Patophysiology of Snow Avalanche Death

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Abstract
Our article is focused on pathophysiology of snow avalanche death. It analyses available information based on literature search. The goal is the summarization and clarification, based on numerous researches and case interpretations, in the field of pathophysiology when buried under a snow avalanche. It is mainly focused on the hypercapnia and hypoxia issues during breathing into the snow and also on hypothermia and gas diffusion. We assume that our results will be used for next surveys and for improvement the recent findings.

Key words:
hypoxia, hypercapnia, hypothermia, avalanche, air cavity

Souhrn
Tento článek se zabývá patofyziologií úmrtí ve sněhové lavině. Analyzuje současný stav poznatků na základě rešerše literatury. Cílem je sumarizace a objasnění na základě četných výzkumů a kasuistik v oblasti patofyziologie úmrtí při zasypání sněhovou lavinou. Zejména se zaměřuje na problematiku hyperkapnie a hypoxie při dýchání do sněhu, ale také se zabývá hypotermií a difuzí plynů. Předpokládáme, že tyto poznatky budou využity pro další výzkum a zpřesnění současných poznatků.

Klíčová slova:
hyperkapnie, hypoxie, hypotermie, lavina, sněhová kapsa

Introduction

Recently, high-mountain tourism has been going through a great boom which is connected with other sport disciplines (ski-alpinism, mountaineering and other outdoor sports). These activities might be the risky ones and that is why the athletes should have appropriate knowledge and skills. One of the most serious problems at the mountains during winter is the avalanche jeopardy. It is often underestimated even when dozens of people die in avalanche every year (www.ikar-cisa.org/ikar-cisa). Mountaineering, ski-alpinism, and off-piste skiing are activities which cause absolute majority of avalanche accidents. For people moving at places with avalanche risk, it is crucial to know the procedures when swept by avalanche. More important is the knowledge of avalanche risk, to be able to recognize it, know how to avoid it, use the proper routes through slopes and to have proper and working avalanche equipment (avalanche transceiver, probe, snow shovel and first aid kit).

According to the researches and statistics data of alpine countries, 52% of buried people die under avalanche (Falk 1994, Brugger 2001). Factors, lowering the survival probability under avalanche are mostly linked with hypercapnia, hypoxia and hypothermia. There is enough air in powder snow yet problem is the increasing concentration of CO_2 in snow air cavity. Another factor affecting the time of survival is the compression of chest by its mass and snow impact. Not the last are also the matters of psyche. Fast and effective help together with the existence of an air-cavity and the possibility of CO_2 diffusion are important for increasing the probability of survival under avalanche.

Present Czech literature gives only general information about human staying under snow avalanche. It was particularly authors Vrba and Urbánek (1957), who focused on metamorphosis of snowflake what was very useful in their times for avalanche prevention. There are many recommended general procedures for people buried under avalanche which are mainly based on processed casuistic. Survey in this field presently conducts Mašek (2014) who measures human physiological changes during breathing into snow cavities of various volumes and compares it with breathing into death-space. This research should clarify the issue of survival under snow avalanche.

Nowadays, avalanches come under the scrutiny in the world. Primarily, it is due to the reasons of prevention yet the rescue of avalanche victims plays also important role. The most common victims are ski-alpinists, skiers and snowboarders who ride off-piste, mountaineers and, in the USA and Canada, it is snowmobile riders (http://avalanche.state.co.us). All these activities are being conducted at remote areas, far from ski resorts what means that it is difficult to check them for avalanche accidents (Brugger 2001, Boyd 2009). During years 1994 – 2003, the median of annual mortality rate of avalanche accidents in Europe and the North America was 141 people (Hohlrieder 2007).

Avalanche accidents in Europe have been monitored by ICAR – CISA (International Commission for Alpine Rescue) when information are available in the internet (www.ikar-cisa.org) and majority of recommendations are based on statistics and evaluated causalities. In European region, it is just ICAR – CISA which is unwritten authority for high-mountain medicine and which evaluates the mentioned statistics. In the Czech region, these are gathered and evaluated by security committee of the Czech mountaineering association (www.ikarcisa.org) in coop with medicine committee (www.horosvaz.cz) and the Society of mountain medicine (www.horskamedicina.cz).

According to Falk et al. and other authors, the chance to survive an avalanche accident depends on a few factors:

- seriousness of a traumatic injury
- time of a bury under snow
- extent of a bury under snow
- depth of a bury under snow
- existence of an air-cavity

Goal

The goal of our article is to analyses the findings published in specialized journals and publications focused mostly on avalanche issues in branches like hypercapnia, hypoxia and hypothermia. The surveys are based on casuistic and experiments which were conducted on volunteers and animals.

The literature search was conducted by looking out specialized articles on specialized servers (web of science, web of knowledge) and at the library of ČVUT Prague through computer-aided retrieval of key words and authors who work on determined issues.

Pathophysiology of avalanche deaths

On the basis of European and American analysis of death cause in avalanche, the main cause of death is suffocation, reaching the rate of 90% (Falk 1994, Logan 1996, Grossman 1989). Hypothermia and traumatic injuries is less statistically important. Analysis of some authors indicates high rate of traumatic injuries (almost 25% of all accidents) see Table No. 1. These differences are due to diverse geographic determinants. At wooded or rocky areas, it is possible to expect higher probability of traumatic injury rather than at open and plain slopes. It is important to count with these results when applying at different geographic areas. Higher rate of traumatic injuries as a cause of avalanche deaths is also caused by new technologies, e.g. Airbag system which is active avalanche protection which prevents an avalanche victim against bury and decrease their probability of suffocation.

Face, skull and rib fractures linked with pneumothorax and pulmonary contusion together with internal bleedings and long-bone fractures are typical avalanche injuries.

Table 1 Death causes in avalanche (Hohlrieder 2007, McIntosh, Boyd, et.al, 2009)

	Suffocation (%)	Trauma (%)	Hypothermia (%)	In total (%)	Incidents
Hohlrieder et al.	92	6	2	100	39
McIntosh et al.	95	5	---	100	56
Boyd et al.	75	24	1	100	204

Time of burial

Survival probability of completely buried victims in open terrain, based on data of Alpine countries from years 1982 – 1998 (n=735) shows quick decrease from 91% in 18th minute to 34% in 35th minute. This period is called "phase of acute suffocation without air-cavity." Another decrease between 35th and 90th minute is not as steep. A victim has free respiratory system, set up air-cavity which is being closed, though. As a result of temperature difference between outer area and exhaled humid air, this humidity began to condense, followed by its freezing at the walls of air-cavity. Emerged crust makes impossible any process of gas diffusion (O2 and CO2). This phase is called "phase of air-cavity closure" and brings consequences of hypoxia and hypercapnia. Upcoming decrease to about 7% in 130th minute is the result of slow hypercapnia at created air-cavity altogether with hypothermia (Falk 1994, Brugger 2001), sees Picture No. 1.

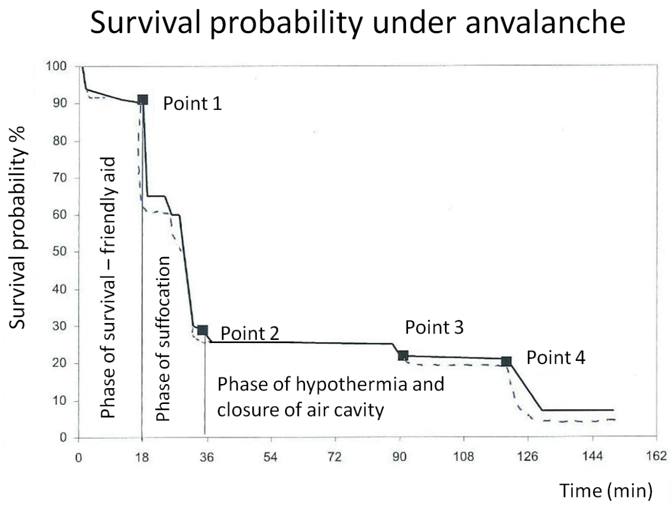

Figure 1 Survival probability curve of completely buried of Alpine countries between years 1981 and 1998, n=735 (full line) (Falk 1994) compared with survival probability curve from years 1981 – 1991, n=422 (dashed line) published earlier (Brugger 2001).

Extent of burial

The extent of burial is one of the key factors influencing probability of survival under the snow avalanche. The definition of complete burial states that this is when a victim is completely buried and the snow covers their body and head. All the other cases mean that we speak about partial burial (Brugger 2001). The analysis of Alpine countries avalanche accidents between years 1981 and 1998 on 2000 accidents shows that total mortality reaches 23%. This rate grows up to 52% for victims who were completely buried. On the other hand, for cases of partial buried victims, the mortality rate decreases at only 4% (Brugger 2001). In these numbers, we can assume that most of partial buried were not reported. It is estimated that the number of non-recorded cases might be as twice higher as the recorded ones. This effect reduces probability of death during partial burial under mentioned 4% (Brugger 2009). The most of avalanche deaths are connected with complete burial. This is why the active avalanche protection systems are recommended for skiing and off-piste activities. The systems are built in a carried backpack, might be activated by users themselves and increase the chance of survival by protecting them from complete burial. Probability of user not being buried or being buried only partial is 95% or higher (Chardon 2007, Brugger 2007). The producer of avalanche backpacks ABS presents even 97% of survival out of 250 avalanche accidents when using ABS system (http://abs-airbag.de). Other producers are SNOWPULSE and BCA companies whose systems are used at Deuter and Mamut backpacks.

Depth of burial

Depth of burial is closely connected with the extent of it (Burtscher 1994). In average, a head is buried 70 cm under the surface. A dependency between depth of burial and probability of survival, when counting with the time of burial, was impossible to prove. We cān only assume that probability of survival depending on time is linked with the longer time of extrication yet it is unknown if the probability is influenced by snow pressure.

Air cavity existence

A big amount of surveys and authors research the procedures and methods for victim rescue (Brugger 2001). They deal with forms of digging to avoid collapse of an air cavity in front of face, management of rescue and the time schedules of every operation step. Some surveys focus on measurement of asphyxia or hypercapnia under the snow (Windsor 2009, Grissom 2000, Radwin 2001, Brugger 2009). Important for our research is the one which measured hypercapnia during breathing into air-cavity of one and two liters volume (Brugger 2003). His research was conducted at 1640 meters above sea level altitude with 12 subjects (4 female and 8 male). Their average age was 25 years (between 18 and 29 years). Implementation of the research was conducted during 4 days (15th – 16th APR 2000 and 17th – 18th FEB 2001. The conditions of the first measurement were: air temperature median 4,8°C (range 6 – 6,8°C), air pressure median 84,3 kPa (range 84 – 84,7 kPa), snow temperature median 0°C (range -1 – 0,1°C), snow density median 470kg/ m^3 (range 330 – 593 kg/ m^3). The conditions of the second measurement were: air temperature median -1°C (range -2,8 – 0°C), air pressure median 82,5 kPa (range 82,3 – 82,7 kPa), snow temperature median -1,4°C (range -2,3 – 0 °C), snow density median 275kg/m^3 (range 139 – 376 kg/m^3). This research was mainly focused on measuring the variance SpO_2 (%) and the variance of $ETCO_2$ (kPa) increase. Also, the time until the interruption was measured in both air-cavity volumes altogether with quantifying the differences between SpO_2 when breathing either into 1 liter or 2 liter volume of air-cavity. The authors chose non-parametric Mann-Whitney U-test for comparison. The evaluation of relationship between air-cavity size and lowering peripheral O_2 by SpO_2 saturation was executed by Box-test. The research also showed the correlation between specific snow density (kg/m³) and lowering peripheral O_2 by SpO_2 saturation in the first 4 minutes (r = 0,50, P = 0.021).

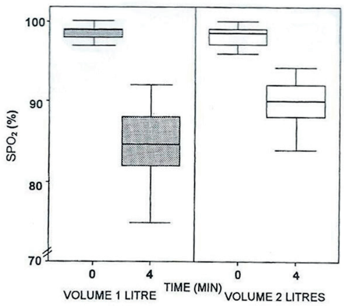

Figure 2 Box graph of relationship between lowering peripheral O_2 (SpO_2 %) saturation and the size of air-cavity (n=28). Boxes show inter--quartile range. The line inside the graph means median. Up and down antennas point at the highest and lowest figures. Median SpO_2 % is lowering during first four minutes of breathing into the air-cavity of 1 liter volume from 99% (range 96 – 100 %) to 84% (range 71 – 92%). When speaking about 2 liters air-cavity, the SpO_2 % is lowering from 98 % (range 93 – 100 %) to 90 (range 82 – 94 %). Mann – Whitney U-test, P = 0,003 (Brugger 2003).

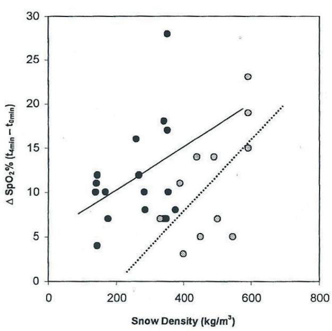

Figure 3 Shows correlation between the peripheral O2 (SpO2 %) saturation and the specific snow density (kg/m³) in the first four minutes of burial. The grey points show results of the first part of experiment (n=12) while the black ones show results of the second measurement (n = 16), (Brugger 2003)

Another source is the research conducted on pigs (Paal, 2012) which compared breathing into 1 liter cavity and open, unlimited space during complete burial. Out of so called "Triple H Syndromes" (hypoxia, hypercapnia, hypothermia), mainly hypothermia was measured. The Declaration of Helsinki (2008) forbids hypothermia experiments on humans, and so the pigs were used for that purpose. Even though the Ministry of Science and Research approved it and survey itself was conducted by University of Medicine in Innsbruck altogether with Institute of Urgent Medicine of European University in Bolzano, mostly environmentalists protested against it and so the research was terminated earlier. Nine animals were successfully measured during complete burial, though. They were always put into sleep and subsiding preparations were applied. The temperature of core decreased very quickly, in average of 15 °C h^{-1} in first ten minutes at both groups. The first group breathed into unlimited air cavity while the second one breathed into air cavity of 1 liter volume. Lowering the temperature this quickly brings also decrease in metabolism. Another studies, according to the authors, should focused on relationship among the size of air cavity, specific snow density, speed of hypothermia, hypoxia and hypercapnia during avalanche burial (Paal 2012). Problems of rising hypercapnia considering the snow cavity closure are topic of other researches (Radwin 2001, Grissom 2000, Windsor 2009). These surveys are focused on increasing the chance of survival when using special breathing devices. The common attribute of these devices is utilization of snow diffusivity and gaining O2 for inhaling, when exhaling is led behind the body of a subject by tubes what does not lead to hypercapnia and the time of survival dramatically increases. A big disadvantage of these devices is the necessity of putting them into victim´s mouth during being swept by avalanche. Measuring the gas diffusion in snow (Seok, 2009) was the issue of research in Colorado, when a group of scientists measured simple gas diffusion in snow which fell onto the device assembled for measurement. This survey has been conducted during whole winter season and its results are mostly focused on environment.

Discussion

According to researches, digging a victim out off the avalanche is crucial for their survival in first 15 to 18 minutes. This particular time, when victims die mostly due to acute phase of suffocation, is critically short. That is why so called "friendly aid" is decisive. Not only proper equipment (avalanche transceiver, probe and snow shovel) is needed for this type of rescue but also the knowledge how to use it. Today, localization of victims is very precious thanks to modern, digital avalanche transceivers. The biggest delays occur during digging victims out. Therefore, this phase of rescue should be well organized and trained. Airbag backpack is another part which appears nowadays among protection tools. Although it is financial demanding, it is the only active protection of present days. This system works on a base of big volume of inflated bags which help to swim out of the avalanche. Particular producers claim the successfulness of victim not being buried or being buried only partial as 94% or higher under condition of activating the system in time. The same importance has services of experienced instructors and mountain guides who can move in risky terrain and know the risks and make them as minimal as possible. For safety, it is also important to respect the levels of avalanche risk and adjust your movement according to them altogether with the other information (weather, size and experience of a group, equipment, etc.).

According to valid norms ICAR - CISA (Soar 2010), the air cavity is a condition of victim not having snow in respiratory system and mouth. It was the reason why authors Sýkora and Mašek decided to follow prior study of Brugger (2003) and manage a measurement of human functional changes during breathing into air cavity of 0 or 1 liter volume. We were able to record more values thanks to better devices which were not disposal for our predecessors. We use the same number of subjects breathing both into 1 liter and 2 litres volume and so calculation will be conducted by Wilcoxon pair non-parametric test. The part of the survey is also finding out a diffusivity of snow during burial. Creating a model of CO2 diffusivity can contribute to better understanding of phenomenon happening during burying. We also hope our research can be helpful for products which increase survival chance of avalanche accident victims.

Conclusion

Out of particular studies, it is obvious that quick and correct help given to avalanche accident victims increases their chance to survive. The most common death cause is asphyxia. It is very often combination of hypoxia and hypercapnia. That is why the existence of air cavity is crucial during burial under snow avalanche. Another factor which is not to be omitted is hypothermia. We speak about so called "triple H syndrome" (hypoxia, hypercapnia and hypothermia). Some studies also show a link between hypercapnia and hypothermia pointing out the fact that hypercapnia victims suffer of distinctively faster hypothermia (Paal 2012, Radwin 2001, Grissom 2000, Windsor 2009).

We have to pinpoint the fact that not even up-to-date technical avalanche systems lead to lowering the avalanche risk to zero. Except for airbag backpacks, all the other systems are passive avalanche devices which simplify and accelerate seeking and digging the victims out of avalanche. Also the only active system, airbag backpack, is not hundred percent effective due a high percentage of their successfulness influenced by statistical data in avoiding a burial or partial burial. These statistics do not count with mechanical injuries which, according to Falk (1994) and Brugger (2001), are a reason of 8% deaths. According to these data, 52% of dug out victims are dead.

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