Resuscitation 85 (2014) 1197–1203

Contents lists available at ScienceDirect

Resuscitation

journal homepage: www.elsevier.com/locate/resuscitation

Clinical Paper

The effectiveness of avalanche airbags☆

Pascal Haegeli[a,b,*], Markus Falk[c], Emily Procter[d], Benjamin Zweifel[e], Frédéric Jarry[f], Spencer Logan[g], Kalle Kronholm[h], Marek Biskupič[i,j], Hermann Brugger[d]

[a] Avisualanche Consulting, 2-250 E 15th Avenue, Vancouver, BC, V5T 2P9, Canada
[b] School for Resource and Environmental Management, Simon Fraser University, 8888 University Drive, Burnaby, BC, V5A 1S6, Canada
[c] Inova Q Inc., Tinkhauserstrasse 5b, 39031 Bruneck/Brunico, Italy
[d] EURAC Institute of Mountain Emergency Medicine, Drususallee 1, 39100 Bozen/Bolzano, Italy
[e] WSL Institute for Snow and Avalanche Research SLF, Flüelastrasse 11, 7260 Davos, Switzerland
[f] National Association for Snow and Avalanche Studies (ANENA), 15 rue Ernest Calvat, 38000 Grenoble, France
[g] Colorado Avalanche Information Center, 325 Broadway WS1, Boulder, CO 80305, USA
[h] Norwegian Geotechnical Institute (NGI), Sognsveien 72, N-0855 Oslo, Norway
[i] Avalanche Prevention Center, Jasná, 032 51 Demänovská Dolina, Slovakia
[j] Institute for Environmental Studies, Charles University, Ovocný trh 3-5, 116 36 Praha 1, Czech Republic

ARTICLE INFO

Article history:
Received 13 March 2014
Received in revised form 15 May 2014
Accepted 21 May 2014

Keywords:
Avalanche accidents
Mortality
Safety equipment
Burial prevention

ABSTRACT

Aim: Asphyxia is the primary cause of death among avalanche victims. Avalanche airbags can lower mortality by directly reducing grade of burial, the single most important factor for survival. This study aims to provide an updated perspective on the effectiveness of this safety device.
Methods: A retrospective analysis of avalanche accidents involving at least one airbag user between 1994 and 2012 in Austria, Canada, France, Norway, Slovakia, Switzerland and the United States. A multivariate analysis was used to calculate adjusted absolute risk reduction and estimate the effectiveness of airbags on grade of burial and mortality. A univariate analysis was used to examine causes of non-deployment.
Results: Binomial linear regression models showed main effects for airbag use, avalanche size and injuries on critical burial, and for grade of burial, injuries and avalanche size on mortality. The adjusted risk of critical burial is 47% with non-inflated airbags and 20% with inflated airbags. The adjusted mortality is 44% for critically buried victims and 3% for non-critically buried victims. The adjusted absolute mortality reduction for inflated airbags is −11 percentage points (22% to 11%; 95% confidence interval: −4 to −18 percentage points) and adjusted risk ratio is 0.51 (95% confidence interval: 0.29 to 0.72). Overall non-inflation rate is 20%, 60% of which is attributed to deployment failure by the user.
Conclusion: Although the impact on survival is smaller than previously reported, these results confirm the effectiveness of airbags. Non-deployment remains the most considerable limitation to effectiveness. Development of standardized data collection protocols is encouraged to facilitate further research.

1. Introduction

Between 2004 and 2010, an average of 160 recreationists died per winter in avalanches in Europe and North America.[1] The majority of victims are young, healthy individuals recreating in avalanche terrain on skis, snowboards or snowmobiles.[2] If caught in an avalanche, grade of burial (defined as either *critically buried*, i.e., head under the snow and breathing impaired, or *non-critically buried*, i.e., unobstructed airways) is the strongest single factor for survival[3] and asphyxia is the primary cause of death among critically buried avalanche victims.[4–6] An analysis of Swiss avalanche accidents showed that while the mortality of critically buried individuals was 52% (385/735), the mortality of non-critically buried individuals was only 4% (48/1151).[7] Furthermore, survival analyses have shown that survival of critically buried victims is strongly correlated to duration of burial.[6–8] While survival rates are high in the first few minutes of critical burial, they drop precipitously after 10–18 min, leaving only a very short time window for successful extrication. Consequently, the prevention of critical burial is fundamental for increasing avalanche survival.

☆ A Spanish translated version of the abstract of this article appears as Appendix in the final online version at http://dx.doi.org/10.1016/j.resuscitation.2014.05.025.

* Corresponding author at: Avisualanche Consulting, 2-250 E 15th Avenue, Vancouver BC, V5T 2P9, Canada.
E-mail address: pascal@avisualanche.ca (P. Haegeli).

http://dx.doi.org/10.1016/j.resuscitation.2014.05.025
0300-9572/

Avalanche airbags are a relatively new avalanche safety device that consists of a backpack or vest with one or two inflatable balloons. When caught in an avalanche, users manually deploy the device by pulling an activation handle, which instantly inflates the stowed balloon(s) to a total volume of approximately 150 l. As long as the user is flowing freely within the avalanche, airbags function through a physical process called *inverse segregation* where larger particles are sorted toward the surface, thus reducing the user's chance of becoming critically buried.[9] In comparison to the currently recommended standard avalanche safety equipment (avalanche transceiver, shovel and avalanche probe)[10] that can reduce the duration of burial, avalanche airbags are the only avalanche safety device that can directly prevent critical burial.[11]

Robust statistical evaluations of airbag use in avalanche involvements are scarce; though the effectiveness of airbags has been supported,[11] such statistical analyses have important limitations and results should be interpreted accordingly. First, analyses focus exclusively on avalanche involvements with airbags from Switzerland and may not be applicable to other geographic regions. Second, sample sizes are too small to precisely isolate the effect of avalanche airbags. Third, the criteria used to include accident records are not adequately reported (i.e., was there potential for mortality). Fourth, comparing survival rates for avalanche airbag users with survival rates of non-users extracted from other existing avalanche accident databases is questionable because of probable differences in reporting biases and other unknown confounding factors. The interest of the community in the new device and encouragements from manufacturers to submit incident reports likely resulted in a higher reporting rate of accidents without injuries or fatalities among airbag users than non-users, which inadvertently leads to an overestimation of the effectiveness of airbags.

The aim of this study is to provide an updated and more thorough perspective on the effectiveness of avalanche airbags by evaluating (i) their influence on the grade of burial and mortality in individuals involved in avalanches with the potential of mortality using a multivariate approach with an unbiased control group and (ii) the frequency and reasons for deployment failures.

2. Materials and methods

2.1. Data sources

Existing records of well-documented avalanche accidents involving at least one avalanche airbag user were collected from data sources in Canada (Canadian Avalanche Association), France (National Association for Snow and Avalanche Studies), Slovakia (Avalanche Prevention Center), Norway (Norwegian Geotechnical Institute, Norwegian Red Cross), Switzerland (WSL Institute for Snow and Avalanche Research SLF) and the United States (Colorado Avalanche Information Center). Available accident reports were examined in detail and newly coded to produce a consistent dataset. Collected data included background information on accidents and victims (country, date, activity, avalanche professional) and parameters known to affect burial depth (e.g., presence of terrain traps), mortality (e.g., grade of burial, traumatic injuries, use of avalanche transceiver) or suspected impact on inverse segregation (e.g., relative location when avalanche was triggered—victims located in the runout zone when the avalanche is triggered will likely not be effectively sorted toward the surface of the avalanche) (Table 1).

Since avalanche airbags are designed to reduce the likelihood of critical burial, the analysis focused exclusively on avalanche involvements with potential for critical burial. Accident records were therefore only included if the destructive size of the avalanche was ≥2.0 according to the Canadian avalanche size classification (Table 2),[12] since sizes <2.0 are too small to bury a person by definition. Furthermore, only seriously involved users and non-users of airbags were included, which means severely involved in the flow of the avalanche or hit by the avalanche from above and non-critically or critically buried as a result. Marginally involved individuals (e.g., only slightly moved at the edge of the avalanche, remained standing during entire involvement or managed to ride out of avalanche) were excluded as airbags are unable to affect the outcomes of these types of involvements (Supplemental Table 1).

Supplementary table can be found, in the online version, at http://dx.doi.org/10.1016/j.resuscitation.2014.05.025.

Table 1
Parameters included in dataset.

Parameter	Levels
Accident information	
Country of accident location	See Table 3
Date	1994–2012
Activity	Backcountry skiing Mechanized skiing Out-of-bounds/off-piste skiing (incl. snowboarding) Ski patrolling Snowmobile riding
Avalanche characteristics	
Avalanche size	Numeric sizes ranging from 2.0 to 4.0 (incl. half sizes; Table 2) according to Canadian avalanche size classification[12]
Characteristics of runout zone	Smooth runout Terrain trap
Victim information	
Avalanche professional	Yes (e.g., mountain guide, ski patroller) No
Use of avalanche transceiver	Yes No
Use of avalanche airbag	No Yes—non-inflated (also includes partially inflated) Yes—inflated
Reason for non-inflation	Destroyed in accident Technical device failure Deployment failure by user Maintenance error Unknown reason
Relative location when triggered	Starting zone Track or runout
Grade of burial	Non-critical (no impairment of airways) Critical (impairment of airways)
Traumatic injuries	None or minor (not requiring hospitalization) Major (requiring hospitalization)
Fatality	Yes No

2.2. Data analysis

2.2.1. Effectiveness of avalanche airbag on grade of burial and mortality

The dataset for this analysis included only accidents with multiple involvements and different users of avalanche airbags (non-users, users with non-inflated airbags, users with inflated airbags) (Fig. 1). This allowed extraction of both the treatment and control groups from the same set of accidents, which eliminates the likely reporting bias and potential influence of additional unknown confounding factors. The effectiveness of avalanche airbags was examined from two perspectives: (i) effectiveness of only inflated airbags (users with inflated airbags versus non-users and users with non-inflated airbags) and (ii) effectiveness when non-inflations are taken into account (non-users versus users with non-inflated

Table 2
Canadian avalanche size classification.[12]

Size & data code*	Avalanche destructive potential	Typical mass	Typical path length
1	Relatively harmless to people	<10 t	10 m
2	Could bury, injure, or kill a person	10^2 t	100 m
3	Could bury and destroy a car, damage a truck, destroy a wood frame house, or break a few trees	10^3 t	1000 m
4	Could destroy a railway car, large truck, several buildings, or a forest area up to 4 hectares (~10 acres)	10^4 t	2000 m
5	Largest snow avalanche known; could destroy a village or a forest of 40 hectares (~100 acres)	10^5 t	3000 m

* Half-sizes may be used for avalanches that are between two size classes.

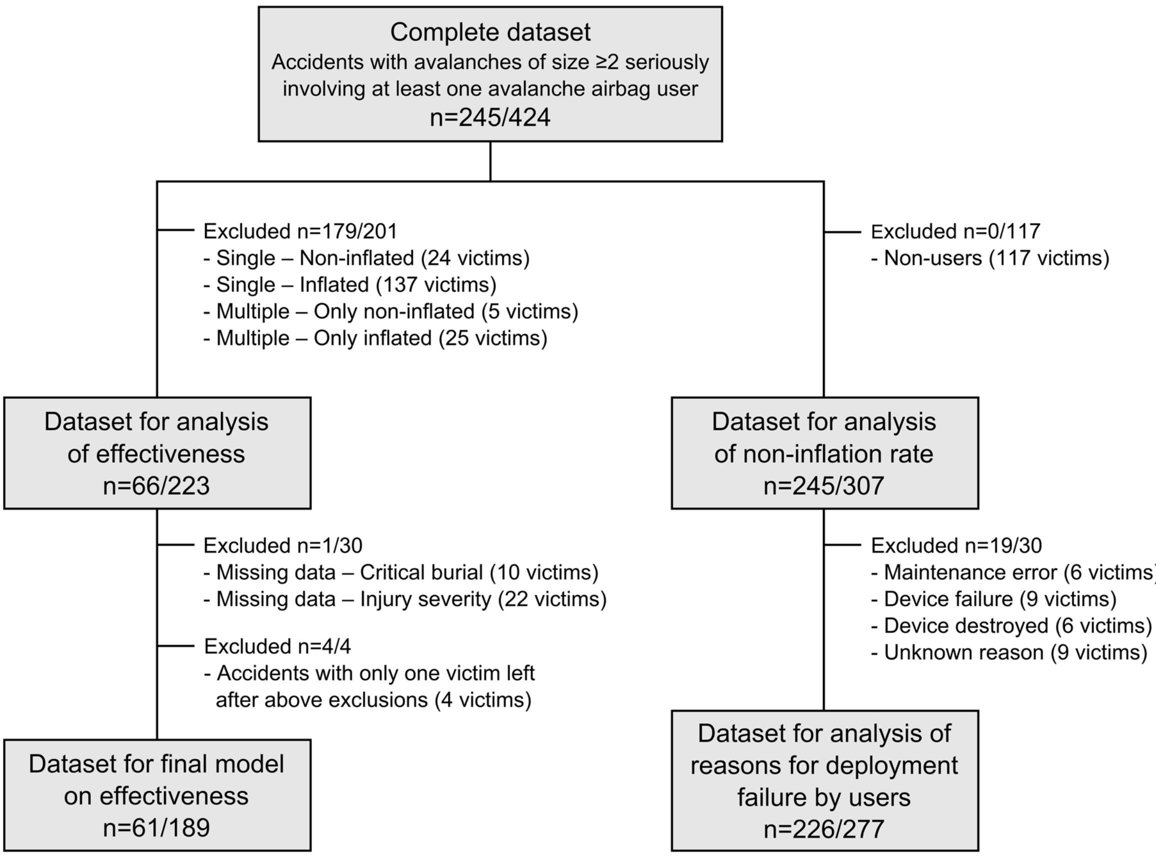

Fig. 1. Data included in the analysis on effectiveness and non-inflations (reported as number of accidents/number of victims).

airbags and users with inflated airbags). While the first perspective offers insights on the performance of the device in its intended use alone, the second assessment is more comprehensive as it examines the combined performance of the device and its user, who has to actively deploy the device.

For the univariate analyses we used Fisher's exact tests for count data and Wilcoxon rank-sum tests for ordinal or non-normal numeric parameters. Two-sided $P < 0.05$ was considered statistically significant and $0.05 \leq P < 0.10$ marginally significant. Effectiveness of avalanche airbags was expressed as absolute risk reductions for critical burial and mortality.

For the multivariate analyses we used stepwise binomial logistic regression models starting with all available factors influencing grade of burial and mortality. $P > 0.10$ was used as the exclusion criteria for factors to prevent overfitting of the models. To make the results more interpretable, the parameter estimates were converted to adjusted absolute risk reduction and adjusted risk ratios for critical burial and mortality using the method of Kleinman and Horton.[13] A Monte Carlo simulation with 10,000 random samples from the analysis dataset was used to estimate the overall effect of avalanche airbags on mortality by combining their effect on grade of burial with the mortality model and to calculate associated confidence intervals.

2.2.2. Non-inflation rates and underlying causes

The dataset for this analysis included all accidents with avalanche airbag users (inflated and non-inflated) (Fig. 1). Information on the causes of non-inflations was taken from accident reports. The influence of external factors on deployment failure during involvements was analyzed using a univariate approach.

3. Results

3.1. Overview of dataset

The complete dataset consists of 245 avalanche accidents with information on 424 seriously involved individuals (Table 3). Eighty-three percent (204/245) of accidents records were from Europe and 15% (38/245) were from North America. Accidents occurred between the winters of 1994 and 2012 and 75% (183/245) occurred between 2007 and 2012. Out-of-bounds/off-piste skiing (including snowboarding) and backcountry skiing were the most prominent

Table 3
Number of accidents and seriously involved victims by country (percentages in brackets).

Country	Number of accidents	Number of seriously involved victims				
		Total	Non-users	Non-inflated	Inflated	Fatalities
Austria	63 (26)	110 (26)	30 (27)	14 (13)	66 (60)	13 (12)
Canada	28 (11)	62 (15)	25 (40)	15 (24)	22 (35)	19 (31)
France	74 (30)	95 (22)	7 (7)	10 (11)	78 (82)	13 (14)
Italy	12 (5)	23 (5)	9 (39)	2 (9)	12 (52)	6 (26)
Norway	4 (2)	15 (4)	9 (60)	0 (0)	6 (40)	8 (53)
Switzerland	49 (20)	93 (22)	28 (30)	17 (18)	48 (52)	15 (16)
USA	10 (4)	16 (4)	6 (38)	2 (13)	8 (50)	4 (25)
Others[a]	5 (2)	10 (2)	3 (30)	1 (10)	6 (60)	2 (20)
Total	245 (100)	424 (100)	117 (28)	61 (14)	246 (58)	80 (19)

[a] Denmark – Greenland (1 accident/1 victim), India (1/3), Russia (1/4), Slovakia (1/1) and Turkey (1/1).

activities, comprising 43% (102/245) and 35% (84/245) of accidents, respectively. All other activity types accounted for <10% each.

Overall mortality in the dataset was 19% (80/424) (Table 3). In total 58% (246/424) of victims had inflated airbags, 14% (61/424) had non-inflated airbags and 28% (117/424) did not have airbags. Ninety-nine percent (362/365) of victims carried avalanche transceivers.

3.2. *Effectiveness of airbags on grade of burial and mortality*

The reduced dataset for this analysis included 66 accidents with at least one user and one non-user leading to a total of 223 seriously involved individuals (Fig. 1; Supplemental Table 2). Compared to the excluded cases, the sample was older ($P = 0.033$) and included a higher proportion of backcountry skiing accidents (47% versus 31%; $P = 0.002$). While the avalanches included in this sample were larger (median size 2.5 versus 2.0; $P < 0.001$), no difference was found in the character of the runout zone. Furthermore, the percentage of avalanche professionals (e.g., mountain guides, ski patrollers) was lower (9% versus 29%; $P < 0.001$) and a higher percentage of victims was located in the track or runout zone when the avalanche was triggered (56% versus 24%; $P < 0.001$). Whereas no difference was observed in the severity of traumatic injuries, the mortality was higher in the analysis sample (26% versus 11%; $P < 0.001$). No difference was observed in the mortality of airbag users between the two samples ($P = 0.318$), but the rate of non-inflation in the sample dataset was higher (30% versus 14%; $P = 0.001$).

The univariate analysis showed an association between avalanche size and both grade of burial and mortality, where larger avalanches were associated with higher percentages of critical burials and fatalities (both $P < 0.001$). Location of the victim when the avalanche was triggered and grade of burial exhibited a marginally significant association, where a higher percentage of victims were critically buried when caught in the track or runout zone compared to the starting zone (55% versus 40%; $P = 0.059$). There was an association with severity of traumatic injuries, where major injuries were associated with higher percentages of critical burials (54% versus 34%; $P = 0.033$) and fatalities (46% versus 15%; $P < 0.001$). Critical burials were associated with a higher percentage of fatalities (61% versus 2%; $P < 0.001$). All non-critically buried fatalities were due to trauma. Finally, the univariate analysis showed an association between use of airbags and both critical burial and mortality (both $P < 0.001$) (Table 4). The absolute risk reduction for critical burial was −35 percentage points for users with inflated airbags and −29 percentage points when non-inflations were taken into account. The absolute mortality reduction was −23 percentage points for users with inflated airbags and −17 percentage points when non-inflations were taken into account (Table 4).

The multivariate analysis for critical burial and mortality included 61 accidents with 189 seriously involved individuals (Fig. 1, Supplemental Table 1). The non-inflation rate in this dataset was 28% (27/95). The regression model for critical burial showed main effects for airbag use, avalanche size and injuries (Table 5) without any interaction effects. Since initial models with airbag use as a three-level variable (not used, non-inflated and inflated) showed that non-inflated airbags did not have an impact on grade of burial, this variable was reduced to two levels (not used/non-inflated and inflated) for the regression analysis. Whereas the use of airbags reduced the odds of critical burial (Table 5), only grade of burial, injuries and avalanche size were significant in the regression model for mortality, highlighting that avalanche airbags only affect mortality indirectly by reducing the risk of critical burial.

Based on the method of Kleinman and Horton[13] the adjusted risk of critical burial was 47% for non-users and users with non-inflated airbags and 20% for users with inflated airbags. Similarly, the adjusted mortality was 44% for critically buried victims and 3% for non-critically buried victims. The overall effect of avalanche airbags on mortality was calculated by combining the results of the two models (Fig. 2). The overall adjusted mortality was 11% (95% confidence interval: 6 to 16%) for victims with inflated airbags and 22% (95% confidence interval: 15 to 29%) for victims with no or non-inflated airbags. The resulting adjusted absolute mortality reduction with inflated airbags was −11 percentage points (95% confidence interval: −4 to −18 percentage points), i.e., mortality was cut in half with inflated airbags (adjusted risk ratio: 0.51; 95% confidence interval: 0.29 to 0.72). Using the same two-step calculation but taking non-inflated airbags into account (not shown in Fig. 2), the adjusted absolute mortality reduction is −8 percentage points (from 22 to 14%; 95% confidence interval: −2 to −14 percentage points) and the adjusted risk ratio is 0.65 (95% confidence interval: 0.44 to 0.86).

3.3. *Non-inflation rates and underlying causes*

The overall non-inflation rate in the sample of airbag users was 20% (61/307). Information on suspected causes of non-inflations was available for 52 cases: 60% (31/52) were attributed to deployment failure by users, 12% (6/52) to maintenance errors (e.g., canister not attached properly), 17% (9/52) to device failures (i.e., performance issues that resulted in design and/or production revisions) and 12% (6/52) to destruction of the airbag during involvements. Relative to the total number of users, the rate of airbags destroyed in involvements was 2% (6/307) and the rate of device failures was 3% (9/307).

Of the users with inflated or non-inflated airbags due to deployment failure by the user, the non-deployment rate was 11% (30/277). Based on univariate comparisons the absolute risk of non-deployment for avalanche professionals was 5% (3/67) compared to 14% (28/196) for non-avalanche professionals ($P = 0.030$), resulting in an absolute risk difference of +10 percentage points. No association was observed between deployment and avalanche

Table 4
Univariate absolute risk reduction in critical burials and absolute mortality reduction with (a) inflated airbags and (b) non-inflated or inflated airbags (pp: percentage points).

a) Airbag use	Critical burial No	Critical burial Yes	Risk of critical burial	Fatality No	Fatality Yes	Mortality
No	49	62	54% (No and Yes – non-inflated)	77	40	34% (No and Yes – non-inflated)
Yes – non-inflated	15	13		22	10	
Yes – inflated	60	14	19%	66	8	11%
	Absolute risk reduction		-35pp	Absolute mortality reduction		-23pp

b) Airbag use	Critical burial No	Critical burial Yes	Risk of critical burial	Fatality No	Fatality Yes	Mortality
No	49	62	56%	77	40	34%
Yes – non-inflated	15	13	27% (Yes – non-inflated and Yes – inflated)	22	10	17% (Yes – non-inflated and Yes – inflated)
Yes – inflated	60	14		66	8	
	Absolute risk reduction		-29pp	Absolute mortality reduction		-17pp

Table 5
Regression models for critical burial and mortality.

Parameter	Level	Estimate	*P*-value	OR (95% conf. interval)
(a) Model for critical burial with inflated airbag				
Intercept		−3.753	<0.001	0.023 (0.005–0.109)
Airbag use	No or Yes—non-inflated	0.000		
	Yes—inflated	−1.504	<0.001	0.222 (0.098–0.472)
Traumatic injuries	None or minor	0.000		
	Major	0.799	0.072	2.223 (0.935–5.375)
Avalanche size		1.377	<0.001	3.965 (2.258–7.278)
(b) Model for critical burial with non-inflated and inflated airbags combined				
Intercept		−3.715	<0.001	0.024 (0.005–0.114)
Airbag use	No	0.000		
	Yes—non-inflated or inflated	−1.029	<0.001	0.357 (0.181–0.693)
Traumatic injuries	None or minor	0.000		
	Major	0.831	0.055	2.295 (0.983–5.431)
Avalanche size		1.370	<0.001	3.936 (2.257–7.158)
(c) Model for mortality				
Intercept		−6.970	<0.001	0.001 (0.000–0.011)
Burial	Non-critical	0.000		
	Critical	3.983	<0.001	53.653 (14.026 – 364.873)
Traumatic injuries	None or minor	0.000		
	Major	2.032	0.002	7.630 (2.289–31.177)
Avalanche size		0.951	0.020	2.589 (1.190–6.019)

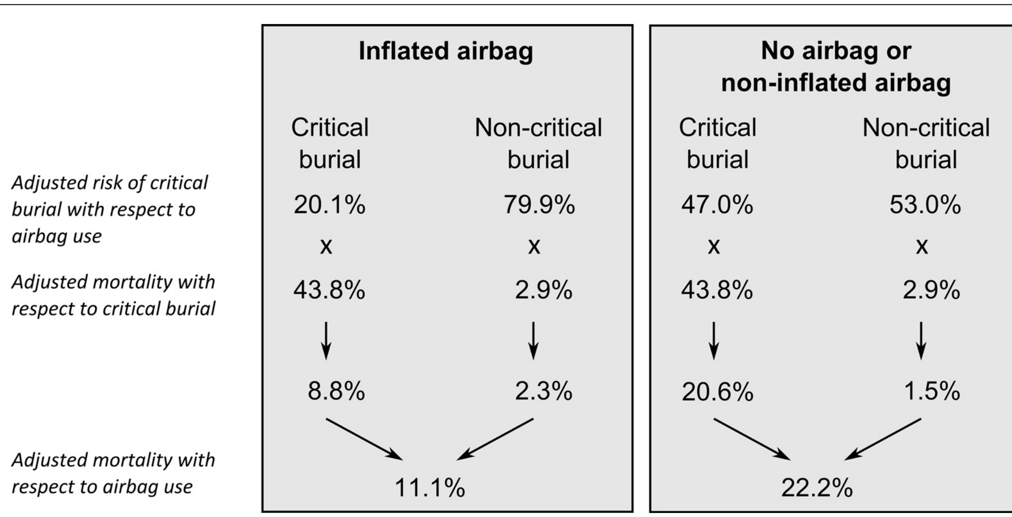

Fig. 2. Calculation of adjusted mortality with respect to avalanche airbag use.

size. Univariate analyses for other causes of non-inflation were not possible due to small sample sizes.

4. Discussion

This study evaluated the effectiveness of avalanche airbags for the first time in a process-oriented fashion that explicitly acknowledges that airbags affect mortality indirectly by reducing the risk of critical burial. In comparison to a previous statistical evaluation,[11] these results were derived using a multivariate approach with a larger and geographically more diverse dataset, focused on serious involvements only and with an unbiased control group.

Whereas these results support findings that airbags reduce mortality in serious avalanche involvements, the effect is lower than the previously reported absolute mortality reduction of − 16 percentage points (19% mortality in non-users versus 3% mortality in users of inflated and non-inflated airbags).[12] While the absolute mortality reduction in our dataset is similar using an equivalent univariate analysis (−17 percentage points), the adjusted absolute mortality reduction using a multivariate perspective is lower (−8 percentage points; 95% confidence interval: −2 to −14 percentage points). The difference in the two estimates highlights the importance of both controlling for other factors that affect mortality (i.e., avalanche size and traumatic injuries) and properly representing the effect of airbags via critical burials. The lower mortality reduction in this particular comparison is partially caused by the considerably higher non-inflation rate in the present dataset (28% versus 20%[11]), However, the adjusted absolute mortality reduction of −11 percentage points (95% confidence interval: −4 to −18 percentage points) revealed by the comparison of users of inflated airbags versus non-users and users with non-inflated airbags—the upper limit of the effectiveness of airbags under the conditions of the analysis dataset—is still lower than previous estimates.

The observed overall non-inflation rate of 20% (61/307) clearly highlights that non-inflations still pose a considerable threat to the performance of avalanche airbags. Deployment failure by the user was identified as the main cause of non-inflations. Whereas the independence of deployment rate and avalanche size indicates that non-deployments are not the result of more violent avalanche involvements, the lower failure rate among avalanche professionals suggests that familiarity with avalanche airbags and their deployment may improve the use of these devices. By extension, familiarity with deployment procedures and proper maintenance are paramount for ensuring that airbags work properly.

Furthermore, absolute mortality for airbag users was higher (11%) than in a previous study (3%).[11] While this difference is partially a result of the cases included in this analysis (i.e., larger avalanche accidents with multiple involvements), it also highlights that avalanche airbags do not guarantee survival under all circumstances. Even if every victim in the present dataset had been equipped with inflated airbags, one of every nine victims would have died.

While there is no empirical evidence to date on risk compensation behavior with avalanche airbag use, it is a common concern when weighing their potential benefits. Interestingly, the parameter estimates from the binomial regression model on critical burial indicate that the effect of using an airbag on critical burial is roughly the same size as the effect of avalanche size. Thus, the risk reduction gained from the use of an airbag is equivalent to the risk increase from being involved in an avalanche of one size class larger. Even though risk compensation was not explicitly analyzed in this study, these results show that personal safety benefits from airbags are quickly nullified if used to justify increased exposure to avalanche hazard.

4.1. Limitations

In order to extract an appropriate control group, the sample used for the analyses was substantially smaller than the complete dataset—65% (201/307) of all records with avalanche airbag users were accidents with single users—and included larger avalanches with multiple involvements. The analysis dataset also had a lower percentage of avalanche professionals and a higher percentage of victims located in the track or runout when the avalanche was triggered. While absolute mortality in the complete dataset (i.e., with single involvements and smaller avalanches) was lower than in the analysis dataset, it is unclear how the effectiveness of airbags shown in the present analysis transfers and contributes in relation to the reduced mortality from the smaller avalanche sizes and other differences.

5. Conclusions

Avalanche airbags are a valuable avalanche safety device, but the impact on mortality is lower than previously reported and they do not guarantee survival. Non-deployment remains the most considerable limitation to effectiveness. While our results show that avalanche airbags can reduce mortality in serious avalanche involvements, a larger dataset of accidents with airbag users would allow the integration of interaction effects to better define situations where this device does or does not provide benefit. However, collecting reliable avalanche accident data is challenging and records are often incomplete. We encourage national avalanche safety agencies, international bodies and airbag manufacturers to develop standardized data collection protocols and reporting guidelines to increase the comparability of data and avoid misleading statements on the impact of these devices.

Conflict of interest statement

This study was not supported financially or materially by any manufacturers of avalanche airbags. None of the authors are involved financially in the production or sale of avalanche airbag nor have they received any related grants or patents.

Acknowledgements

We thank the many individuals who contributed to the collection of avalanche accident information and made this research possible.

References

1. International Commission for Alpine Rescue (ICAR) [accessed 10.03.14] http://www.ikar-cisa.org/eXtraEngine3/WebObjects/eXtraEngine3.woa/wa/menu?id=298&lang=en
2. Boyd J, Haegeli P, Abu-Laban RB, Shuster M, Butt JC. Patterns of death among avalanche fatalities: a 21 year review. CMAJ 2009;180:507–11.
3. Brugger H, Durrer B, Elsensohn F, Paal P, Strapazzon G, Winterberger E, et al. Resuscitation of avalanche victims: Evidence-based guidelines of the international commission for mountain emergency medicine (ICAR MEDCOM): intended for physicians and other advanced life support personnel. Resuscitation 2013;84:539–46.
4. Hohlrieder M, Brugger H, Schubert HM, Palvic M, Ellerton J, Mair P. Pattern and severity of injury in avalanche victims. High Alt Med Biol 2007;8:56–61.
5. McIntosh SE, Grissom CK, Olivares CR, Kim HS, Tremper B. Cause of death in avalanche fatalities. Wilderness Environ Med 2007;18:293–7.
6. Haegeli P, Falk M, Brugger H, Etter HJ, Boyd J. Comparison of avalanche survival patterns in Canada and Switzerland. CMAJ 2011;183:789–95.
7. Brugger H, Durrer B, Adler-Kastner L, Falk M, Tschirky F. Field management of avalanche victims. Resuscitation 2001;51:7–15.

8. Falk M, Brugger H, Adler-Kastner L. Avalanche survival chances. Nature 1994;368:21.
9. Kern M, PhD thesis Inverse grading in granular flow. Lausanne, Switzerland.: École Polytechnique Fédérale de Lausanne; 2000 http://biblion.epfl.ch/EPFL/theses/2000/2287/EPFL_TH2287.pdf [accessed 10.03.14].
10. Tremper B. Staying alive in avalanche terrain. 2nd ed. Seattle, WA: The Mountaineers; 2008.
11. Brugger H, Etter HJ, Zweifel B, Mair P, Hohlrieder M, Ellerton J, et al. The impact of avalanche rescue devices on survival. Resuscitation 2007;75:476–83.
12. Canadian Avalanche Association (CAA). Observation guidelines and recording standards for weather, snowpack, and avalanches. Revelstoke, Canada: Canadian Avalanche Association; 2007.
13. Kleinman LC, Norton EC. What's the Risk? A simple approach for estimating adjusted risk measures from nonlinear models including logistic regression. Health Serv Res 2009;44:288–302.