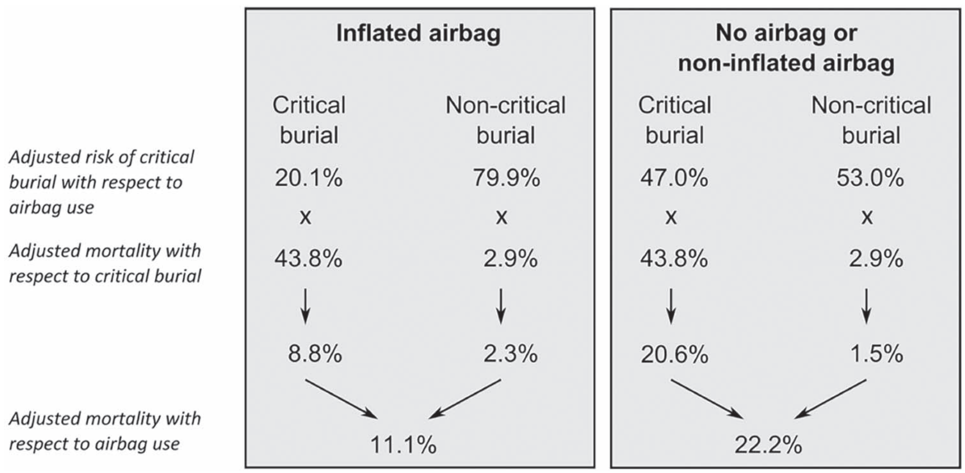

Figure 1. This artwork is from 'The effectiveness of avalanche airbags'—Haegeli *et al*. 2014[30]

of the accidents and the runout zone where the avalanche was triggered and about parameters that affect mortality such as grade of burial, traumatic injuries and use of avalanche transceiver. No historical data were used as the control group. It included 424 individuals and only avalanches that were able to cause critical burial (size $\geq$ 2.0 according to the Canadian avalanche size classification[30,39]). This study is summarized in Figure 1. It included (i) airbag users whose devices correctly deployed, (ii) users whose devices did not deploy and (iii) non-users. Non-inflation rate—main limitation to the effectiveness of airbags—was 20%. This happened because of users' mistakes in 60% of the cases; device failure in 17% of the cases, i.e. performance issues that eventually resulted in the design and/or product revision; maintenance errors in 12%, e.g. canister not attached properly; and destruction of airbag during the incident in 12%. After adjusting for relevant factors, such as avalanche size and presence of injuries, users' mortality whose airbag correctly inflated was compared with that of non-users and of individuals whose airbag failed to inflate. Adjusted critical burial rate for correctly inflated airbag users was 20 vs 47% of non-inflated or non-users. Adjusted recorded mortality of the correctly inflated airbag users was 11 vs 22% of the control group.

Comparison between overall users (regardless of if correctly inflated or not, i.e. Groups I and II) and non-users (Group III) showed a critical burial rate of 27 vs 56% and a mortality rate of 14 vs 22%, respectively. Mortality for critically buried victims, regardless of with or without inflated airbag was 44 vs 3% for non-critically buried victims. Finally, using a regression model, the authors concluded that the main effect of airbags on mortality reduction lies in their ability to prevent critical burial.[30]

Potential limitations

The design of some of the presented studies inevitably allow for potential biases, especially when historical controls were used and because of the incomplete datasets. Indeed, information on the type and size of avalanche, location of the victim and terrain obstacles which may cause traumatic injuries are missing, thus omitting relevant data that may affect mortality calculation.[6,40] More importantly, the use of airbags in historical controls was not reported, thus potentially affecting the overall results.[18] Finally, only one of the presented studies was able to conduct a multivariate analysis and to discern the effects of other factors on burial and mortality, e.g. avalanche size and presence of injuries.

Discussion

Overall, literature shows that many factors contribute to mortality in the case of avalanche incidents. These are represented by asphyxia—whether caused by the obstruction of airways, displacement of CO_2 and O_2, the formation of an ice lens or chest compression— fatal injuries, and to a much lesser extent, hypothermia. Most of these death causes are secondary to the critical burial of the body, head and airways, making it the most decisive element.

Avalanche airbags have proved to reduce the overall mortality among their users; however, scientific data regarding the way they ultimately function are still scarce. Notably, the last study that focused on this topic was conducted in 2014. It seems that airbags reduce mortality by decreasing the chances for critical burial. Yet, only one study that is able to support this hypothesis with a multivariate analysis.[30] Moreover, it seems that prospective articles are missing from the literature, which are commonly more reliable in terms of data collection and reduction of biases than retrospective ones.[17] Nevertheless, authorities and researchers may face a scarcity of data. A 2012 survey showed that only 50% of the accidents experienced by participants were reported to authorities.[37] Therefore, a correct education of the population in reporting incidents may be conducive to a bigger databank, thereby to more research.

More research is needed to clarify if the airbags can be effective in reducing trauma and in delaying asphyxia by creating an air pocket, as claimed by some manufacturing companies[34] and as suggested by some field experiments with test dummies[6] and with volunteers.[24] Similarly, more efforts should be paid to decrease the risk of non-deployment, which is the main limitation to airbags effectiveness. However, since non-deployment is caused in 60% of cases by users' errors,[16] more training on the use of airbags should be encouraged across the mountaineering community.

Among some backcountry skiing communities, there is the concern that although deploying an avalanche bag could keep the skier on the surface, it could result in carrying the skier further down the avalanche slope, possibly putting the skier at the risk of going over a cliff or hitting trees. However, no official source addresses this claim, and dedicated research is still missing.

Implementation of education programmes may also be beneficial to decrease risky behaviour in the mountains. Indeed, it has been shown that when equipped with airbags, backcountry skiers choose riskier tracks and behaviours because of a greater sense of safety given by the airbag,[29] a phenomenon termed as risk compensation.[41,42] To some extent, some have speculated that the positive effects that airbags have on mortality may be nullified by this increased sense of safety.[43] However, general recommendations speak in favour of wearing an airbag despite risk compensation.[29]

Meanwhile, given the scarce knowledge in the literature, it may be appropriate for manufacturing companies to consider all the elements on which airbags may have a decisive effect to reduce mortality, i.e. reduction of critical burial, protection from fatal injuries and formation of an air pocket. Eventually, companies may want to foster the production of light, single devices that act on the prevention of all these aspects without increasing rucksack weight, cost or impairing agility or sight. On the other hand, users should consider appropriate training and possibly the use of a combination of different protective devices to minimize the chances of death. Without any doubt, this should be accompanied by general education and training on use of search and rescue devices, avalanche prevention, forecasts and general high-altitude behaviour.

Conclusions

Avalanches are a major threat to winter-recreationists. Several methods and devices are available on the market to minimize death risk in case of avalanche. Among others, airbag avalanches seem to be the device of choice to reduce the risk of critical burial, the most decisive factor in avalanche incidents, and to consequently reduce mortality. However, scientific literature on the effectiveness and functioning mechanism is still scarce. As a possible life-saving tool, more research should be conducted. Simultaneously, more attention should be paid by manufacturing companies and users in achieving fully functioning airbags—maybe in combination with other life-saving device, e.g. artificial airways—their correct use, and appropriate education.

Funding

The authors did not receive any financial support for the conference as well as for the research.

Conflict of interest

None declared.

Acknowledgements

We thank Saimir Kadriu for the assistance with English language and wilderness medical training and for having given us the inspiration for our work.

References

1. Bejiga MB, Zeggada A, Melgani F. Convolutional neural networks for near real-time object detection from UAV imagery in avalanche search and rescue operations. *Int Geosci Remote Sens Symp* 2016; **2016**:693–6.
2. Strapazzon G, Schweizer J, Chiambretti I *et al.* Effects of climate change on avalanche accidents and survival. *Front Physiol* 2021; **12**:1–10.
3. Mbbs JB, Haegeli P, Mhsc RBA *et al.* A 21-year review, Canadian Medical Association Journal (CMAJ), 2009; **180**:507–12.
4. BBC. *Coronavirus Pandemic: Germany Seeks EU Deal to Close Ski Resorts*. 26 November 2020.
5. Greene K, Hendrikx J, Johnson J. The impact of avalanche education on risk perception, confidence, and decision-making among backcountry skiers. *Leis Sci* 2022; 1–21.
6. Brugger H, Durrer B, Adler-Kastner L *et al.* Field management of avalanche victims. *Resuscitation* 2001; **51**(1):7–15.
7. E. Avalanche Warning Services. *Fatalities - European Avalanche Warning Services (2017/2018)*.
8. Luhn A. Backcountry skiing sees resurgence – and the deadliest week for avalanches since 1910. *The Guardian* 2021.
9. Brugger H, Falk M. Analysis of avalanche safety equipment for backcountry skiers. *Avalanche News* 2004; **66**:34–8.
10. ZHM Zentraler Hochschulsport München. *Risikomanagement - Schneesport*.

11. Regione Lombardia. *"ARPA Lombardia - Agenzia regionale per la protezione dell'ambiente." [Online].* https://www.arpalombardia.it/Pages/ARPA_Home_Page.aspx.
12. Etter H-J, Stucki T, Zweifel B *et al.* Developments in avalanche forecasting and other prevention measures and their potential effects on avalanche fatalities. In: *2008 International Snow Science Workshop*, Whistler, BC, Canada, 2008.
13. Harvey S, Zweifel B. New trends of recreational avalanche accidents in Switzerland. *Int Snow Sci Work*. Whistler BC, Canada 2008 (900-906).
14. Valt M, Pivot S, Pradat V. Avalanche accident documentation is of fundamental importance to under- stand the dynamics, taking place in snow, of risky activities in order to imple- ment the best possible prevention strategies. 2013; 1142–7.
15. McCammon I, Hägeli P. An evaluation of rule-based decision tools for travel in avalanche terrain. *Cold Reg Sci Technol* 2007; **47**(1–2):193–206.
16. Haegeli P, Zweifel B, Jarry F *et al.* On the effectiveness of avalanche balloon packs. In: *Proceedings, 2012 International Snow Science Workshop*. Anchorage, Alaska, 2012, pp. 324–8.
17. Brugger H, Etter HJ, Zweifel B *et al.* The impact of avalanche rescue devices on survival. *Resuscitation* 2007; **75**(3):476–83.
18. Tschirky F, Brabec B, Kern M. "Avalanche rescue systems in Switzerland: experience and limitations. *Proceedings of the 2000 International Snow Science Workshop*, October 1–6, Big Sky, Montana.
19. McIntosh SE, Grissom CK, Olivares CR *et al.* Cause of death in avalanche fatalities. *Wilderness Environ Med* 2007; **18**:293–7.
20. Radwin MI, Grissom CK. Technological advances in avalanche survival. *Wilderness Environ Med* 2002; **13**:143–52.
21. Stalsberg H, Albretsen C, Gilbert M *et al.* Mechanism of death in avalanche victims. *Vichows Arch A Pathol Anat* 1989; **414**:415–22.
22. Haegeli P, Falk M, Brugger H, Etter HJ, Boyd J. Comparison of avalanche survival patterns in Canada and Switzerland. *CMAJ* 2011; **183**:789–95.
23. 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**:173–6.
24. McIntosh SE, Little CE, Seibert TD *et al.* Avalanche airbag post-burial active deflation — the ability to create an air pocket to delay asphyxiation and prolong survival. *Resuscitation* 2019; **146**:155–60 2020.
25. Falk M, Brugger H, Adler-Kastner L. Avalanche survival chances [4]. *Nature* 1994; **368**:21.
26. Sheets A, Wang D, Logan S, Atkins D. Causes of death among avalanche fatalities in Colorado: a 21-year review. *Wilderness Environ Med* 2018; **29**:325–9.
27. C. della R. Italiana. *DECRETO LEGISLATIVO 28 febbraio 2021*. 2021.
28. Van Tilburg C. Should airbag backpacks be standard avalanche safety equipment? *Wilderness Environ Med* 2021; **32**:495–8.
29. Haegeli P, Rupf R, Karlen B. Do avalanche airbags lead to riskier choices among backcountry and out-of-bounds skiers? *J Outdoor Recreat Tour* 2020; **32**:100270.
30. Haegeli P, Falk M, Procter E *et al.* The effectiveness of avalanche airbags. *Resuscitation* 2014; **85**:1197–203.
31. Kern MA, Ammann WJ, Vulliet L. Inverse grading in granular flows. In: *Numerical Models in Geomechanics. Proceedings of the 7th International Symposium*. Graz, September 1999, p. 1999 doi: 10.1201/9781003078548-93.
32. Gray JMNT, Ancey C. Segregation, recirculation and deposition of coarse particles near two-dimensional avalanche fronts. *J Fluid Mech* 2009; **629**:387–423.
33. Kern M, Buser O, Peinke J *et al.* Stochastic analysis of single particle segregational dynamics. *Phys Lett Sect A Gen At Solid State Phys* 2005; **336**:428–33.
34. Kern M, Tschirky F, Schweizer J. Field tests of some new avalanche rescue devices. *Paper presented at the International Snow Science Workshop*, Penticton, BC, 2001.
35. Kern MA, Tschirky F, Schweizer J. Feldversuche zur einigerneuer Lawinen-Rettungsgeräte (Field experiments onthe effectiveness of some new avalanche rescue devices). *Jahrbuch 2001 der Oesterreichischen Gesellschaft fuer Alpinund Hoehenmedizin*, Innsbruck. Raggl digitalgraphic & print. 2002; 127–45.
36. Tschirky F, Schweizer J. *Avalanche Balloons - Preliminary Test Results*, Avalanche control, rescue and education, 1996 pp. 309–12.
37. Bovet E, Chiaia B, Maggioni M *et al.* Proceedings, 2012 International Snow Science Workshop, Anchorage, Alaska. *Int Snow Sci Work* 2012; 617–21.
38. Brugger H, Kern M, Mair P *et al.* Effizienz am Lawinenkegel: Notfallausruestung fuer Tourengeher und Variantenfahrer. Eine kritische Analyse. *BergUndSteig* 2003; **4**:60–5.
39. C. A. A. (CAA), Observation guidelines and recording standards for weather, snowpack, and avalanches. *Revel Canada Can Assoc* 2007; 47–59; 2007.
40. Jamieson B and Jones AST, The effect of under-reporting of non-fatal involvements in snow avalanches on vulnerability. *12th International Conference on Applications of Statistics and Probability in Civil Engineering, ICASP 2015*. Vancouver, Canada, July 12–15 2015.
41. Wilde GJS. The theory of risk homeostasis: implications for safety and health. *Risk Anal* 1982; **4**(2):89–91.
42. Wilde GJS. *Target Risk 2: A New Psychology of Safety and Health*. PDE Publ, 2001, p. 255.
43. Wolken NJ, Zweifel B, Tschiesner. Avalanche airbags and risk compensation: An empirical investigation. *Pap Present Int Snow Sci Work Banff AB*, Banff, Canada 2014; 957–62.